THE NEED FOR AN INTEGRATED COMPUTER-BASED TOOL TO SUPPORT BUILDING ENVELOPE DESIGN

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ABSTRACT

The building envelope design process has to reconcile two value systems: the qualitative aspects stemming from architectural design and the scientific requirements of building science and engineering. The product, the building envelope, is the result of a selection process among numerous materials, systems and their configuration. A need for computerized assistance to support this design process, which has a complex array of performance attributes and alternatives, explains the development of some tools. However, there is seldom any integrated support with characteristics like qualitative and quantitative validation, user-friendliness and effective database. To develop such an integrated system, a complete understanding of the building envelope design process and of the existing computer tools is required. This paper presents a review of the building envelope design process, and the support rendered by the existing computer tools. The paper highlights the different aspects of this process and their related knowledge base that has not been incorporated in tools so far. This paper therefore is a first step in analysing the integration of qualitative and scientific aspects of the building envelope design with the same computer tool.

INTRODUCTION

Due to the ongoing developments in technology, and understanding of the relationship with the environment, there is a consistent increase in complexity of engineering problems. Problems are not solved by individuals anymore, but by teams characterized with mutual co-ordination, between professional disciplines, methods and modes related to the subject problem. A familiar mode at present, to solve the complexity of many engineering problems is to support the human mind with computer applications.

Building envelope design is one such domain, where a contribution of diverse disciplines mainly architecture and building engineering with support from material science, thermodynamics, chemistry, project management etc., are required to meet the multiplicity of needs posed by the human and the environment. The steady increase in the understanding of the building envelope performance has been somewhat coupled with a growth in the automation of the building envelope design process. Nevertheless, this automation is scattered and only serves the tasks imposed on their related disciplines, which are realised as 'island of automation' [Howard *et al*., 1989].

The building envelope design process has to reconcile two value systems: the qualitative aspects stemming from architectural design and the scientific requirements of building science and engineering. The decision-making approach on subjective issues, like colour, texture, form and pattern, in architecture is open-ended, and is very meekly bounded by scientific rules, codes or regulations. A systematic design approach can support and refine the architectural design process, however the limitation, i.e. the incapability of evaluating design decisions entails a logical approach, which can only be handled by human capabilities such as experience, tradition and intuition. On the other hand, the building science and engineering aspect of the building envelope design process is amalgamated with analytical and logical approaches. The scientific approach, with the aid from building science principles, started around the late 30's [Bomberg and Brown, 1993], but was mostly introduced in practice after the energy crisis of the 70's. This approach with the available extent of knowledge plays a role in the conceptual and preliminary design stages for better building envelope performance, specifically in terms like building failures and energy efficiency. There are many computer tools with analytical and numerical backgrounds to provide a quantified evaluation of various systems of building envelope, supporting the scientific aspect. However, due to the difference in nature of approaches, i.e. the logical and analytical approaches, and the difference in the working trend of architects and engineers, it is not clear to what extent the available tools effectively help designers. Hence, there is a need for an integrated tool to support and synchronise the approaches and working trend of building envelope design process.

Hutcheon, [1963] delineates the function of building envelope as, to control heat flow, air flow and vapour flow; prevent ingress of rain; and control solar radiation, noise, airborne pollutants, and smoke and fire propagation. Furthermore, the envelope needs to be structurally sound, durable, aesthetically pleasing, economical, and should support the function of the building. Among the factors, heat, air and moisture (HAM) control are found to be critical and to some extent described using scientific theories. The problem of HAM control in the building envelope design process however cannot be solely solved with the available analytical capabilities, with confidence and completeness. In almost all instances, there is interdependence between the various scientific methods, such as experimental, numerical and analytical, braced with the decisions made out by humans. Hence, the building design problems related to HAM control in practice are usually tackled by logical thinking with the help of a knowledge base, developed by proven design situations and scientific results. The currently available models allow some checking of performance but are not structured to support the building envelope design process. Hence, there is a need to address the issue of inclusion of knowledge base into a computer tool to better support the building envelope design process.

REQUIREMENTS

Building envelope design process requires three levels of integrated computer support within a design tool: (i) support the integration of different working trends, mainly architectural design and engineering design; (ii) support both logical and analytical methods; and (iii) include a knowledge base obtained from the scientific community and proven design practices. To assess the existing solutions for the above stated supports, two subjects were investigated: (i) literature survey of the building envelope design process; and (ii) literature survey and evaluation of existing computer tools.

BUILDING ENVELOPE DESIGN PROCESS

The Building envelope design process can be looked at from two perspectives: architectural and engineering. Building envelope design, in general, is a decision-making process requiring expertise for the selection of materials and construction systems [Fazio *et al.,* 1989].

The building envelope design process, from a perspective of architectural practice, is ill defined. There is no clear-cut methodology to explain the working trend of an architect in the building envelope design process. However, there are some attempts to understand and systemise the design process, which is dealt in detail in the *Architectural Design Process* section.

The envelope assembly cannot exist by itself in a building. It is one of the four systems of a building. It is closely related to the other systems: interior, structure and services. All the four systems are considered together in some part of the envelope design process in order to achieve a specified level of integrated performance [Rivard *et al*., 1995]. The envelope components like exterior walls, roofs, windows and doors are developed during the conceptual, preliminary and detailed design stages of the building.

Rivard *et al.* [1995] decomposes the building envelope design process, into five phases: (i) definition of major envelope components; (ii) building energy simulation; (iii) structural design of the building envelope; (iv) detailing of connections between envelope components; and (v) initial and maintenance costs estimation. The first phase, *i.e.* definition of major envelope components, is decomposed further into two activities: (i) determining the building envelope sections; and (ii) selecting the opening. The conditions for evaluation of these two activities are mostly based on the HAM control, which are discussed in the *Building Science and Engineering* section.

ARCHITECTURAL DESIGN

Architectural design is the source of several decisions, which involves a complex array of analytical, logical, and subjective issues. The primary challenges of the architectural design are to be more responsive to needs and to be more predictable and reliable [Laseau, 1980]. It involves synthesis and judgment on the basis of tradition, intuition and experience.

In practice the diverse challenges of architectural production, are tackled through a process of graphic thinking. Graphical language as denoted by Laseau [1980], serves two purposes: it reinforces the logical thinking of the architect; and it helps to convey the idea to other members involved in the project.

"Most creative architects had developed impressive freehand sketching skills and felt comfortable sketching while thinking. Some architects drew observations or design ideas in small sketchbooks they carried with them at all times [Laseau, 1980]."

The successive stages of the process are usually recorded in some kind of graphic model. In the early stages, the drawings are conceptual, made of free hand (quick sketches and diagrams), whereas in the later stages, they are in highly formalized graphic languages such as those provided by descriptive geometry [Laseau, 1980]. Laseau reports and relates various graphical forms, their grammar and characteristics used in the design process.

The design process can be thought of as a series of transformations going from uncertainty towards information. Technological innovations and advancements require more of a systematic approach than an artifact approach. A systematic approach provides a clear understanding of the goal, the problem and the process of design. It attempts to provide a holistic solution for any design problem. Moreover, a systematic approach is the essence required for automating any process using information technology. Archer [1963a] identifies a systematic approach for design process, through fragmentation and systemizing. A design process such` as building design is a goal seeking activity, which can be divided into fragments of design problems using guidance factors like constraints in case of a close-ended project (a problem primarily driven by constraints) [Archer, 1963b]. The fragmented design problems can be more easily solved than the un-fragmented whole design problem. Hence, some of the characteristics of the architectural design process are generating creative ideas, graphical thinking, logical reasoning, case based reasoning (reasoning by experience), and fragmentation and systemising the design process. The corresponding computer tools for the architectural design process are EsQUIsE and Archie, which are dealt in the *Existing Computer Support* section.

BUILDING SCIENCE AND ENGINEERING

The analysis of the performance of envelope assemblies with respect to HAM control must consider the envelope as an integrated system, where constituents are connected to each other and where heat, air and moisture have interrelated effects [Derome, 1999]. Compared to heat transfer, moisture transfer is a more complex phenomenon that involves different materials, and moisture (vapour and liquid) movement and accumulation. Also, moisture transfer has a slower time of response. The many parameters involved in moisture movement, i.e. time, temperature, relative humidity, moisture content of material, sorption history etc., make the description of its physical process complex.

HAM models can be first denominated into moisture models and non-moisture models, since 90% of the building failures are due to moisture problems. On the basis of the capabilities to provide a realistic simulation situation, moisture related models can further be categorized into three types: (i) Simplified models, to simulate the effect of vapour diffusion and identify the possibilities of interstitial condensation and their location (*e.g.* Steady state dew point method or Glaser method [ASHRAE, 1997]); (ii) Simplified models, to simulate the effect of vapour diffusion, effect due to rain load, identify condensation and quantify the amount of moisture contained in the envelope section with respect to time (*e.g.* Numerical Models recommended by International Energy Agency (IEA), Annex 24 [Hens, 1996] and WUFI model [Kuenzel, 1995]); and (iii) Advanced Hygrothermal Models capable of simulating realistic situations, considering the complex phenomena such as air infiltration, rain penetration, moisture content dependent material properties etc., in two or three dimensions (*e.g.* hygrothermal model used in MOISTURE-EXPERT [Karagiozis, 2001], Transient Coupled Convection and Conduction in 2D structures (TCCC2D) [Ojanen, 2001] and hygIRC [Kumaran, 2001]).

On one hand, simplified models incorporate more limiting assumptions with respect to physics, environmental loads, geometry, and material property inputs. As a consequence, these design tools cannot be applied to all building envelope conditions of interest [Karagiozis, 2001]. On the other hand, the advanced models are sophisticated to the level where they cannot be used directly by designers.

EXISTING COMPUTER SUPPORT

Rivard *et al.* [1995] lists a series of packages used in Canada, under the following classification: (i) drafting packages; (ii) word processors; (iii) tools to analyze and design envelope sections; (iv) building energy simulation software; (v) estimating packages; (vi) tools to analyse window energy performance; (v) tools to evaluate the structural performance of the building frame; and (vi) tools to establish maximum percentage of glazing area. All of the applications are generally self-contained in addressing the problems of their own domain, and do not communicate among themselves [Rivard *et al.,* 1995].

The architectural design process as explained in the above sections follow a subjective working trend and lacks defined procedures. Nevertheless, there are attempts to develop computer tools to support the architectural design process.

EsQUIsE is an experimental computer based prototype for capturing and interpreting the architect's sketch by locating: border line, functional space, and topology. The aim of this prototype is to compose a spatial semantic representation of the architectural project in order to feed diverse evaluation routines and serve as a tool with interface that complies to the designer's working technique. EsQUIsE uses a pen-based interface, which performs the capture and the synthesis of the lines drawn on the digital tablet. The lines are drawn in black, blue and magenta representing opaque walls, glazed walls and comments respectively [Hauglustaine, 2001]. This is an effort towards a better man-machine graphic mode interaction.

Archie is a small computer-based library system developed by Pearce *et al.* [1992], which is a prototype for a case-based design support for decision-making in architecture. The concept of Archie is on the basis of few initial decisions: (i) the system is able to support common design tasks but leave all decisions to users, (ii) the system applies only to the design of office buildings and (iii) the system supports the conceptual design stage [Pearce *et al.,* 1992].

The concerns for moisture control in buildings have increased significantly since the early 1980s. There are more than 30 computer models that can analyze the hygrothermal performance of building envelopes [Treschsel, 2001]. Treschel classifies them into simplified models, that are usable by building practitioners on PCs, and sophisticated models, that require trained knowledge and can run on mainframe computers. The book, *Moisture Analysis and Condensation Control in Building Envelopes*, edited by Treschel (2001), lists WUFI-ORNL/IBP, MOIST, WUFI 2D, MOISTURE-EXPERT, LATENITE, SIMPLE FULUV, TRAMTO2 (Transient Analysis of Thermal and Moisture behaviour of 2D-structures), TCCC2D (Transient Coupled Convection and Conduction in 2D structures), HMTRA (Heat Mass Transient Analysis), DIM3.1, FRET (A simulation program for FREezing-Thawing processes) and FSEC 3.0.

The computer models, which include air infiltration and rainwater leakage (advanced models in terms of moisture analysis), are excellent research tools. However, complex models are difficult to provide accurate input [Treschsel, 2001] due to:

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

Therefore, simpler models available to practitioners and that do not deal with the complexities, may be useful. This paper discusses two computer tools: CONDENSE and WUFI-ORNL/IBP, as examples for simplified models.

EVALUATION OF COMPUTER TOOLS

CONDENSE 2.0 provides the basic calculation for condensation using the Steady State Method as prescribed by ASHRAE [1997]. It is a user-friendly system tool with the AutoCAD interface, used to simulate the one-dimensional moisture transfer through the given building envelope by diffusion only. CONDENSE 2.0 is provided with an in built material database of 700 building materials, with the flexibility to add and modify material information and edit the attribute values of the materials in the database. CONDENSE 2.0 contains the in built weather data for 203 cities in Canada [Rivard, 1993].

The boundary conditions required for the analysis are indoor and outdoor conditions and an envelope assembly. The options for envelope assembly are the

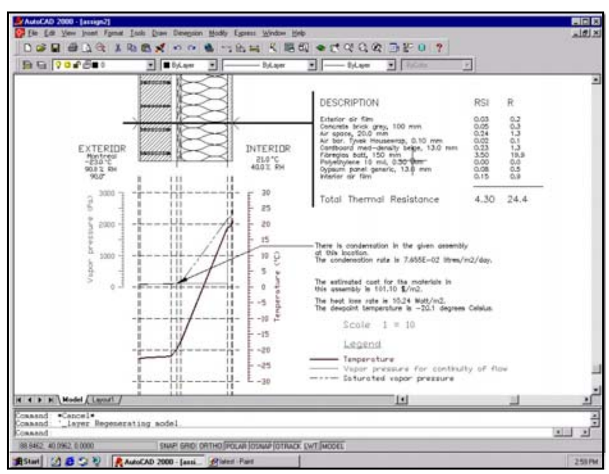

Fig1: Envelope section and the result in CONDENSE

wall, flat roof, slope roof (with the options of any slope angle) and cantilevered floor. The outputs obtained from the tool are, the thermal resistance (RSI) of individual layers and the total assembly, location and rate of condensation (g/sec m^2), heat loss (W/m^2) and the estimated cost of the envelope.

CONDENSE suggests the level of user-friendliness and data interpretation, that designers appreciate for an analytical model to support design. The user friendliness, ready to use interpreted results, and graphics, as shown in *fig1,* are the significant features of the tool. The extent of in-built material and weather database provided is impressive, which is capable of providing accurate and specific results.

WUFI-ORNL/IBP, jointly developed by Oak Ridge National Laboratory, USA and the Fraunhofer Institute for Building Physics, Germany, is a version of the WUFI model specifically developed to provide an educational overview of the complicated moisture transport phenomenon occurring in construction assemblies. The WUFI-ORNL/IBP model is a transient, one-dimensional heat and moisture transfer model that can be used to assess the hygrothermal behaviour for a wide range of building material classes under climatic conditions found in North America. It provides an insight for building envelope designers and architects to make informed design decisions [Karagiozis, 2001]. It can also be applied for other purposes similar to WUFI 2D, as stated by Kuenzel [2001], which are, to assess: (i) the drying time of masonry with trapped construction moisture; (ii) the chances of interstitial condensation; (iii) the influence of driving rain on exterior building components; (iv) the analysis of the effects of repair and retrofit measures; and (v) the hygrothermal performance of roof and wall assemblies under unanticipated use or in different climatic zones.

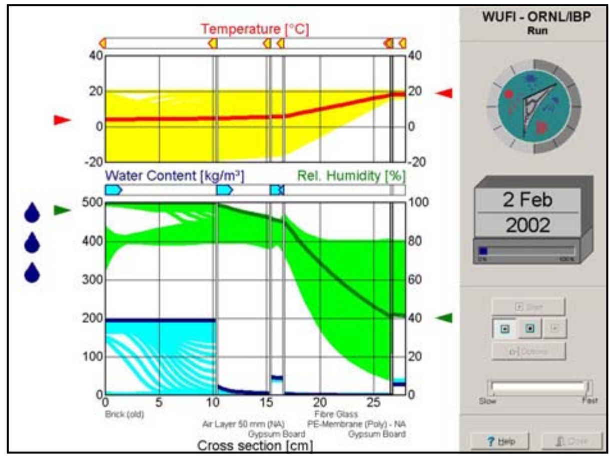

Fig3: Animation screen generated in WUFI-ORNL/IBP

WUFI-ORNL/IBP is a window-based menu driven program, with inbuilt and user managed data input parameters like material properties, building profile, interior and exterior environmental conditions. The building envelope assembly is composed as shown in *fig 2.* The source for inbuilt material database is a North American Material Database [Karagiozis *et al.,* 2001], which provides material properties such as density (kg/m^3), porosity (m^3/ m^3), heat capacity (J/KgK), thermal conductivity (W/mK) and moisture differential resistance factor. Characteristics of the materials are represented in both graphical and tabular format. The characteristics of materials represented are: (i) moisture storage function; (ii) liquid transport coefficient suction; (iii) liquid transport coefficient redistribution; (iv) moisture dependent thermal conductivity; and (v) water vapour diffusion resistance factor. In the educational version there are only 16 inbuilt materials that can be readily used.

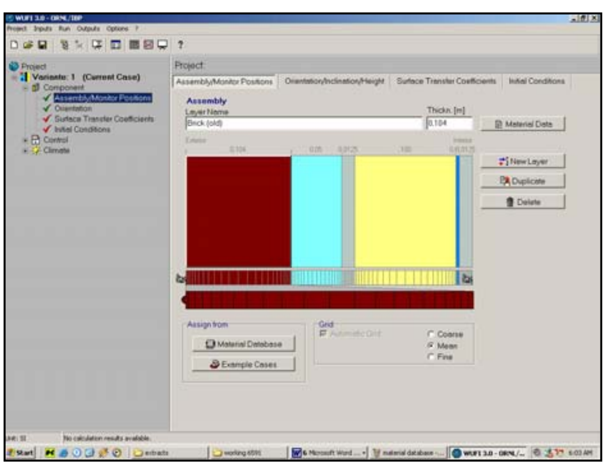

Fig2: Envelope section as in WUFI-ORNL/IBP

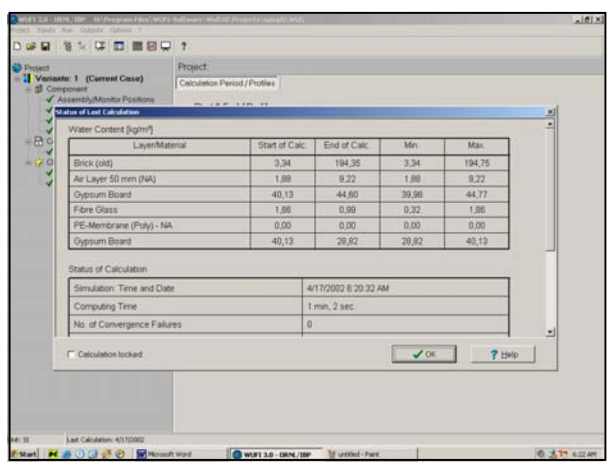

Fig4: Results generated by WUFI-ORNL/IBP

The boundary conditions for an analysis by WUFI-ORNL/IBP are indoor and outdoor air temperature; relative humidity; direct and diffuse solar radiation; precipitation, wind-speed and direction. The optional data for a refined performance analysis are clear sky radiation and driving rain. Input requirements about the building profile are orientation, inclination, height, exterior and interior finish properties.

The result of analysis is represented by an animation as shown in *fig3*, in relation to time. The final results generated in this tool are represented in two formats: graphical representation and tabular representation, as shown in *fig4*. Graphs generated by the analysis are: (i) rain and solar radiation (exterior climate); (ii) air temperature and relative humidity (exterior and interior); (iii) heat fluxes (exterior and interior); (iv) total water content in construction versus time; and (v) water content of individual materials. The numerical data as an output is provided for the water content of the assembly and individual layers, and their maximum and minimum values.

A valuable feature of the WUFI-ORNL/IBP tool is the generation capability of the moisture accumulation in all the layers of the envelope cross section. It can help the prediction of the probable failures in the given envelope, with respect to time, and would benefit to be coupled with a knowledge base. The tool does not incorporate the integration features under discussion; however, the analytical capability of the WUFI-ORNL/IBP model could be integrated for a complete building envelope performance assessment. Another drawback is the large demand for data not easily obtained.

KNOWLEDGE BASE

Building science principles form a base of knowledge for the design process. This knowledge base can be translated and incorporated into a computer tool to support the building envelope design process. The knowledge base for building envelope design can be derived from two different classes of sources: (i) those prescribed by the scientific community, and (ii) those proven in the practical world. The knowledge base from the scientific community can be derived from various levels, ranging from experimental studies to proven models.

Derome [1999], illustrates a methodology of knowledge transfer for a flat roof design in two levels: knowledge transfer at the conceptual level and knowledge transfer at the detailing level. The roof design in the conceptual stage is perceived to be a task of arranging and ordering the four main components: interior finish, insulation layer, roof deck and roofing membrane. Three basic geometrical roof configurations are identified as the probable alternatives for the roof: (i) both the roofing layer and the interior layer are horizontal; (ii) both the roofing layer and the membrane are sloping; and (iii) the roofing layer is sloping and the under layer is horizontal. However, only the analysis of flat roof was considered. The alternatives could then be generated and evaluated against a series of design guidelines, for example according to National Building Code of Canada [1995], the insulation should be placed on top of the deck, if ventilation is not provided. Otherwise, when insulation is placed below the roof deck, a space is required between the insulation and the deck. This space must be vented on the outside. This approach is purely based on knowledge base transfer during the design process. Another example for this approach could be the sound design principle of envelope assemblies by redundancy. This requires the deliberate repetition of functions by different elements against the more severe causes of degradation, i.e. vapour condensation and water ingress.

One source of knowledge from the scientific community is the conclusions and observations made during experimental works. The expense and difficulty involved in experimental evaluation of building envelope performance have instigated development of alternative techniques, such as simplified and advanced models. Instead of using models directly in an integrated computer tool or as an isolated support feature for the design purpose, the performance results of simulations on building envelope systems can be used as sources of design knowledge. Thus, there are two sublevels of knowledge source from the scientific community: direct knowledge from experiments; and knowledge from models.

The challenge is then to develop tools and packages that incorporate scientific knowledge, which can aid the decision process, involved in design. The process of design requires different quantity and quality of inputs during its unfolding. One way to tailor the available information is to cater to the level of intervention in the design process of a building, which are recognised to be: (i) performance specifications (also called program or objectives); (ii) overall architectural concept; (iii) design development; (iv) detailing; and (v) construction supervision. These five levels overlap each other and strive to fulfil the main purpose of the design process [Derome, 1999].

The other important knowledge source is proven design practices. Treschel [2001], summarises some of the prescriptive rules (design knowledge) available to the design community: (i) Install a vapour retarder on the inside of the insulation in cold climates; (ii) Install a vapour retarder on the outside of the insulation in warm climates; (iii) Prevent or reduce air infiltration; (iv) Prevent or reduce rain water leakage; and (v) Pressurise or depressurise the building so as to prevent warm, moist air from entering the building envelope.

Knowledge based systems have been used for building envelope design process before. BEADS, developed for a Ph.D. thesis by Gowri [1990], is a prototype developed to investigate the application of knowledge-based system techniques for automating, the information-handling and decision-making problems encountered during the preliminary stage of building envelope design. A knowledge base containing information on performance requirements and constraints from building codes is interlaced with a database of material properties to solve the information-handling problem. Feasible design alternatives are synthesised using a 'plan-generate-test' strategy with multiple levels of constraint checking [Fazio *et. al.,* 1989]. Nevertheless, the system approach of BEADS is not integrated as it does not incorporate the design knowledge from the scientific community nor the prescriptive rules from practice. BEADS has a text based interface. Hence, it does not have a suitable environment for architectural design process, which relies on graphical thinking.

CONCLUSIONS

The envelope system is a subsystem of the building, composed of a large number of constituents that together must separate the indoor conditioned environment from the outdoor environment. The building envelope design process involves some scientific analysis, and a large amount of logical and intuitive decision making, to provide an enhanced performance. Knowledge and experience, in architecture, and a constant updating of the increasing contributions of building science plays a major role in the building envelope design process. Nevertheless, designers do not always have the time nowadays to study all that there is to know on one specific assembly, however they are open to improve their design and integrate new technology that could improve their practice [Derome, 1999]. The current tools that support the building envelope design process do not support the working approach of the principal participant of the building envelope design process, the architect.

The challenge, hence, is to seek for knowledge and develop tools and packages that can incorporate the obtained knowledge, which can aid the design process. The various levels of knowledge source available are; experimental results, results generated by experiment based analytical and numerical models, and prescriptive rules from practice. The process of design requires different quantity and quality of inputs during its unfolding. One way to tailor the available information is to cater to the level of intervention in the design process of a building, which are recognised to be: (i) performance specifications (also called program or objectives); (ii) overall architectural concept; (iii) design development; (iv) detailing; and (v) construction supervision. These are the five levels, which overlap each other and strive to fulfill the main purpose of the design process. The inferences from the BEADS prototype and the recommendations for the future work by Fazio *et al.* [1989] can be used as a line of thought for an integrated system.

The other integration problem as identified in the paper is the synchronisation of the working trend of diverse disciplines, i.e. mainly the architectural design process and engineering design process. An integrated tool supporting the graphical thinking enhanced with the knowledge and analytical background around the line of what EsQUIse prototype is presently offering could provide an effective solution.

REFERENCES

Archer B.L., (1963a), 'Systematic Method for Designers - Part1: Aesthetics and Logic', *Design 172*, pp. 46 – 49.

Archer B.L., (1963b), 'Systematic Method for Designers – Part3: Getting the brief', *Design 176*, pp. 52 – 57.

ASHRAE 1997, 'Thermal and Moisture Control in Insulated Assemblies – Fundamentals: Steady State Design Tools', *ASHRAE Fundamentals Handbook (SI)*.

Bomberg M. and Brown W.C., (1993), 'Building Envelope: Heat, Air and Moisture Interactions', *Journal of Thermal Insulation and Building Envelopes,* Technomic Publishing Co., Mancaster, PA, USA vol.16, pp. 306-311.

Derome D (1999), *Study of Performance of Envelope Assembly with Moisture Storing Insulation Layer,* Ph.D. Thesis, Concordia University, Montreal, Canada.

Fazio P., Bédard C., and Gowri K. (1989), 'Knowledge-based System Approach to Building Envelope Design', *Computer Aided Design*, Vol. 21 No. 8, pp. 519-527.

Gowri K. (1990), *Knowledge-Based System Approach to Building Envelope Design,* Ph.D. Dissertation, Centre for Building studies, Concordia University, Montreal, Canada.

Hauglustaine J. (2001), 'Multicriteria Interactive Tool to sketch the Building Envelope during First Stages of Architectural Design', *Buildings VIII/Energy in Buildings–Practices,* ASHRAE, Florida, US.

Hens, H. (1996), 'Modeling' *Final Report, IEA-Annex 24*, Task 1, Acco, Leuven, pp.90.

Howard H.C., Levitt R.E., Paulson Jr. B.C., Pohl J.G., and Tatum C.B. (1989), 'Computer Integration: Reducing Fragmentation in the AEC industry*', Journal of Computing in Civil Engineering*, American Society for Civil Engineers 3(1), pp. 18-32.

Hutcheon N.B. (1963), 'Requirements for exterior walls'*, Canadian Building Digest 48*, National Research Council: Division of Building Research, Canada.

Karagiozis A.N. (2001), 'Advanced Hygrothermal Models and Design Models', *Esim 2001 conference proceedings*, June 13-14, Ottawa, Canada, website: http://buildingsgroup.nrcan.gc.ca/eSim/documents/proceedings/Session3-4.pdf.

Karagiozis A.N., Kuenzel H., Holm A. and Desjarlais A. (2001), 'An Educational Hygrothermal Model WUFI-ORNL/IBP', *workshop manual,* National Institute of Building Sciences, website: http://www.nibs.org/BETEC/Pres/Desjarlais.pdf.

Kuenzel H.M. (1995), *Simultaneous Heat and Moisture Transport in Building Components – One and Two Dimensional Calculation Using Simple Parameters,* Ph.D., Thesis, University of Stuttgart, Stuttgart, Germany.

Kuenzel H.M. (2001), 'WUFI'*,* Appendix A, *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM Manual, Philadelphia, US.

Kumaran K. (2001), 'Innovation', *Construction,* Institute for Research in Construction, Ottawa, Canada, Vol.6, No.2.

Laseau P. (1980), *Graphic Thinking for Architects and Designers*, Van Nostrand Reinhold Company, Canada.

Ojanen T. (2001), 'Transient Coupled Convection and Conduction in 2D structures (TCCC2D)'*,* Appendix E, *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM Manual, Philadelphia, US.

Pearce M., Goel A.K., Kolodner J.L., Zimring C., Santosa L., and Billington R., (1992), 'Case-Based Design Support: A Case Study in Architectural Design', *IEEE Expert*, Vol. 7 No. 5, pp. 14-20.

Rivard H., (1993), *CONDENSE Version 2.0: User's Manual*, Quebec Building Envelope Council, Montreal, Canada.

Rivard H., Bédard C., Fazio P and Kinh H. Ha (1995), 'Functional Analysis of the Preliminary Building Envelope Design Process'*, Building and Environment,* Vol.30, No.3 pp. 391-401.

Trechsel H.R. (2001), 'The current prescriptive rules to prevent moisture problems in building envelopes & Analytical methods and models and their limitations', *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM Manual, Philadelphia, US.