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The Virtual Lab: A Research Complement to the Integrated Design Process

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ABSTRACT

As the Integrated Design Process (IDP) approach is beginning to make a difference in the construction industry so too is the concept of the Virtual Lab beginning to change the process of evaluating the performance of building systems, specifically envelope systems. This paper elaborates the concept of the virtual lab and provides an example, evaluating the hygrothermal performance of wall systems. The virtual lab could be viewed as one component of the IDP or as a complimentary framework designed to provide information about the performance and durability of wall systems. The impetus behind the development of the Virtual Lab is cost. Performance testing in the laboratory or in the field can be expensive. Assessing durability can be even costlier and results may not be available in a timely fashion. The proposed solution to these difficulties is the judicious combination of computer modelling to predict performance and durability with laboratory testing. The basic framework of the Virtual Lab is presented here. Development of the simulation components of the virtual lab, as described in this paper, comprises three stages: (1) development of the model or simulation of a component, assembly or system providing estimates of performance or durability, (2) the laboratory testing providing information on boundary conditions and loading to be used by performance and durability models as well as benchmarking tests to enhance confidence in the simulation results, and (3) the field testing or evaluation to provide further validation of the model, information on boundary conditions, and valuable information on in-service conditions and performance.

INTRODUCTION

Global trends are increasing the pressure on developers and designers to produce buildings having a high level of performance. Examples of such performance demands are, from the IEA Annex 23 [1]: a) minimize the consumption of non-renewable resources, b) minimize greenhouse gas emissions, c) minimize liquid effluents and solid wastes, d) minimize the negative impacts on ecosystems, and e) maximize quality of the indoor environment, including but not limited to indoor air quality, thermal comfort, illumination, acoustics, and noise. In addition to the performance objectives mentioned one might add the following objectives that pertain to building owners: adaptability/flexibility to accommodate changes in occupancy or client demands and the minimization of the life cycle cost. The minimization of life cycle cost subsumes issues of durability, longevity, and maintainability, which, as will be seen, are key topics to be addressed by the Virtual Lab (VL). As well, more stringent performance requirements are being imposed by regulation. Regulations are moving more towards performance-based objectives and less towards prescriptive requirements. How a design or building meets these performance objectives is the domain of the VL and regulatory issues are those that take precedence to all other objectives.

The Integrated Design Process (IDP) is a response to the trend of requiring high levels of performance in buildings while managing cost. Essentially the IDP consists of a series of design loops. The design loop as in any other design process (e.g. building envelope design) is a composition of several decision-making stages with support of knowledge from multiple disciplines. It is a complex task in which issues such as structural integrity, energy efficiency, durability, and aesthetics should be assured at the design stage. Each loop ends with a milestone characterized by decisions, which indicate a transition to the next stage. A series of workshops or design sessions progresses from site planning to materials selection. The number of sessions or loops ranges from 4 to 10 [2]. In the current context, the IDP methodology is most often purportedly used to significantly reduce energy demand and water use. Typical design loops or meeting groupings targeted towards energy use might be [2]: i) site planning, ii) envelop design, fenestration design

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and preliminary daylighting assessment, iii) lighting and power design, iv) ventilation, v) heating and cooling, vi) material selection and detail coordination, vii) pre-tender considerations, and viii) commissioning and monitoring. Annex 23 [1] gives a general description of the IDP, the focus being the design of low energy solar buildings while a more general set of actions is given in [2].

Some essential actions of the IDP are: i) begin at the earliest design stages, ii) designate a coordinator, iii) allow additional time and money for the IDP, iv) incorporate performance objectives (identify mandatory performances, they are prior), v) incorporate performance-based fees to encourage innovation, vi) simulate interactions among building systems (presumably materials and components as well), vii) analyse the life cycle cost options, viii) maximize the quality of the indoor environment, and ix) employ commissioning during construction and after [3]. Question: How are tasks v to viii inclusive, to be completed (i.e. how is a performance objective assessed)? One possible answer: use of a VL tool.

Quoting from [2], "An enthusiast would say that it is important to use IDP in all design opportunities. This condition however is likely to be tempered by the future building owner or other team members." So far the current focus is still energy related; see Annex 23 [1], C2000 [2], and DOE [4]. In this discussion, however, the scope of application the IDP is generalized or expanded. Why? Performance objectives can be complicated and sometimes conflicting, necessarily involving a trade-off of levels of different performance requirements to achieve an optimization of the overall life cycle cost, in relation to life cycle analysis, or service life of the facility. Objectives required by regulation are prior (e.g. health and safety) and may preclude the realization or optimization of various other performance requirements. For example daylighting objectives may adversely affect the U-value rating of a wall, trading off the thermal performance of the envelope for performance *qua* lighting. However mandatory regulations may have specific performance requirements with respect to moisture accumulation and deterioration that are prior to any objectives regarding daylighting or energy use.

Building design is a process to identify an assembly system, composed mostly of layers, to perform pre-specified functions with maximum economy and efficiency. The basic functions contributing to the selection of major components of a building are control of heat, air and moisture, rain, wind, structural stability and aesthetics. The functional requirements of a building envelope are interrelated; hence design synthesis is not only a response to the requirements identified, but also to the preceding actions. Thus the design paths taken by the designer may vary from one situation to the other in a design action. A representation of this multi-faceted building envelope design process would provide a base to attach all the relevant knowledge at appropriate stages in the design and develop an integrated computer tool to support the design process.

Recognition of the complexity of building systems and the related performances has lead for example to the creation of Annex 41, Whole Building Heat, Air and Moisture Response [5]. The annex aims to acquire a better knowledge of the whole building heat, air and moisture balance and its effects on indoor environment, on energy consumption for heating, cooling, air humidification and air drying, and on the envelope's durability. The scope is fairly narrow, yet the task is quite substantial. Despite the narrowness of scope the annex appears to recognize the holistic nature of the endeavor required for the effective design of modern high performance buildings.

From the above discussion it can be seen that one of the key actions or tools of the IDP is simulation, i.e. computer modelling of systems, components, or materials to evaluate absolute or relative performance. This is especially obvious with respect to energy given the number of simulation tools available, energy pricing, and environmental concerns. Hence the current focus on energy in the IDP literature. Suppose the scope of application of the IDP was broadened to a more general perspective of whole building performance, as is proposed in Annex 41. What tools are available to the designer to assess performance? Without an assessment of the potential performance of built assets, no conclusions can be drawn *qua* durability and consequently, neither it is possible to perform meaningful life cycle cost analysis. The development of the Virtual Lab would provide tools to complement the existing and developing suite of IDP tools.

THE VIRTUAL LAB

What is it? The VL is intended to provide designers and developers with the performance related information needed for decision making within the IDP, hence the complementary role. The idea of the VL is to provide researchers and professionals with a set of tools similar in concept to those used in the automotive and aerospace industry. The VL is in the process of conceptual development, however, the current focus is to develop an integrating philosophy and methodologies for the building design process.

Integration occurs at several levels; data integration whereby information about the building and its environs can be passed seamlessly between one tool to another, a higher level where the tools are integrated and "coupled", i.e. the results are passed back and forth between tools dynamically, and finally at a level where the results from one tool are "piped" to other tools. In explaining the VL it helps to consider how the component parts of the VL, specifically the simulation components are developed, calibrated and verified on the basis of these tests so that performance can be reliably predicted using the VL. Developing parts of the VL so that performance can be reliably predicted through its use using, requires 3 stages: development (see Figure 1), verification and calibration (see Figure 2a) and, validation (see Figure 2b) on the basis of laboratory and field tests. The relation between these stages of development is shown in Figure 3. The field and laboratory testing generally contribute data and information to the VL simulation components that contain knowledge. Knowledge here means the ability to predict performance. The veracity of that knowledge is checked against observations in the field and in the laboratory leading to confidence in the predictions.

What is it for? The purpose of the VL is to predict the performance of proposed design options, i.e. materials/components/systems with respect to the a priori defined performance objectives. Objectives are for example to: a) reduce the life cycle cost, b) minimize green house gas emissions, c) maximize the quality of the indoor environment, d) meet or exceed health and safety requirements or other mandatory requirements. Subsumed by the requirements listed above are issues of durability, used here to illustrate the VL. The scope of application of the VL includes the assessment of new designs or concepts as well as retrofit solutions. In the broadest possible sense the VL would be used to analyse whole building performance not only from the durability point of view but also from an all-embracing perspective, including but not limited to the quality of indoor environment for example.

Why use it? As discussed above the trend is towards high performance buildings, either by regulation or by economy or by owner/occupant demand. The primary use of the VL is to evaluate the projected (absolute or relative) performance of proposed designs or solutions comparing performance savings with incremental costs and/or determining whether certain objectives are indeed even met. Using the VL allows knowledge of performance to be obtained at significantly reduced costs. How? Using the VL through the judicious use of computer simulations and testing in place of more comprehensive test programs and mock-ups, perhaps required by owners or regulators, reduces the cost and time of development of enhanced designs or innovative products. In fact some performance standards can already be met by the results of computer simulations alone. For example the fenestration thermal performance requirements of CSA A440 [6] can be demonstrated with the Frame and Vision [7] computer programs. McGowan's paper [8], for example, shows the benefit of combining simulation and testing, especially the benefits of simulating situations and solutions that cannot by effectively tested in the laboratory.

New materials systems or designs can also be assessed with a minimum of fuss by using simulations and only the necessary and sufficient laboratory tests for giving confidence in the simulation results. The VL thus enables innovation to proceed at a quicker pace and at lower cost while still assuring an adequate assessment of performance, short and long term. An example of this is the Mews methodology [9] and the eventual development of a series of cladding assessment protocols for the Institute for Research in Construction that rely to a large extent on the results of computer simulations [10]. These protocols combine simulation and testing to evaluate the long-term durability rather than relying on the results of testing alone to estimate long term-term durability. To summarize, the VL speeds up the design process and reduces costs by using simulations to predict performance and reducing the required testing to a minimum.

Who should use it? The Virtual Lab is intended to be used by: i) researchers in building science; ii) building design professionals (e.g. engineers, architects); iii) product developers or manufacturers (materials/components/systems); iv) evaluators (e.g. testing laboratories, consultants, regulatory officials).

SIMULATION TOOLS

What are they for? The purpose of the VL is to use the simulation tools to assess the absolute or relative performance of building materials/systems/components hence the simulation portion of the VL is the essential component. The approach to this in respect to the IDP is the parametric study of various design options. Ultimately in the case of building envelopes, the example used in this paper, the predicted response to loads affects the immediate performance that can lead to damage or deterioration resulting in a cumulative loss in performance and hence an assessment of the long-term performance (i.e. durability). Durability assessments of various options, new and retrofit, are then used in life cycle cost analysis to produce cost effective solutions that meet stated performance objectives all based on the results of simulation. In other domains predicted performance can be used to maximize the quality of the indoor environment, see the COPE project for example [11].

FIGURE 1
The simulation component of the Virtual Lab

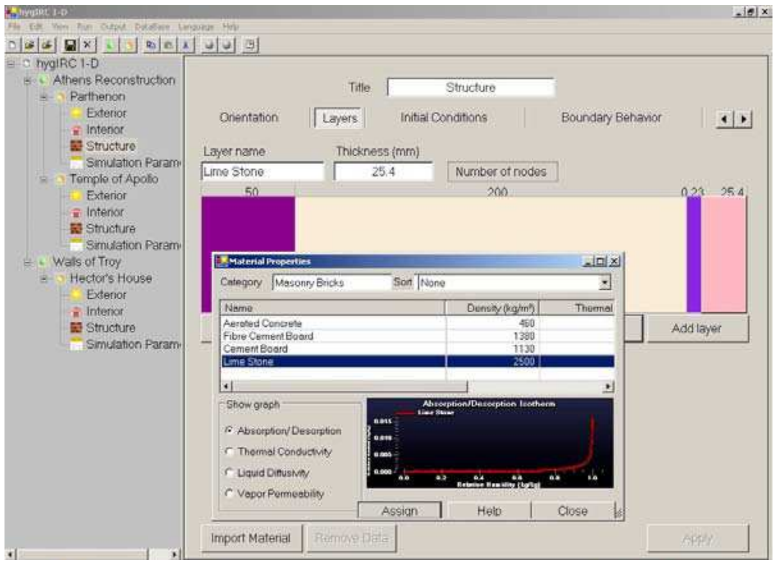
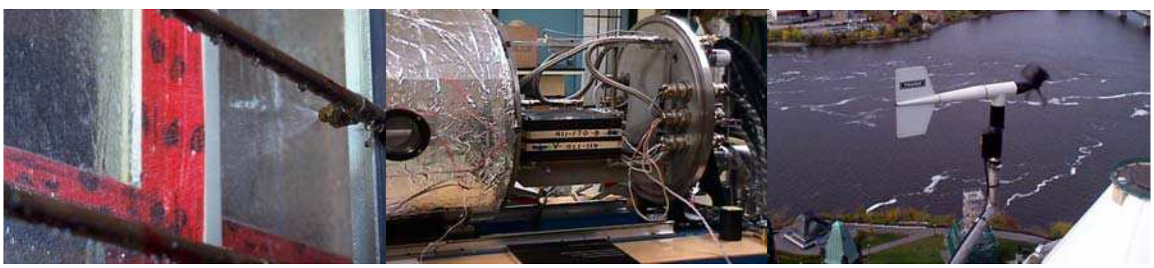


FIGURE 2
Laboratory (a and b) and the Field (c) testing of Virtual Lab components

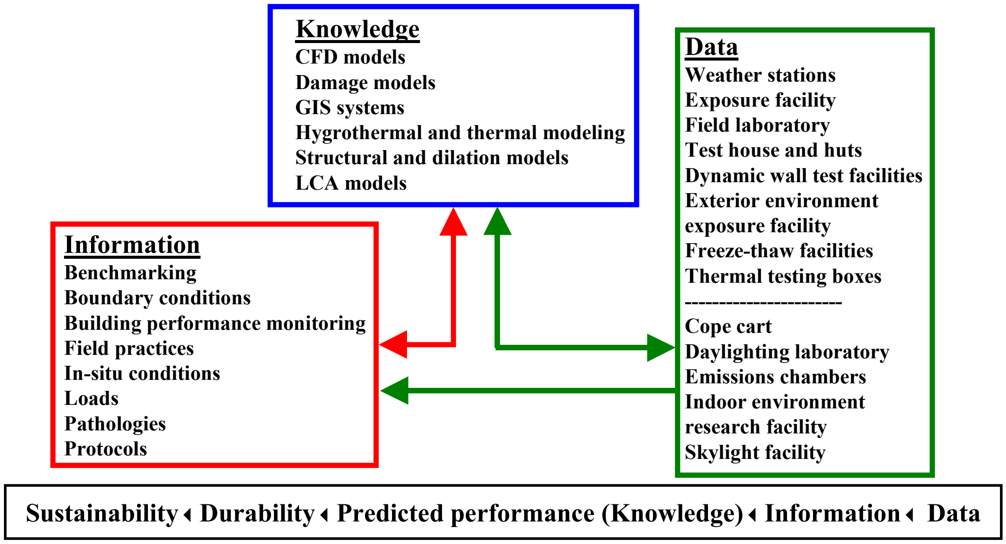


(a) **(b)** **(c)**

What are they? Simulation tools should be relatively familiar to most building science practitioners/professionals. Sometimes called models the preferred term is simulations. A simulation comprises:

a) *A model*. Models are simplifications or abstractions of the real world. We distinguish two types of models; models of the physical laws, and representations or abstractions of real world entities. The physical models or equations that relate to physical laws are applied to abstractions. For example imaginary volumes representing solids, from which responses to loads are calculated (various states or conditions). In hygrothermal modeling for example the layers comprising the envelope can be represented as volumes to which bulk material properties, liquid diffusivity for example, are assumed to apply throughout the volume. The physics is embodied in the equations governing energy and mass transfer and applied to the representation of the envelope through various numerical solving techniques (Equation 1). A possible abstraction of the envelope is to represent the structure as a series of volumes connected to each other by nodes at their center (Figure 4). Over the course of a simulation a time dependent response is generated. In a broader scope, more general representations can be created that describe the universe of building entities. Representations such as STEP [12], IAI/IFC [13] allow for information regarding building entities, either essential or accidental, to be described in such a way as to be application independent [14]. This becomes of increasing importance as the focus of the VL broadens from particular domains; say envelope hygrothermal performance, to whole building performance.

Figure 3
The essence of the Virtual Lab is the application of Knowledge to predict performance



b) *Properties.* Simulations require some basic information or data from which to make predictions. Examples of these are the essential properties of materials (see Figure 5), components, and systems. Accidental properties such as geometry and topology are excluded for the present discussion.

c) *Loads.* Another kind of information or data required by simulations is loads. Loads, although not an ideal term, will serve to cover any kind of stimulus or process that initiates change. Loads can be in the form of data or information or analytical or empirical models that can be implemented as part of a simulation. Data might be in the form of weather tapes etc, information (engineered data) could be expressed in terms of extremes (return periods) or typical years or models such as solar models, interior conditions models (see Figure 6). In general the data can be obtained in field or to a lesser extent in the laboratory. Examples of loads might be: i) *external loads* such as wind, wind driven-rain, ground acceleration, solar irradiance, weather tapes, solar models, and so on, ii) *internal loads* such as temperature relative humidity, lighting, equipment, and occupant load either in the form of measured data or models. Site related factors are related to loads; they might represent things such as location, terrain, obstructions, shading, distance from bodies of water, altitude etc. Site factors can be in the form of data or information or empirical or analytical models.

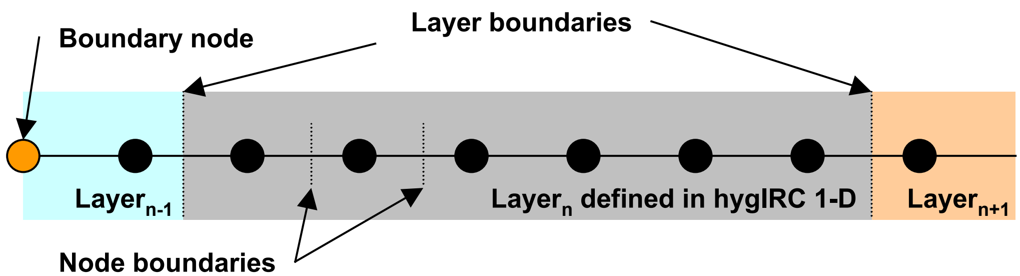
d) *Output*. The output of simulation tools is data. This has to be converted into information and ideally knowledge (see Figure 7). In the VL the desired output is the response of an object to the loads imposed on it (to which it is subjected). It is this (data, info or knowledge?) that will eventually be used in the IDP as a design making aid. As part the of the VL, simulation tools require a way of processing or visualizing data to make decisions, such as pass fail criteria, or a way to facilitate interpretation (i.e. predict performance) and/or a method of passing results to other VL tools.

Verification: Simulation tools should be verified implying that the models have been correctly implemented in the simulation. Verification is done by comparing results of a simulation with analytical solutions, and comparing the results of a simulation with other simulation tools, or comparing with results with laboratory experiments, or in ideal circumstances, both methods. Verification helps establish confidence that the models have been correctly implemented and that models adequately mimic the physics. An example of this is type of procedure can be found in [16].

EQUATION 1
A mass transfer governing equation, a model of the physics [15]

$$\rho_0 \frac{\partial(u)}{\partial t} + \nabla \cdot \left(- \rho_0 D_w \nabla u + K_w \rho_w \overline{g} - \delta_p \nabla P_v + \rho_v \overline{V}_a \right) = Q_m$$

FIGURE 4
A Simple 1D representation of a building envelope



LABORATORY TESTS

Although the simulation of components of the VL defines its essence and are intended to be the principle tools by which performance is assessed the support of a laboratory is essential. The laboratory provides essential data, information, and knowledge to the simulation. The contributions of the laboratory to the VL are three.

FIGURE 5
Material properties, for example, are necessary components of a simulation

i) *Basic Data and Information*. The properties, performance, and behaviour of materials systems and components (e.g. air leakage, water penetration), and long-term performance (durability) are important contributions (see Figure 2 (a) and (b)). However, some situations cannot be practically or adequately tested in the laboratory, or in the field. McGowan [8] describes a situation where the laboratory tests did not represent the real world situation, requiring recourse to simulation to generate and assess design alternatives.

ii) *Generation of models*. Since a discussion on the philosophy of science is outside the remit of this paper it is assumed that models of behaviour or performance are based on an understanding of the phenomenon that cause or bring about the response. These are first derived from results of field studies from which conceptual models are developed. Thereafter, the essence of the complex behaviour may be distilled into single and multi-parameter models. The models ought to be verified in laboratory-controlled conditions. Thus it is from the field and laboratory that models of performance, deterioration, and damage are developed.

iii) *Benchmarking of models*. Benchmarking lies somewhere between verification and validation (to be discussed below). Benchmarking consists of devising an experiment and comparing the simulation results with the laboratory results. An example such a procedure is reported by Maref [17].

FIGURE 6
Models (Knowledge) can be included in the Virtual Lab to estimate loads

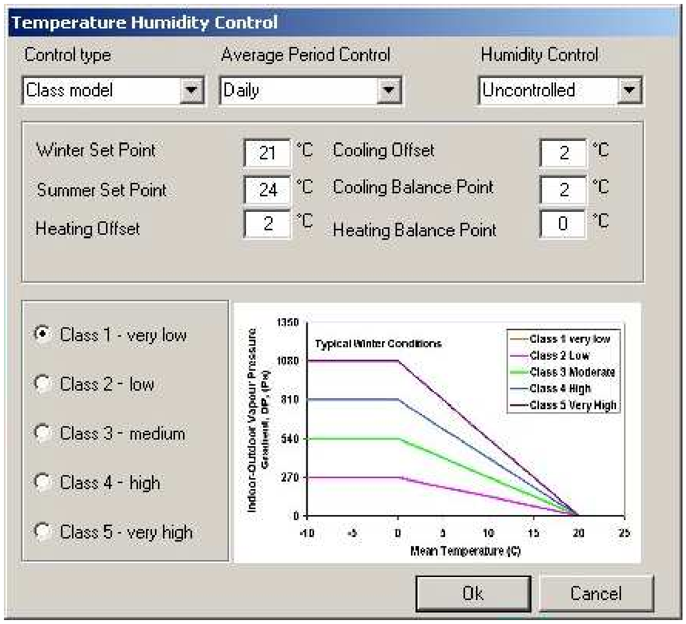
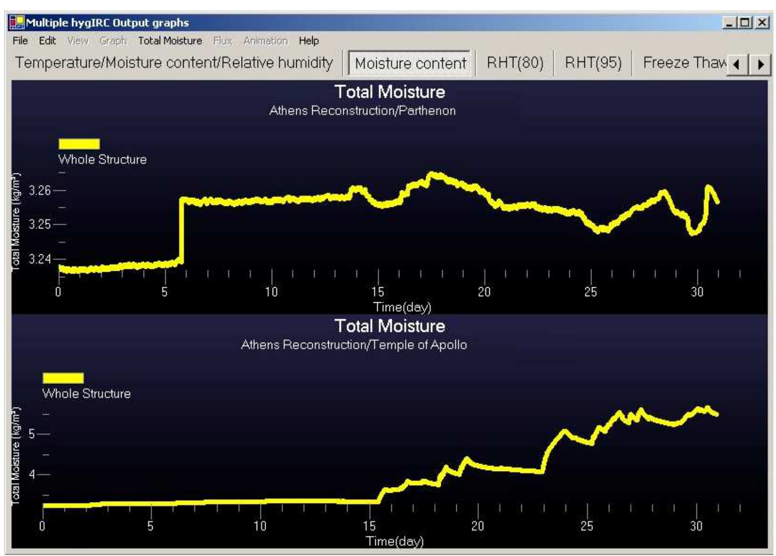


FIGURE 7
The output of the Virtual Lab ultimately must lead to an assessment of performance



FIELD TESTING

Another essential element needed to support the VL is the "field laboratory". The primary contributions from the field laboratory are to: i) provide the loads as input for the simulations in the form of in-situ data (see Figure 8), ii) provide design conditions from which performances can be obtained, iii) provide the in-situ conditions of entities as well field practice, and iv) provide operations schedules. Examples of i) are external loads such as weather, concentration of pollutants and internal loads, such as contaminant sources. Examples of ii) are in-service conditions and extreme conditions. Examples of iii) and iv) can be found in [18].

It is clear of course that real world data can be used in the VL and might be preferable in many cases especially with regards to external loads. It is also possible to generalize from data obtain from the field to generate models of behaviour that could be incorporated into the VL (see *Generating Models* above). The example shown in Figure 6 is an empirical model used to predict interior relative humidity in buildings based on building occupancy and ambient conditions derived by surveying the conditions of buildings in the field [19]. A classic example is a simple empirical model of wind driven-rain. The amount of wind driven-rain impinging on a façade can be estimated from Equation 2.

A second but important purpose of the field laboratory is the validation of models, perhaps the most difficult task in establishing the reliability of a simulation tools. Validation compares the real world performance of an actual entity to the predicted performance generated from the simulation. The correspondence of the results indicates the validity of the model.

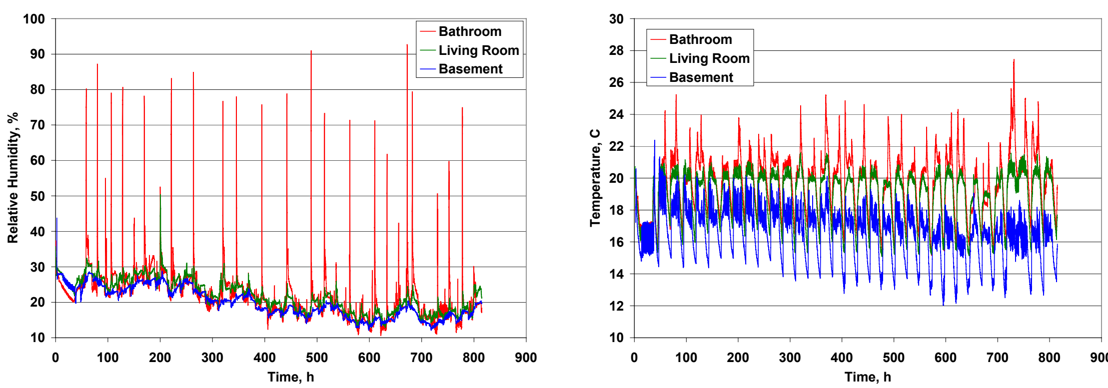
EQUATION 2
An empirical model for wind-driven rain [20]

$$WDR = 0.222Ur_h^{0.88}$$

AN EXAMPLE: HYGROTHERMAL ASSESSMENT OF BUILDING ENVELOPES

How might this all work? The assessment of the hygrothermal performance of the building envelopes, as an example of the VL integrated process, has been an on-going research project at the Institute for Research in Construction [15]. The key element of this portion of the VL in this example is a hygrothermal simulation tool that is used to predict the hygrothermal response of wall cladding assemblies in response to external and internal loads. The simulation has the following elements: i) a model of the physics (Equation 1), ii) a representation of the structure (Figure 4), iii) a database of material properties of common construction materials (Figure 5), iv) a database of external loads in the form of hourly weather tapes, v) models of the internal loads (Figure 6), vi) Output tools and measures (Figure 7), and viii) Links to other simulations for further analysis and interpretation [21] (see Figure 9).

FIGURE 8
Thermal conditions in a typical house are an example of real world data obtained from the field.



THE FUTURE

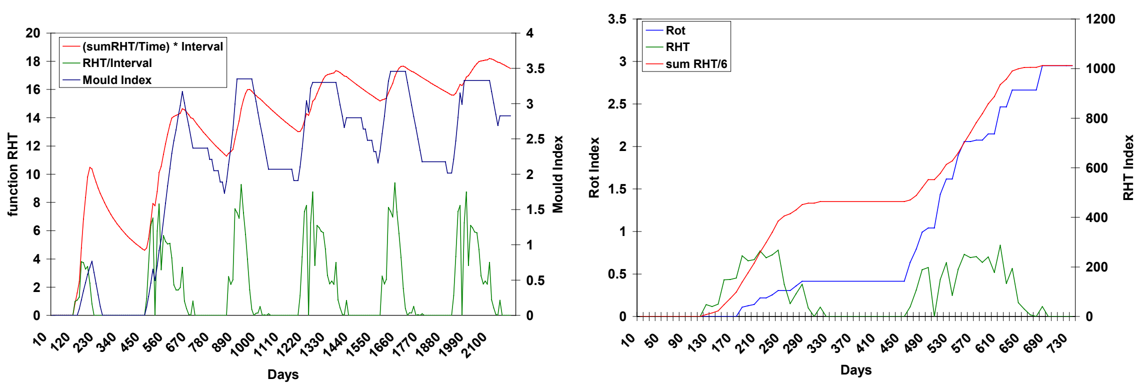
Suppose the scope of the example given here was broadened to consider whole building performance. To the VL suite one could add energy, computer fluid dynamics, and structural analysis packages. Daylighting models [22] or skylighting [23] models could also be added to provide a more holistic picture of building performance and the interaction amongst various building systems. VLs combining structural, computational fluid dynamics, and heat transfer do exist [24] but these tools are only now being targeted at the building industry. Still many of these tools are stand-alone or the results from one are "piped" to others without the type of integration that takes into consideration performance assessment. The situation is changing however as the focus of building design is likewise evolving from one of designing to prevent failure or meet minimum standards to that of predicting performance focusing on durability and life cycle cost in addition to former requirements.

What are some of the current limitations of a VL? The current limitation is a lack of integration among existing tools for the building industry when compared to the level that exists in the aerospace, automotive, and high technology industries. The envisioned future of the VL is further integration of the simulation models, dynamically linking various models (e.g. durability, glazing thermal and moisture performance, solar gain/illumination, energy performance, mechanical design, structural, indoor environment, and life cycle cost analysis), in series or in parallel, through common data representations. Another current limitation is the development of models to predict the durability of building elements and systems and the validation of those models linked explicitly to performance criteria.

What might a future VL targeted to the building industry or building mangers look like? A geographic information system would be used to integrate, a least conceptually, the VL and would provide the ability for the building science professional, owner developer, manager to assess the performance of buildings with respect to location and time. External loads from data, analytical or empirical models, would be obtained for specific geographical locations making possible the assessment of performance of proposed solutions accounting for geography, for example, identifying risk of deterioration (see Figure 10). Linked to other information, such as regional energy and materials costs. A geographic information system augmented VL would permit a thorough life cycle cost analysis [25]. There is already an example of such an application, specifically the spatial modelling of exposure environment [26] described in the work of the CIB Commission W106 Geographical Information Systems [27]. Also consider that the objective of the CIB W106 is to promote a widest possible implementation of geographic information system applications for the built environment. Finally there is an on-going project at the Institute for Research in Construction the objective of which is to develop a risk-based framework for the evaluation of façade performance, and prioritisation of required maintenance. The project is to be implemented in a geographic information system based framework and focus on high and medium-rise buildings with consideration of the likely environmental loads. The system will incorporate models, such as a hygrothermal model and damage models for corrosion and deterioration. The first phase of this project is scheduled to last four years and is currently funded during first phase.

FIGURE 9

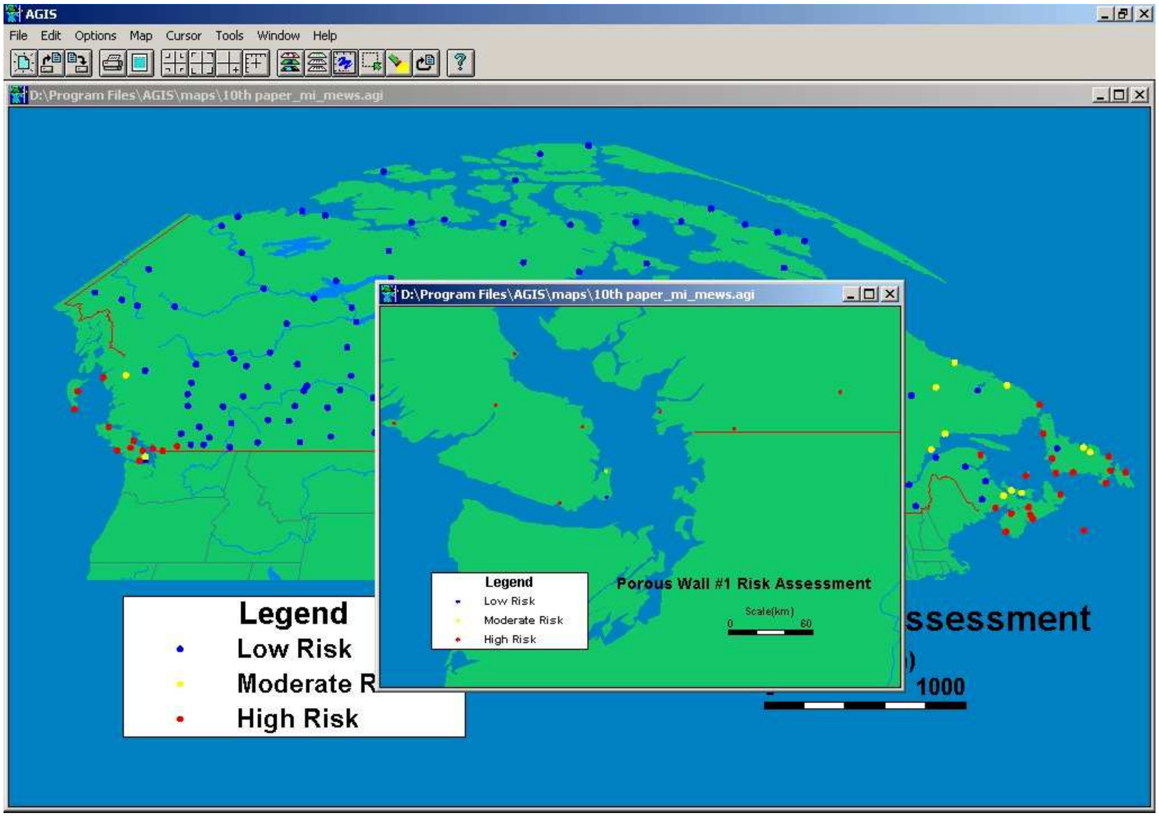
Estimating the damage to walls using dose-response models



SUMMARY

The virtual lab is an integrated set or suite of simulation tools strongly supported by laboratory and field-testing facilities. It is intended primarily to predict the absolute or relative performance of buildings, systems, components or materials with respect to various performance objectives enabling decisions regarding design and retrofit. Innovative products and solutions combined with the demand for higher levels of performance are changing the way design is done; witness the IDP. The VL, through the judicious use of simulation, testing, and monitoring, allows the evaluation of performance to be done in a timely, cost effective, and rational way. The VL also permits building science professionals and researchers to assess responses or performances not practicable in the laboratory or field or otherwise prohibitively expensive. Furthermore, the proposed technology offers manufacturers of new construction systems the benefit of speeding up research and development while simultaneously reducing these costs. If building science is the glue that binds the IDP then the VL is the applicator. The VL is in the process of conceptual development, however, its current focus is to develop an integrating philosophy and methodologies.

FIGURE 10
Geographical information systems integrated in the Virtual Lab



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