Multi-Criteria Evaluation Framework of Factory-Built Wood-Frame Walls

Caroline D. Frenette
Student Member ASHRAE

Robert Beauregard, PhD

Dominique Derome, PhD
Member ASHRAE

ABSTRACT

There is a constant demand for improving wood-frame exterior wall assemblies currently used in North American residential construction. This demand is the consequence of the availability of new building products, requirements to improve performance, exports to countries with different climates or performance requirements, etc. This paper presents the development of a multi-criteria framework aiming to support the evaluation of improved factory-built wood-frame exterior walls. The multi-criteria model in development seeks to simultaneously consider several wall performance criteria that so far have been studied and optimized independently. Structural integrity, moisture transfer, durability, thermal performance, energy efficiency, sound insulation and environmental impacts are the main criteria included in this analysis. This paper summarizes the level of knowledge and design methods related to each criterion, as well as some interactions between these criteria. It also presents the development of the multi-criteria tool, highlighting the impact of each component on the overall assembly performance. Analytical methods that may be used to quantify these impacts in order to enable a comparison of the global performance of the different wall assemblies are presented. Finally, the added value of the tool is presented with a case example demonstrating how the selection of the assembly components affects the criteria evaluation.

INTRODUCTION

The main function of a building is to provide an interior space protected against the exterior environment. Integrated systems, such as light-frame wood construction, insure an appropriate level of performance for a set of criteria, namely: structural integrity; protection against exterior environment; capacity to sustain indoor RH variation; acoustic insulation; and more recently the environmental performance of the system. This construction system is the preferred choice in North America for low-rise residential building since it offers a good performance, is economical and simple to build. Although this system performs generally well, it can still be further improved. A problem arises however when one tries to improve an element of the system for a specific purpose without evaluating the impact of this modification and its interaction with the other performance criteria.

A modification of a given concept of light-frame wood wall may be desirable for many reasons. Exports to other geographical locations often imply distinctive outdoor solicitations as well as different cultural and socio-economical contexts that lead to modifications to the required performance levels. Also, even within a given area, the requirements relative to residential construction vary with time and market segments. For example, considerations regarding the environmental impact of a construction on global warming, the minimal level of thermal insulation or the quality of acoustic insulation of a construction have changed over time. Moreover, it may sometimes become necessary to adapt an existing construction system following a failure, such as the "leaky condos" situation that occurred in the Greater Vancouver area (Morrison Hershfield Ltd 1998). Another reason for concept modifications may simply be to include new building materials expected to improve performance or reduce costs.

***Caroline D. Frenette** is a PhD candidate and **Robert Beauregard** is a professor in the Department of Wood Sciences, University Laval, Québec, Canada. **Dominique Derome** is an associate professor in the Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada.*

The current techniques used in light-frame wood construction have been developed over the years and are adapted to given climates and socio-economical contexts. Since the performance related characteristics of the building envelope are complex to understand and model as a whole, studies have concentrated on individual performance evaluations. The measurement of the pertinent performance criteria is therefore done on an individual criterion basis through specific fields of expertise, thereby rendering the work of designers who must integrate many aspects in their decisions quite difficult. This situation encourages members of the industry to be conservative since changing any design element may have repercussions that are too complex to evaluate. Although it is important to understand each phenomenon independently, all the pertinent characteristics should be studied simultaneously in order to obtain a system that is globally optimized.

The combination of the type, thickness and location of thermal insulation is a good example of the interactions between the various performance characteristics. The choice of a given thermal insulation has a direct impact on moisture transfer through the wall assembly and can therefore affect the risk of condensation, thus impacting durability. On the other hand, the presence of high moisture content within the assembly could negatively impact certain types of insulating materials, while leaving others intact. Another example is the choice of the intermediate sheathing. OSB could be selected to ensure the adequate structural stability of the bracing system, but it also has an influence on the hygrothermal behavior of the wall. Its low water vapor permeance increases the risk of condensation inside the walls while decreasing the drying capacity of the assembly in case of accidental wetting (Teasdale-St-Hilaire and Derome 2005).

Recently, the importance of developing integrated approaches was emphasized as a possible remedy to the lack of information on the actual consequences of design modification on all the performance criteria deemed important. Working towards this goal, a recent protocol was developed to assess the acceptability of light-frame building envelopes in relation to building code requirements (Horvat 2005). The next logical step is to develop an analytical tool to compare the overall performance of specific components, such as the wall assembly, thus helping to choose the best suited configuration to a given situation.

The use of multi-criteria decision analysis (MCDA) could assist in making a clearer choice between alternative wall assemblies based on many, often conflicting, criteria. The main objective of MCDA is to help the decision maker, here the design professional, organize and synthesize information in order to bring an integrated perspective in the decision-making process. Multi-criteria decision analysis thus seeks to integrate several goals in order to reach the best possible solution, considering the relative importance of each goal in the studied context. By formalizing the evaluation of the consequences related to the various potential solutions, it offers the possibility of developing a deeper understanding of the problem (Belton and Stewart 2002). The process implies the definition of the decision problem, of a set of feasible alternatives, of adequate criteria and their measurement mechanisms, the evaluation of the alternatives based on the criteria, the choice of an aggregation method, and the application of this method to obtain a ranking of the alternatives.

The main objective of this project is to develop a multi-criteria decision analysis framework to globally evaluate the performance of factory-built light-frame wood walls considering various combinations of wall assembly components. More specifically, this study includes:

- Identification of performance criteria for evaluating external wall assemblies;
- Assessment of analytical methods for measuring performance against the identified criteria;
- Integration of the codes and standards requirements related to these performance criteria;
- Development of a multi-criteria decision analysis framework allowing the comparison of various wall assemblies based on the selected performance criteria.

The project considers more specifically factory-built walls since the manufacturing process implies a better knowledge of the building conditions, such as moisture content of building materials. It also limits its scope to residential construction.

This paper will present the development of the multi-criteria framework including the identification of the criteria, the choice of the multi-criteria aggregation method, and the exploration of alternative components. It will also illustrate a case example showing the potential added-value of the tool in development to rank different wall assemblies in a specific application context. The actual multi-criteria decision model is being developed and will be presented in future work.

METHODOLOGY

In order to allow the evaluation of light-frame exterior wall assemblies, the various performance criteria had first to be identified and analyzed. The actual level of knowledge related to the evaluation of each criterion had to be assessed, and the most appropriate analytical methods were selected. In order to provide a background context in this study, we consider a residential building located in Quebec City. A summary inventory of the building materials used in the selected area for light-frame wood walls is made. This allows us to define the alternatives in terms of adequate wall assemblies that we wished to evaluate, compare and rank in a multi-criteria framework.

Criteria and Constraints

The main contribution of this work is to develop a multi-criteria analysis framework to help making a choice between several wall assemblies in a given situation. We start by modeling the decision situation, identifying and defining appropriate criteria, and quantifying their relative importance. In order to obtain a coherent, operational, measurable and exhaustive set of criteria, we use the top-down multiple objectives modeling approach developed by Keeney (1992). This approach starts with fundamental objectives and creates a hierarchy of goals and sub-goals, all the way down to specific measurable attributes on which the different alternatives are evaluated (Figure 1). In this project, we pursue three fundamental objectives: to ensure the comfort of the occupants by providing a durable protection, to reduce costs and to limit environmental impacts.

The attributes obtained at the lowest level of the objective hierarchy serve to either define constraints or to act as criteria: all wall assemblies must meet the required minimum levels of performance for the constraints-defining attributes. Constraints are used at the design stage to define feasible alternatives. Subsequently, feasible alternatives are compared and ranked in the multi-criteria analysis. Some attributes can both define a constraint and act as a criterion. For example, thermal insulation is a constraint since a minimum level of performance is prescribed in building codes, mainly to minimize condensation, but it is also a criterion on which we can express that a wall assembly with a higher thermal insulation is preferred over one with a lower thermal insulation, when considering the energy efficiency of the building. The work presented in this paper uses the attributes acting as criteria to compare the feasible alternatives. It therefore implies that the design phase of selecting feasible alternatives was completed beforehand and that all alternatives retained for comparison purposes meet the minimal performance requirements on the constraints-defining attributes. Nonetheless, in our top-down modeling approach, the three main objectives are fully developed to the lowest level including both types of attributes.

The first objective, which seeks to ensure the comfort of the occupants by providing a durable protection, involves several aspects: structural integrity of the envelope, control of the interior environment, and durability of the envelope.

The structural integrity of the envelope defines several constraints. It includes the resistance to gravity loads, wind pressure loads, seismic loads, as well as internal stresses due to heat and moisture variations in the building. Besides, it accounts for the capacity of the envelope to protect the occupants or to enable them to leave in case of emergency such as a major earthquake or fire. Moreover, factory-built walls must resist specific transportation and handling loads. Several of these constraints are not included in this analysis since these constraints apply to the whole construction system, or are project dependant. The three major constraints retained for the design of the wall assembly are therefore the stud resistance to combined loading, the in-plane shear resistance of the wall panel, and the duration of structural integrity in case of fire. It is understood that an increased structural resistance beyond the Code requirements does not bring an added-value to the construction. Therefore, no structural attribute acts as a criterion to compare the feasible wall assembly alternatives.

The control of the interior environment involves, amongst other things, the influence of the wall on interior temperature, relative humidity, air quality and sound level, as well as its contribution to aesthetics and natural lighting. The specific properties of the wall assembly influencing these attributes are its thermal resistance and thermal capacity, its airtightness, its surface reflectance, its sound attenuation capacity, its permeability to moisture, as well as the presence of contaminants or mold that could affect the interior air quality (ASHRAE 2005). Some code requirements prescribe or recommend minimal thermal resistance, maximal air permeance of the air barrier and adequate moisture management. These items represent the constraints used during the design phase. On the other hand, attributes chosen to act as criteria are the sound attenuation capacity and the heating and air-conditioning demand, the latter being influenced by thermal resistance, thermal capacity, and added airtightness.

The durability of the envelope depends on the materials capacity to resist the in-service conditions without degrading, as well as on the control of these in-service conditions. The robustness of the interior and exterior finishing to external loadings is an added-value property, and it is accounted for in the maintenance cost criterion described later. The control of relative humidity within the wall assembly is particularly important when using hygroscopic material, such as wood, which can be particularly sensitive to degradation and mold growth in the advent of high moisture contents. The moisture management constraint also related to water infiltration is therefore directly related to the durability of the envelope.

The second objective aims at reducing the overall costs of the building. Construction costs related to the exterior wall assembly therefore represents a criterion. Furthermore, maintenance costs as well as heat, ventilation and air-conditioning (HVAC) costs, both evaluated for an appropriate service lifetime, and actualized to building time (t=0), also act as criterion in the analysis.

The third objective is to limit environmental impact, by minimizing the flows from and to nature. Nowadays, life cycle assessment (LCA) can be used to assess the direct environmental impacts of a product in terms of environmental indices such as primary energy use, global warming potential, resources use, solid waste, water pollution and air pollution. Using available life cycle inventory (LCI) database, these evaluations aim to take into account the whole life of the building, including harvest, manufacturing and transportation of materials; manufacturing, transportation, on-site construction and disposal of the building; as well as the energy used during the building's life (Trusty and Horst 2002; Wilson 2005). The availability of appropriate and reliable LCI database is therefore crucial. In North America, although LCI studies have been completed for many materials and a protocol of development is documented through ISO standards 14040 and 14041, much work still need to be done (Norris and Notten

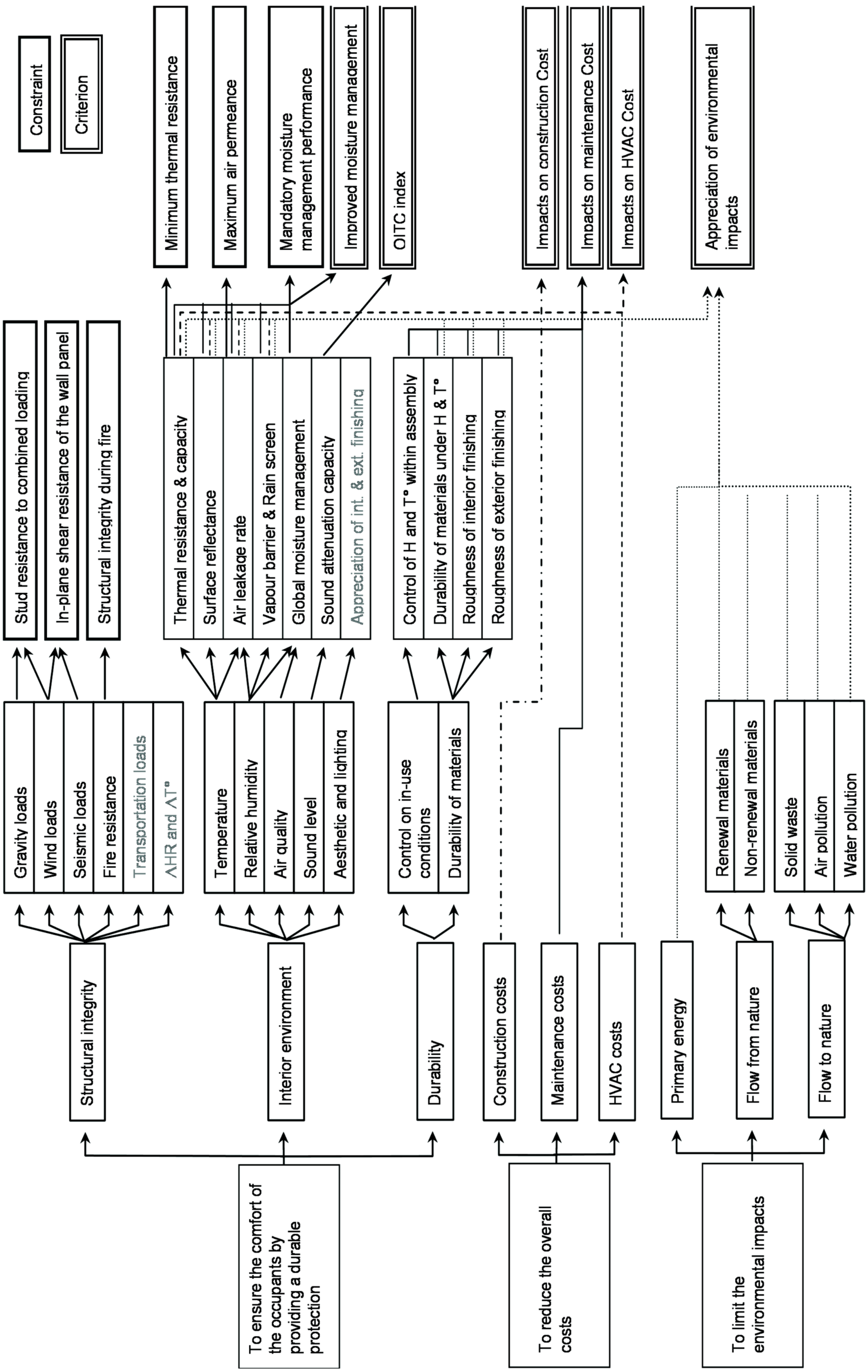


Figure 1 *Top-down development of main objectives.*

2002). Specific software, such as ATHENA® Environmental Impact Estimator, have been developed to provide LCA analysis of entire buildings (Trusty et al. 1998). However the evaluation of the relative importance of the various LCA impacts in the overall environmental appreciation depends strongly on the context. In this study, it was chosen as a first step to consider mainly the global warming potential index since it seems nowadays of great importance. However further investigation regarding the aggregation of these indices seems of importance.

The top-down approach allowed to identify a series of constraints and criteria involved in the design and the evaluation of exterior light-frame wall assemblies. Table 1 summarizes the ones included in this first phase of the study. This list could be adjusted as part of future development, when additional attributes more specific to a given context are needed. The following section describes the attributes with more details. For the constraints, it presents the prescribed evaluation methods and acceptable threshold. For the criteria, it proposes evaluation methods allowing the determination of the performance level, as well as scales on which these levels are measured along with the preferred direction for optimization purposes.

Constraints

Stud resistance to combined loading. According to the CAN/CSA-O86 standard, the internal stresses resulting from the combination of factored loading in the wood studs must stay below the prescribed wood resistance. Moreover, the horizontal deflection due to wind loads is limited to a 180th of the stud height (h/180), (CAN/CSA-O86-01 2005, par. 5.5.10 and 4.5.2). In Canada, the National Building Code prescribes the appropriate loading, while the resistance is provided by the CAN/CSA-O86 standard.

In-plane shear resistance of the wall. The lateral resistance of a building is difficult to predict since it depends on a system composed of several elements, such as shearwalls and diaphragms. The structural behavior of a standard shearwall panel, made of a structural panel assembled to wood framing, is relatively well known. A difference was however observed between the real lateral resistance of wood light-frame residential buildings and the results of calculation based on the performance of standard panels, since current calculations do not easily integrate system effects or the redundancy observed in a real construction. In spite of this difficulty, a calculation method is prescribed in the "Engineering Guide for Wood Frame Construction" (CCB-CWC 2004).

Fire performance. The National Building Code requires a fire resistance rating of the structure long enough to ensure the evacuation of the occupants. For example, concerning residential building with a maximum of three storey and more than one dwelling units, the minimum fire-rating for exterior wall is 45 minutes (NRCC 2005, par. 9.10.8.3). In wood light-frame construction, the fire performance is usually controlled by the presence of an interior gypsum panel, protecting the wall and the framing from the flames and the temperature increase. Empirical test results are available in the literature, as well as in the National Building Code Appendix to determine the fire resistance of standard wall assemblies (Sultan and Lougheed 2002; NRCC 2005 par. A-9.10.3.1).

Thermal insulation. Heat transfer through envelope elements may occur by conduction, convection, radiation, mass transfer or any combination of these. For porous materials, the apparent thermal conductivity, measured in W/m.K (or Btu /°F.ft.h), includes these various modes of heat transfer, and must be defined for a specific mean temperature and moisture content. In the building industry, the thermal resistance RSI-value, in m^2.K/W, (or R-value in °F.ft2.h/Btu) combines the thermal conductivity with the thickness of each material, and gives a global thermal resistance under steady-state conditions for a combination of materials, such as a wall assembly (ASHRAE 2005 p. 23.1). The effective RSI-Value must be calculated for a complete wall assembly including the thermal bridges caused by the wood elements. In Canada, the National Building Code requires a minimum thermal insulation to insure comfortable conditions for the occupants and to avoid condensation on the warm side of the wall (NRCC 2005 par. 9.25.2.). Besides, Model National Energy Code of Canada for Houses recommends a RSI-value of 4.1 for opaque wall assembly above ground in Quebec (NRCC 1997).

Air barrier. To build an airtight building, a system layer has to be continuous around the entire building envelope. The lack of airtightness is usually caused by discontinuity at the junction of components or when an element has to pass through the envelope. When evaluating a complete building, this property can be measured through a blow-door test, revealing the airtightness level for the entire envelope. At the design stage, the National Building Code requires the continuity of an air-tight system using an air barrier material with an air leakage characteristic not greater than 0.02 L/s.m^2@75 Pa. The Appendix also recommends a maximum air leakage rate of 0.05 L/s.m^2@75 Pa for the opaque parts of exterior walls, when the interior relative humidity reaches over 55% (NRCC 2005 par. 9.25.3; 5.4.1.2 and A-5.4.1.2).

Mandatory moisture management measures. In addition to minimum thermal resistance ratio and envelope airtightness, mandatory measures to avoid moisture problem in wall assemblies include the use of wood with a moisture content below 19% at the time of installation, a continuous protection against water ingress, use of a vapor-barrier on the warm side of insulation, and specific requirements regarding low air and vapor permeance materials installed on the exterior side of the wall (NRCC 2005 par. 9.25.1 and A-9.25.1). The maximum relative humidity may be calculated through a steady-state method, such as the dew-point method, to ensure that no condensation will occur within the wall assembly under design conditions (ASHRAE 2005 p. 23.10). Moreover, SPC 160P specifies performance-based design criteria for predicting moisture damage to the building envelope. It recommends to limit the relative humidity within the assembly

Table 1. Constraints and Criteria for Wall Assembly Assessment

	Constraints	Measure	Target
A	Studs resistance to combined loading	$\frac{P_f}{P_r}+\frac{M_f}{M_r}$	≤ 1.0
B	In-plane shear resistance of the wall	V_f/V_r	≤ 1.0
C	Fire performance	Fire rating	≥ ¾ or 1 h
D	Thermal insulation	RSI	avoid condensation
E	Air permeance of air-barrier components Air-leakage - opaque system (RH>55%)	air leakage characteristic max air leakage rate	≤ 0.02 L /s.m^2@75 Pa ≤ 0.05 L /s.m^2@75 Pa
F	Mandatory moisture management measures (in cold climate)	MC of wood Rain screen Vapor barrier Max RH (aver.30 days) Max RH (aver.24 hours)	≤ 19% included ≤ 60 ng/Pa.s.m^2 ≤ 80% ≤ 100%
	Performance criteria		
1	Moisture management - RH < 80%	number of days	maximize
2	Attenuation of sound transmission	log (OITC)	maximize
3	Construction cost	$	minimize
4	Maintenance cost	$	minimize
5	HVAC cost	$	minimize
6	Environmental impact - GWP	kg of carbon emission	minimize

under 80% over an average of 30 days, and under 100% over an average of 24h, in order to prevent problems associated with mold growth in surface temperature ranging between 5°C and 40°C (ASHRAE 2006).

Criteria

1. Moisture management: Studying the moisture content in the various components of wall assembly allows evaluating the adequacy of the components assembly regarding moisture absorption and the drying capacity of the wall. It can help predicting the deterioration of material, as well as mold growth, which is associated to high relative humidity and temperature (Teasdale-St-Hilaire and Derome 2005; Viitanen 1996; ASHRAE 2006). Nowadays, computer programs can perform dynamic simulations to predict transient-state behavior of wall assemblies. However, precise hygrothermal properties of the wall components, as well as representative input data reflecting the fluctuations of climatic conditions are required to obtain accurate moisture and temperature profiles. Besides, it is not simple to capture the relevant information obtained through simulation into a single index that could be included in a multi-criteria analysis. Following the new SPC 160P, which describes design criteria for moisture control in building, it was decided in this study to evaluate the moisture performance of the wall exceeding the minimum performance proposed in this ASHRAE standard (ASHRAE 2006). The criterion includes the number of continuous days with a relative humidity under 80% inside the assembly, evaluated under normal climate, as well as with accidental wetting added inside the stud cavity. The analyses are performed with WUFI heat and moisture transport simulation tool (Karagiozis et al. 2001). As a first step, the 1D simulation tool is used. However, 2D simulation should be included in further developments to consider the effect of the wood studs and therefore better simulate the transient behavior of the light-frame wood wall. This criterion is measured in number of continuous days with a relative humidity under 80%. A longer time under this relative humidity limit indicates a better performance.

2. Attenuation of sound transmission: Sound control depends mainly on three properties: transmission of the sound coming from outside or adjacent volumes, reverberation of the sound inside the volume, as well as background noise level (Warnock 2001). The external wall assembly influences mainly the transmission of the external sounds, while the sound transmission between the different volumes within the building depends on the interior walls and floor system, as well as on the connections between elements (Quirt et al. 2006). The ability of building components to stop air-borne sound is measured using a sound transmission class (STC). The STC is calculated using laboratory measures for a bandwidth

going from 125 Hz to 4 kHz (Warnock 2001). However, for exterior walls, sounds such as aircraft or traffic noises should be considered, and the Outdoor-Indoor Transmission Class (OITC) seems a more appropriate index (Bradley 2004; ASTM-E1332 2003). OITC indices derived from experimental measurements, using large frequency bandwidth, as well as field tests are available in the literature for various configurations of light-frame wood walls (Bradley et al. 2002). In the multi-criteria analysis, the logarithm of the OITC index is judged on a linear scale and a higher value represents a better performance.

3. Construction cost: Construction Costs account for materials, prefabrication process, transportation and on-site construction. The cost of a typical house using standard materials is first calculated. Thereafter, the cost difference involved by the change of materials and, if needed, a different construction process is estimated. In the multi-criterial analysis, this criterion evaluates the construction cost directly related to the wall assembly for the various alternatives considered. It is calculated in Canadian dollars and aims to be minimized.
4. Maintenance cost: Maintenance costs are mainly related to the quality and durability of the products used, as well as on the construction quality. When available, the maintenance cost of the wall assembly will be estimated considering regular maintenance, suggested replacement period as well as product warranties. In the analysis, this criterion, calculated in Canadian dollars, is actualized to today's value and should be minimized.
5. Heat, ventilation and air-conditioning (HVAC) cost: Having a direct impact on heating and cooling loads, the overall thermal resistance and airtightness of the exterior envelope influence greatly the HVAC costs. Specific research projects have also been looking at the influence of the surface reflectance and thermal capacity on the walls on HVAC costs, but these aspects are not considered in the analysis at this point. To enable the estimation of this criterion, the heat loss difference involved by the change of thermal resistance of the various alternatives is considered through steady-state calculation. This method is considered adequate for building with low thermal mass. However, if alternatives with higher thermal mass are considered, transient analysis may represent a more adequate solution method (ASHRAE 2005, par. 23.4). The energy cost directly related to the wall assembly is calculated in Canadian dollars and actualized to today's value. This criterion should be minimized.
6. Environmental impact: The environmental performance of the various wall assemblies is judged by comparing LCA results calculated for entire buildings by the LCA software ATHENA® (Trusty et al. 1998), including products life-cycle "from cradle to grave" and HVAC energy use. To minimize the importance of other factors such as the house occupancy or air-tightness of other envelope elements, only the portion of this impact directly related to the wall assembly is integrated. As discussed earlier, it was chosen, at this stage of the study, to compare the environmental performance of the various assemblies in terms of global warming potential (GWP). This index is measured in kg of carbon emission, and a lower score indicates a lower impact on the environment. This criterion should therefore be minimized.

Multi-Criteria Aggregation Method

Decision analysis methods taking into account several criteria can be divided in three broad families. The first one includes single criterion synthesizing methods, which aggregates the local evaluations of an alternative on each criterion into a global evaluation. This compensatory approach leads to a global score for each evaluation and consequently to a partial ordering of the alternatives from best to worst with the possibility of equal alternatives. The second family comprises outranking methods, which compare the alternatives pair wise in order to build a global preference structure while allowing for the possibility of two alternatives being incomparable. And finally, the third family embraces interactive methods that develop decision models through direct interactions between the analyst and the decision-maker.

Outranking methods have been developed to provide decision-support tools helping either to make a choice among several options, to rank these options or to classify them by category. They can include qualitative and quantitative criteria and often allow for incomparability and/or intransitivity. In order to rank alternative wall assemblies according to various performance criteria, we chose in this study to use ELECTRE II, one of the first outranking multi-criteria aggregation method developed (Roy and Bertier 1973). This choice is based on the simplicity and ease of use of the method, as well as on the availability of the MCMD software used in the present project (Abi-Zeid et al. 2005).

This method uses a pair wise comparison approach which defines an outranking relation between two alternatives: *A* “outranks” *B* means that the alternative *A* “is at least as good as” the alternative *B*. The aggregation process is divided in two steps. The first step is to build an outranking relation between each pair of alternatives. The second step is to use the relation to obtain a global ranking of the alternatives. Mathematically, this outranking method uses the notions of concordance and discordance to ensure comparability. The concordance index, denoted $c(A,B)$, indicates the strength of the assertion "*A* outranks *B*", based on all the criteria. It is computed by adding the weights of the criteria such that *A* is preferred to *B* on these criteria, where $g_j(A)$ is the evaluation of alternative *A* on criterion j, and π_j is the weight of the criterion *j,* as follows:

$$c(A, B) = \sum_{j : g_j(A) \geq g_j(B)} \pi_j \tag{1}$$

The discordance index looks more precisely at the outranking relationship of *A* over *B* on each criterion, and is denoted d_j. It describes the degree to which criterion j disagrees with the assertion that A outranks B, and thus allows the definition of a veto value for each criterion.

$$d_j(A,B) = \begin{cases} 0 & if\_g_j(A) \geq g_j(B) \\ g_j(B) - g_j(A) & if\_g_j(A) < g_j(B) \end{cases} \quad (2)$$

Once the concordance and the discordance indices have been computed, tests are applied using thresholds in order to determine whether A strongly outranks B, A weakly outranks B, or A does not outrank B. Direct and inverse ranking are then obtained from the strong and weak preference relationships, and can be combined to determine the final ranking that will identify whether for example A outranks B, A is outranked by B, A is equivalent to B, or A and B are incomparable. Following the ranking process, sensitivity analysis must be carried out to determine the influence on the final ranking of parameters, such as the concordance and discordance thresholds used, the weights granted to each criterion, and the uncertainty evaluations.

Alternatives

Light-frame wood construction evolves with the evolution of market demand, as well as with the constant emergence of new building materials in market. The process of developing an adapted solution to a specific context starts with the development of feasible alternative solutions that comply with building code regulations, identified previously as performance constraints. Although the multi-criteria analysis framework developed in this study does not aim to generate alternative solutions, but rather to compare them, it seemed important to identify the range of alternative building materials available to the designer. To do so, meetings with six manufacturers of prefabricated houses, as well as trade documentation review, were conducted to identify various materials currently used and their properties. Moreover, an exploration of newly available materials in the North American or European markets was undertaken.

For this review, the wall assembly was divided into five components, from the outside towards the interior of the wall: the external cladding (including furring), the sheathing and water resistive membrane, the framing, the insulation and the interior finishing (including vapor barrier). In addition, the air barrier system must be included in the assembly but has no mandatory position. Figure 2 summarizes the possible alternatives for each of these components, as well as their influence on the wall performance. The majority of these elements affect more than one performance criterion, showing the importance of using a global analysis approach in order to make a judicious choice amongst the various products available.

Once the wall assembly alternatives are identified, the multi-criteria analysis allows comparing them based on a series of performance criteria affected by the building context and customer preferences through individual weights accorded to each criterion.

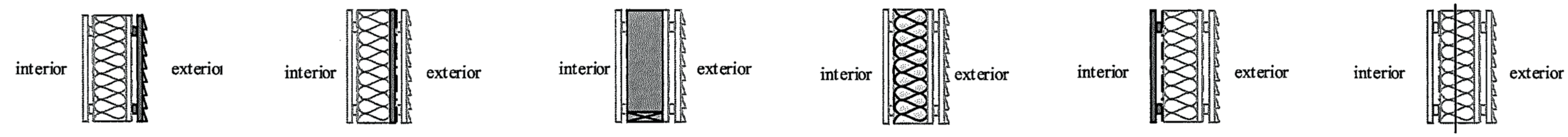
APPLICATION EXAMPLE

As an example, we analyzed three different wall assemblies for a residential building in Quebec City. The wall constructions are described in Table 2. The case considers a two-storey house of 200 m^2, and an assessment time period of 20 years to calculate HVAC energy use and environmental impacts. Energy costs include an actual cost of 0.08$/kWh and an inflation factor of 3 percent per year. The construction and HVAC costs are indicated as a cost difference between the alternative studied and Assembly 1, which is used as a reference. The time period of 20 years limits the importance of maintenance costs, which is not included in this preliminary example.

Once the proposed wall assemblies meet the design constraints presented in Table 1, they are accepted as possible alternatives to be ranked using the multi-criteria analysis. The performance of each assembly must be evaluated according to the identified criteria, as summarized in Table 3. In this example, the first assembly has a lower construction cost but also a lower thermal resistance, and lower acoustic attenuation. The increased need for HVAC energy affects costs as well as environmental impact. Moreover, the hygrothermal behavior needs attention due to the low permeance of the OSB sheathing in association with reduced insulation. The second assembly has a higher construction cost since it uses more expensive and efficient materials. Its higher thermal resistance leads to less HVAC cost. Moreover, the brick veneer and the increased wall thickness increase the sound attenuation. The environmental impact is more problematic in terms of production and disposal of the insulating material and the brick veneer, but it is also affected by the reduced HVAC energy demand. On the one hand the third assembly claims to be more "environmentally friendly" since it uses more wood and cellulose fiber products. However, it does not achieve the same thermal insulation as assembly 2.

As shown by this example, the wall assembly components affect several performances simultaneously. Even considering a defined context, with fixed attributes such as design climate, price of energy, and building service-life time, the advantage of a design over another is not simple to assess. Indeed, even if assembly 2 is the most expensive amongst these choices, it does not offer the best performance regarding all criteria. The weight accorded to each criterion is equally distributed in this simple example. In a more realistic situation, it would be defined by the decision-maker to consider the relative importance of each criterion, influencing the result obtained through the multi-criteria analysis. The final choice therefore greatly depends on the importance granted to each criterion in a given context, showing the added-value of the suggested tool.

The following phase of the study will include the application of the multi-criteria analysis framework being developed to rank the alternatives presented, based on more accurate performance evaluations. Moreover, a sensitivity analysis will verify how the weights granted to each criterion, as well as the concordance and discordance thresholds used, affect the ranking order of these alternatives.



External cladding	Sheathing and water resistive membrane	Framing	Insulation	Interior finishing and vapour barrier	Air-barrier system
Standard · Wood and wood composite siding · Vinyl siding · Brick or stone veneer · Stucco siding · Asbestos cement-board	**Standard** Water resistive membrane · Spun-bonded polyolefin · Building paper Sheathing · Plywood · OSB · Asphalt coated wood fiberboard Sheathing + water resist. m. · Extr. polystyrene with laminated water resist. m. · Rigid insulation, w/ or w/o air-barrier	**Standard** Studs · 2x4, 2x6, 2x8 · D-fir, SPF Spacing · 12"c/c, 16"c/c, 24"c/c, 1 bottom plate 1 or 2 top plates w/ or w/o hold-down connec w/ or w/o metal cross-strap.	**Standard** · Mineral wool batt · Glass fiber batt · Cellulose insulation · Expanded or extruded polystyrene · Polyurethane foam	**Standard** Vapour-barrier · Polyethylene film · Polyethylene matt w/ or w/o aluminium film · Kraft paper · Aluminium coated wood fibre panel · Low permeance paint Interior finishing · Gypsum board · Wood siding · Wood composite finishing	**Standard** Exterior side · Spun-bonded polyolefin · Building paper · Plywood or OSB · Extruded polystyrene **or** Interior side · Polyethylene film · Aluminium film · Kraft paper · Gypsum board
Alternatives · Stucco siding made with lime · Other siding from the commercial bldg industry	**Alternatives** · Rigid wood fibre panels	**Alternatives** · light steel studs (not considered in this project)	**Alternatives** · Wood fiber · Straw or straw-adobe mix · Cellular glass · Hemp wool, Sheep wool, Cork	**Alternatives** Interior finishing · fibre reinforced gypsum board	**Alternatives**
Affected properties · bending resistance of the cladding · drying capacity through air layer ventilation · durability · surface reflectance, surface roughness · sound attenuation (mass and flexibility of the connexion to the main structure) · environmental impact related to material and maintenance · flammability and fire propagation · Ease of construction · Aesthetic	**Affected properties** · bracing strength of the wall · bending strength between the studs · moisture transfer including drying capacity · air-tightness · thermal resistance, thermal capacity · sound attenuation (mass and flexibility of the connexion to the main structure) · environmental impact related to material · flammability and fire propagation · Ease of construction	**Affected properties** · stud strength to combined bending-compress. stress · in-plane shear strength · connections to global structural system · moisture absorption, drying capacity, durability · thermal resistance, thermal bridges · sound attenuation (layout, flexibility of the connexion to other elements) · environmental impact related to material · flammability and fire propagation · Ease of construction	**Affected properties** · bracing strength of the wall - in some cases · moisture transfer including moisture absorption and drying capacity · durability · air-tightness - in some cases · thermal resistance, thermal capacity · sound attenuation -sound absorption · environmental impact related to material · flammability and fire propagation · Ease of construction	**Affected properties** · bracing strength of the wall - in some cases · moisture transfer · durability · air-tightness -in some case · thermal resistance, thermal capacity · sound attenuation (mass and flexibility of the connexion to main struct.) · environmental impact - material and maintenance · flammability and fire propagation · contaminants emanation · Ease of construction · Aesthetic	**Affected properties** · air-tightness · sound attenuation · moisture transfer · durability · thermal resistance, thermal capacity · environmental impact - material and maintenance · flammability and fire propagation · contaminants emanation · Ease of construction

Figure 2 *Wood light-frame exterior wall assembly components.*

Table 2. Example of Application of the Wall Construction Evaluation Framework

	Assembly 1	Assembly 2	Assembly 3
External Cladding	vinyl siding on furring	brick veneer	wood siding on furring
Water Resistive Membrane	building paper	spun-bonded polyolefin membrane	spun-bonded polyolefin membrane
Sheathing	OSB	plywood	asphalt-coated wood fiber board
Framing	2x6 @ 16"c/c SPF stud	2x6 @ 16"c/c SPF stud	2x6 @ 16"c/c SPF stud
Insulation	5½" glass fiber batt	5½" extruded polystyrene	5½" cellulose insulation
Interior Finishing and Vapor Barrier	gypsum board with low-permeance paint	polyethylene and gypsum board on furring	kraft paper and gypsum board on furring

Table 3. Example Of Performance Evaluation For The Application Case

	Performance Criteria	target	weight	Assembly 1	Assembly 2	Assembly 3
1	Moisture management RH < 80% (days)	max	0.20	30 days	40 days	60 days
2	OITC index (log scale)	max	0.20	25	40	26
3	Construction cost ($)	min	0.20	reference	+ 16 000 $	+ 4 000 $
4	Maintenance over 20 years ($)	min	0	*not included*	*not included*	*not included*
5	HVAC cost over 20 years ($)	min	0.20	reference	- 1 850 $	- 1 120 $
6	Environmental impact - GWP (kg)	min	0.20	5 500	11 840	3 140

DISCUSSION AND CONCLUSION

The process of developing the multi-criteria analysis framework aims at exploring the various attributes affecting the global performance of light-frame wood wall assemblies. Many studies available in the literature evaluate some of these performance aspects in detail and help understanding specific behaviors. Bridging over several fields of expertise, a multi-criteria analysis process has the advantage of considering a number of these performance criteria simultaneously. It also brings the possibility of weighting the various criteria in respect of a specific design and building context.

In the future, such analysis should help professionals make a clearer choice regarding assembly components in the design of exterior walls, by giving them the possibility of comparing different alternatives on a common and comprehensive basis. It will also support the exchange of information between the various stakeholders and assist customers in judging the consequences of according varying importance to the various performance criteria based on their needs. Moreover, it can give a new dimension to cost analysis by allowing a better appreciation of the impact of cost on other performance criteria.

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