AIVC 11951

Whole-Wall Building Sustainability Index for IEA ANNEX 32 Integral Building Performance

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ABSTRACT

IEA Annex 32 Integral Building Envelope Performance is developing a number of test procedures and measures that can be used to compare and rate the thermal performance of alternative whole-wall construction technologies for residential structures. In this paper, we address sustainability issues and potential impacts building materials may have on the environment. Specifically, we describe the development of a whole-wall sustainability index. The index includes a number of specific measures of material sustainability—environmental emissions and impacts, material embodied energy, resource efficiency and recycling, and indoor air quality. The index is based on a life cycle analysis (LCA) perspective that encompasses the extraction of resources used in the manufacture of building materials, the impacts during construction, the impacts over building service life (including thermal performance), and the impacts associated with the disposition and recycling of the whole-wall components. To illustrate, we provide an example whole-wall sustainability index for two competing systems—a standard 2x4 dimensional lumber-framed whole-wall and a conventional cold form steel-framed whole-wall. In the future, we expect to develop databases, refine the sustainability index, and apply it to most of the 40 advanced wall systems already thermally evaluated. We also review related work by the American Institute of Architects (AIA), National Institute of Standards and Technology, and the Royal Architectural Institute of Canada.

Introduction

Segments of both the domestic and international construction industry have been working to promote the concept of sustainability and green building and to develop environmental performance rating systems. The concept of sustainability and green buildings centers around constructing buildings in such a manner as to result in less burden on the natural environment than if not constructed "green." The American Society for Testing Materials (ASTM) Green Building Subcommittee (E-50.06) has proposed to define green buildings as "buildings that are designed, constructed, renovated, operated, and reused in an environmentally and energy efficient manner." Although there is no definitive definition of "green" and little certainty about what constitutes a green product, process, or a green building (Cook 1994), there is much agreement about the concept of green or sustainable building. Green or sustainable buildings are constructed "in such a manner that fewer burdens are placed upon the natural environment, that fewer non-renewable materials and resources are consumed, that less waste is generated, and less energy is consumed.... In many cases there are products available which are less burdensome to the environment than others" (Bashford 1995).

One of the performance factors under the IEA Annex Assessment Matrix is *The Environment* defined within IEA Annex 32 to encourage the environmentally sound choice of raw and building materials for the energy efficient exterior envelope. It is anticipated that a fully developed exterior envelope sustainability index if integrated in an internationally recognized "Integral Building Envelope Performance Assessment Procedure," then manufacturers and building designers from around the world would be inclined to select the more sustainable envelopes. For example, the Dutch Government Buildings Agency states in its Integral Client's Brief: "The use of raw materials and building materials has a great impact on the environment. Extraction, transportation, manufacturing, assembly/mounting, use and demolition, each stage produces its own environmental damage. A considerable restriction of this environmental damage must be aimed at."

A number of innovative wall systems are now being offered in the residential building market. These wall systems include steel frame, insulating concrete forms, low-density concretes, structural insulated core panels, engineered wood wall framing, concrete block with insulated core, and a variety of hybrid wall systems. As the cost of dimensional lumber rises, framing lumber quality declines, availability fluctuates, and consumers' confusion about the environmental correctness of harvesting "old growth" wood heightens, these alternative wall systems could gain greater consumer acceptance. Unfortunately, greater acceptance of advanced wall systems will be hindered by a lack of information and accepted methods for making environmental performance comparisons among the many different systems now being offered.

When it comes to the walls, a dominant architectural feature of buildings, the consumer, along with designers, builders, and manufacturers, is uncertain at the least and misled at the worst about the environmental performance attributes of wall systems.[1] Oak Ridge National Laboratory's (ORNL) Buildings Technology Center of Excellence (BTC) has developed four performance measures that can be used to compare and rate the thermal performance of alternative whole-wall construction technologies for residential structures. These measures of whole-wall thermal performance include: whole-wall R-value, thermal mass benefit, air-tightness, and moisture tolerance.[2] Although these measures are important for comparing the relative efficiency of building energy use, they do not consider how material choices affect the environment over a building life cycle. In this paper, we discuss the development of a whole-wall sustainability performance index. The intent of the index is to provide objective information that can be used by building designers and exterior envelope manufacturers to compare the energy and environmental performance of alternative wall systems, make cost and design tradeoffs, and improve the environmental performance of their product. In the next sections of this paper, we discuss life-cycle assessment approaches to measuring sustainability and briefly review three efforts to evaluate the environmental performance of buildings. We then discuss our general approach to developing a sustainability index for whole-wall systems. We end the paper with future extensions and conclusions.

Measuring Sustainability—Life-cycle Assessment

Life-cycle assessment (LCA) is the generally accepted procedure to evaluate systematically the environmental implications of a material, product, or process across its entire life-cycle (cradle-to-grave

[1]For example, building wall energy efficiency usually is marketed solely by the misleading "clear wall" R-value (exterior wall area containing only insulation and necessary framing materials for a clear section with no (fenestration, corners, or connections between other envelope elements such as roofs, foundations, and other walls), or even worse "center-of-cavity" R-value (R-value estimation at a wall cross-sectional point containing the most insulation), which converts to a 0% framing factor and does not account for any of the more conductive structual material thermal shorts through the insulation.

[2]These specific performance measures are discussed by Christian and Kosny (1995).

environmental impacts) (EPA, 1993; Graedel and Allenby, 1995).[3] LCA is most often used in material selection and product evaluation, and to make comparisons among alternatives based on such environmental impact measures as: resources depleted, environmental wastes generated (air emissions, water effluents, solid wastes), embodied energy, recycling and waste management practices, energy used during service life, indoor air quality, and others. For building materials, environmental impacts are generated across all life-cycle stages—when resources are extracted and harvested, when products are manufactured and transported, when products are used in building construction, where the building is used, and when the building reaches the end of its useful life.

As customarily defined, LCA is an objective evaluation process involving four distinct and related steps:

- goal setting and definition of scope,
- inventory analysis,
- impact assessment, and
- improvement analysis.

The first step, goal setting and definition of scope, identifies the purpose of the LCA and draws of study boundaries (i.e., determining what environmental impacts will be assessed and to what degree). It involves decisions about what materials will be evaluated, what sub-materials are to be included, and what, if any, indirect environmental effects are to be included (e.g., including fuel used in harvesting and mining equipment but excluding the energy embodied in the equipment itself). As applied to buildings, the scoping stage would determine, for example, if the environmental effects and impacts of "fasteners" are to be included in the LCA. This step also entails assumptions about geographic/location specificity or how generic to make the LCA. This is important in the assessment stage as many impacts on ecological systems and human health and safety are very site and location specific. For example, soil erosion will produce greater environmental impacts when tree harvesting is done on steep sloped sites in the Pacific Northwest as opposed to relatively flat sites on managed pine plantations in the Southeast. In addition, environmental impacts from transportation of materials will also be highly dependent on the location of resource extraction sites, manufacturing facilities, and construction sites.

The second step is to identify and quantify energy and raw material inputs at each life-cycle stage as well as the environmental outputs—land disturbances, solid wastes, water effluents, and air emissions at each life-cycle stage (Figure 1). The significance of resource and energy use and resulting environmental effects and associated impacts will vary considerably by life-cycle stage. For example, resource and material input use is a critical factor during pre-construction life-cycle stages as opposed to post-construction. The inventory analysis step attempts to quantify as best possible and within system boundaries these life-cycle inputs and outputs. As discussed below, this step can be streamlined by using qualitative data for some environmental outputs when quantitative data are too costly to collect or simply unavailable or inappropriate given the boundaries placed on the LCA.

The third step is the most difficult and contentious. It involves translating the resource and energy inputs and environmental outputs or effects (e.g., amounts and types of solid wastes, water effluents, air

[3] The most accepted definition of LCA is by the Society of Environmental Toxicology and Chemistry (SETAC, 1991). They define LCA as "...an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impacts of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life-cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/re-use/maintenance; recycling; and final disposal."

emissions) into ecological, human health and safety, resource depletion, and other impacts. For example, the inventory analysis might quantify the amount of land disturbed from logging old-growth forests. This disturbance, measured in kg of soil eroded, would then be translated in the impact assessment step into increased sedimentation and, perhaps, harm on aquatic life. Typical impact assessment involves two steps—classification and characterization. Classification is the grouping of all environmental outputs that give rise to a given environmental impact, such as emissions of CO_2, CH_4, (carbon dioxide and methane) and other gases from fuel use during resource extraction and product transport, and from manufacturing processes that give rise to global warming. Characterization is the identification of impacts (e.g., global warming) and the development of appropriate indicators to characterize the impact—global warming equivalency index.

Impact assessment is relatively straightforward when dealing with impacts of a global or even regional nature, such as global warming and acidification. However, a difficulty arises when environmental outputs can only be assessed with reference to specific sites and have relatively localized consequences and cannot be easily aggregated across life-cycle stages (Augood, 1997). Some examples include impacts associated with resource extraction and land disturbance, impacts from water effluents, and impacts from solid waste generation.

The last step, improvement analysis, is designed to identify opportunities to reduce or prevent environmental impacts. For example, improvement analysis could identify high building energy use due to thermal bridging as a major limitation of steel-framed construction and suggest improvements in the wall assembly to reduce or eliminate the thermal bridging.

As practiced, LCA has been subject to substantial criticism on the grounds that it is too data intensive and, generally, too expensive and time consuming to undertake detailed life cycle inventories let alone translating these inventories into impacts and recommendations for product improvements. For example, a 2x4 lumber-framed wall assembly involves at least five major material components (lumber, fasteners, insulation, drywall, and sheathing), and for each of these major components there are vastly different resource extraction and product manufacturing life-cycle stages. Resource and energy requirements and resultant environmental outputs will also vary considerably.

Because of the cost of conducting detailed LCAs and the difficulty in quantifying certain types of impacts, reduced form or abridged approaches to LCA are being advanced. For example, Graedel et al. (1995) recommend LCAs be done in only modest depth and qualitatively in abridged form. These sentiments for streamlined versions of LCA are also echoed by Environmental Building News (Malin and Wilson, 1996) and the American Institute of Architects (AIA, 1997) in the context of building materials.[4]

Graedel et al. (1995) have proposed the use of abridged LCA that encompass all product life cycle stages and environmental concerns, yet be simple enough to permit relatively quick and inexpensive assessments. They recommend that a "figure of merit" be assigned to each stage of the product life cycle with respect to material, energy, and environmental implications. In their example, Graedel et al., (1995) use a 0 to 4 scale (0 - highest impact and 4 - lowest impact) to summarize the LCA inventory and impact analysis. Although they admit that the use of such a scale is subjective, they report that experiments have shown that these type of ratings to be quite accurate (Graedel and Allenby, 1995). Summary ratings are also used in the AIA (1997) Environmental Resource Guide. Specifics of this study and two building LCAs are described below.

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[4]Extensive discussion of LCA as it pertains to building materials and products can be found in AIA's *Environmental Resource Guide*, Appendix A.

Life-Cycle Assessment of Total Building Performance

AIA/ERG. The American Institute of Architects (AIA) began the Environmental Resource Guide (ERG) in 1990 and published its first version in 1992 (AIA, 1997). The primary goal of the ERG is to help architects and builders make environmentally sound choices when selecting among alternative building materials. The current version of the ERG contains material reports, application reports, and project reports. The material reports discuss in detail the environmental implications of specific building materials/systems (e.g., concrete, brick and masonry, steel framing, wood framing, fasteners, glued laminated timbers, laminates, insulation, roofing materials, gypsum board systems, glass, tile, flooring, as well as numerous finish materials). The applications reports are used to make explicit comparisons of the environmental performance of materials and products within a given construction category (e.g., light framing with an environmental performance comparison between steel and wood framing). The project reports profile actual building projects and cover the broader aspects of environmental performance.

The ERG uses a streamlined LCA approach to assess environmental performance of alternative building materials by using quantitative inventory data (e.g., tons of iron ore processed) when available and qualitative and narrative information for factors for which good data are unavailable or unreliable (e.g., effects on biodiversity). This information is compiled, characterized, and used for the impact assessment or valuation stage of the LCA. In the impact assessment stage, the ERG follows the standard two-step approach (1) classifying inventory data into impact groupings and (2) characterizing the environmental and health impacts of concern and selecting actual or surrogate indicators to describe the impacts. The ERG uses expert opinion to determine the relative performance of building materials in various impact categories. They aggregate impacts into four categories—environment and ecosystems, health and welfare, energy, and building operation. An example of the final LCA assessment for wood versus steel framing is summarized in Table 1. One important omission in the list of environmental performance factors listed in Table 1 is total equivalent global warming potential, particularly in light of the international global warming reduction goals back to or as much as 15% below the 1990 emission levels.

ATHENA. The ATHENA Project is a computer-based decision tool that is intended to help building designers and researchers conduct environmental assessments of building materials (Trusty, 1996).[5] The ATHENA model takes a life-cycle perspective covering resource extraction, manufacturing, construction, service use, and post-use disposal. In assessing the life cycle effects of a building, data on the structure can be entered into ATHENA in two ways: by referencing a set of pre-defined building assemblies or by entering quantities of materials calculated from a rough design. The model examines numerous environmental impacts including those associated with natural resource, energy and water use; as well as a number of atmospheric emissions, liquid effluents, and solid wastes. To simplify model output and to make interpretation of model output easier for potential users, a number of summary indices have been developed. Some of these indices include:

- total energy use—summation of all energy used in extraction, manufacturing, transportation, and construction;
- greenhouse gases—heat trapping potential of CO_2, CO (carbon monoxide), No_x (Nitrogen Oxides), and CH_4;

[5] A commercial version of the model is to be made available in the near future. The ATHENA Project is an alliance of private, public, and university researchers coordinated by Forintek Canada with support from Natural Resources Cánada, and incorporated as a non-profit research organization (The ATHENA Sustainable Materials Institute).

- air pollution—index of health effects from emissions [So_x, (Sulfur Oxides) PM, CO, NO_x, VOCs (volatile organic compounds), Phenols] resulting from energy use and production processes;
- water pollution—weighted critical volume index consisting of wastes that deplete oxygen, contain toxics and heavy metals, impose nutrient loadings, and produce sediment;
- solid wastes—mass of the solid waste from all stages of the life cycle that must be stored or landfilled; and
- ecological resource use—panel scoring index on the effect of timber harvesting, mining, and resource extraction on habitat, biodiversity, water quality, etc.

Currently, the model includes steel, wood, and concrete structural products and assemblies and covers only the resource extraction, manufacturing, and construction life-cycle stages. Plans are underway to expand the model to include other materials and the service use and post-use life-cycle stages including demolition and disposal.

The model has been used to analyze raw materials and energy use as well as emissions to air, water, and land for a 50,000 ft^2 office building using primarily wood, steel, and concrete construction. A key assumption about the model is that material choices cannot be made on absolute basis, but only on a relative basis through environmental effects comparisons among alternative materials. For this office building, the wood structure had the lowest environmental effect scores on all indices as shown in Table 2.

NIST/BEES. The National Institute of Standards and Technology with support from the Environmental Protection Agency is developing the Building for Environmental and Economic Sustainability (BEES) system, a decision support software and database for assessing building materials on the basis of tradeoffs between environmental and economic performance (Lippiatt and Norris, 1995; Lippiatt, 1997). BEES will provide users the capability to assess alternative building materials from extraction of raw materials to the reuse and recycling and ultimate disposal. The environmental performance part of the NIST BEES model uses a LCA approach. This approach is cast as a three step analytical procedure after goal identification and scoping has been defined. These steps include inventory analysis to identify and quantify resource and energy inputs and environmental outputs; impact assessment to characterize these inputs and outputs (e.g., relate CO_2 emissions to global warming); and interpretation to combine and commensurate environmental impact performance measures. In impact assessment, the BEES model uses six summary impact categories—global warming potential, acidification potential, nutrification potential, natural resource depletion, solid wastes, and indoor air quality. These categories or indices primarily address global and regional environmental impacts and not impacts dependent on local or site-specific conditions. The last step, interpretation, involves scaling or normalization of each impact index and then weighting each normalized impact category to produce an overall measure of environmental performance.

The BEES model differs from other attempts at LCA of building materials in two important ways. First, it explicitly attempts to rank alternative building materials on the basis of multiple attributes in the interpretation or impact valuation step. This step involves the use of multiattribute decision analysis and the use of importance weights or judgements. The intent here is to combine various environmental impacts into an overall relative environmental score. Second, NIST uses life-cycle costing methods (ASTM E 917-93) to estimate total costs (investment, replacement, maintenance and repair, and disposal) over the useful life of the building material. Results of the LCA of environmental performance and the life-cycle costs can then be combined to (1) winnow building materials that have poor environmental performance or life-cycle cost and (2) assess tradeoffs between environmental performance and life-cycle cost.

Sustainability Index for Whole-Wall Systems Using Life-Cycle Assessment

The purpose of a whole-wall sustainability index is to provide manufacturers and designers of wall systems information about the environmental sustainability of products and to help guide improvements in the product or component materials. In this section, we discuss a prototype sustainability index that is currently under development for whole-wall assemblies based on LCA principles. This sustainability index incorporates the results of thermal performance tests on whole-wall assemblies that are currently offered to manufacturers. The whole-wall sustainability index is illustrated using preliminary data for two competing systems—a standard 5.1 cm by 10.2 cm (2 by 4-in. nominal), 40 cm on center (16-in. o.c.) dimensional lumber-framed residential house of approximately 140 m^2 (1560 ft^2) and a conventional cold form steel-framed structure of the same dimensions.

Scoping and boundary setting. The sustainability index is based on materials contained in a whole-wall system. These materials include wood for the lumber-framed whole-wall system or cold rolled steel for the steel frame wall, insulation (R-11 fiberglass batts), exterior sheathing (1.3 cm or ½-in. plywood), and interior finish (1.3 cm or ½-in. drywall). No exterior finish such as a brick veneer or interior finish is assumed. For this case example the service life and maintenance is assumed to be the same for both the wood frame and cold formed steel stud wall system.

The boundaries of the life-cycle stages are defined as follows:

- Resource and material consumption—includes all activities prior to product manufacturing and fabrication. For wood products, this includes the construction of access roads to forest stands, harvesting operations, slash disposal and recovery, and transport of forest products to lumber and processing mills. For steel components, this life cycle stage includes mining of ores and requisite minerals, on-site processing of ores (e.g., crushing) and product transportation.
- Product manufacturing and transport—includes all processing activities and transportation to produce a product or material ready for use on the construction site. For wood products, this stage includes debarking, sawing, drying, and finishing. For steel components, this stage includes steel making, ingot casting, rolling, forming, cutting, and product transport.
- Building construction—includes acquisition and transport of products and materials to the construction site as well as all building activities prior to occupancy. The two major activities on the construction site are selection of high quality-durable building materials, careful handling and assembly of those materials, waste minimization and on-site separation to enhance reuse and recycling (This is called out in the IEA Annex 32 brief at E 2.2.1).
- Building use—includes all activities related to energy use (This is called out in the IEA Annex 32 brief at E 1), maintenance (This is called out in the IEA Annex 32 brief at Co2.2), and durability of the building (or whole-wall) over its entire service life (This is called out in the IEA Annex 32 brief at Co2.1).
- Reuse, recycling, and final disposition—includes all activities related to handling the building components after useful service life (i.e., demolition, material separation, reuse, recycling, and final disposal). In the existing IEA Annex 32 brief at this time no specific requirement address this stage of the exterior envelopes life.

Inventory Analysis. The major resource and energy input and environmental outputs for building materials by life cycle stage are summarized in Table 3. The five stages are listed in rows with resource and energy inputs and environmental outputs in columns. The elements of the assessment matrix are relatively straightforward and require little additional explanation.

The elements of the generalized assessment matrix were then assessed for the two competing whole-wall systems, which are summarized in Tables 4 and 5. The Tables show the major resource and energy inputs and environmental effects in both quantitative and qualitative terms. For the wood wall system, the majority of environmental effects occur in the resource extraction stage. For the steel wall, there are potentially large environmental impacts in both resource extraction and manufacturing. Both systems have few environmental effects during construction and homeowner use stages with the exception of energy use. In the final stage, waste generated and landfill requirements dominate.

Impact assessment. Translating the environmental effects as well as the resource and energy usage effects into environmental impacts involves classification and characterization. A key issue raised earlier about impact assessment is geographic specificity. This means that many impacts can only be measured or evaluated under location-specific conditions. That is, they are dependent upon what specific ecosystems are at risk and what are the affected populations (biodiversity, human health).

The three building LCAs discussed earlier have, for the most part, used different approaches to classification and characterization. The BEES model (Lipiatt, 1997) does not include impacts that are local in nature and include only those that are of a global or regional nature. These include global warming, acidification, nitrification, indoor air quality, natural resource depletion, and solid wastes. For each impact assessment category, a quantitative measure is developed based on a functional 0.09 m^2 (1 ft^2) of product. The ERG approach (AIA, 1997) provides general summary information including some quantitative data for four impact categories—waste generation, natural resource depletion, energy consumption, and indoor air quality in their material assessment reports. For their application reports (e.g., wood versus steel framing), they provide assessment ratings of environmental performance as shown in Table 1. The ATHENA approach (Trusty, 1996; CWC, 1997) uses quantitative indices for energy use, greenhouse gases, air pollution, water pollution, and solid waste. However, for ecological resource use, they recognize the problems geographic specificity and resort to use of a rating scale based on expert judgement.

For the whole-wall sustainability index, we use both quantitative measures as well as qualitative ratings. We chose to classify and characterize resource and energy usage and environmental effects (emissions, effluents, and wastes) into six impact categories. Three impact categories dealing primarily with material extraction, manufacturing, and product transport–resource and ecosystems impacts, embodied energy use, and global warming potential–and three post-construction impact categories–building energy use, indoor air quality, and reuse/recyclability.

Because our results are preliminary and more for illustration, we discuss only briefly the impact categories.

- Resource and ecosystems effects—For this index we use a qualitative rating based on a five point scale with a rating of five to indicate good environmental performance and a rating of zero to indicate poor performance. This index is meant to cover land and soil disturbances and related impacts as well as impacts associated with depletion of resources (e.g., old-growth timber).
  - wood wall system assigned a value of two
  - steel wall system assigned a value of three.
- Embodied energy use—This index includes estimates of fuel used directly to operate equipment during extraction and manufacturing operations as well as fuel used for product transportation. The index does not include indirect or embodied energy in equipment or processing facilities. The index values are expressed in terms of energy per square meter of wall area.

- wood = total embodied energy ~ 53.2 MJ m^{-2} of wall area (4690 BTU ft^{-2})
- steel = total embodied energy ~ 251 MJ m^{-2} of wall area (22100 BTU ft^{-2})

- Global warming potential—This index is based on global warming potential of CO_2 integrated over a 100-year time period. CO_2 is assigned a value of 1, CH_4 a value of 11, N_2O a value of 270, and various values ranging between 90 and 7000 for CFCs and HCFCs. The index values are expressed in terms of energy per square meter of wall area.
  - wood = global warming potential ~ 2.6 kg CO_2 m^{-2} (0.6 lbs CO_2 ft^{-2})
  - steel = global warming potential ~ 11 kg CO_2 m^{-2} (2.2 lbs CO_2 ft^{-2})
- Building energy use—This index uses actual results from whole-wall thermal testing of 2.4m by 2.4m (8-ft by 8-ft) clear-wall sections in guarded hot box with simulations of wall interface details (corners, wall/roof, wall/foundation, windows, doors, etc.) to account for a representative whole-wall elevation. Index units are whole-wall R-value.
  - wood = whole-wall R-value 1.69 m^2K/W (9.6 hft^2/Btu)
  - steel = whole-wall R-value 1.08 m^2K/W (6.1 hft^2/Btu)
- Indoor air quality—This index is based on off-gasing potential of VOCs and toxics contained in preserved wood and other materials. (No significant indoor air quality issues associated with wood- or steel-framed walls.)
- Reuse/recyclability—This index is based on waste generated at construction/building demolition sites and reuse/recyclability potential of materials. Initially, we use a qualitative rating based on a five point scale with a rating of five to indicate good environmental performance and a rating of zero to indicate poor performance. However, we expect to revise this impact measure with an index based on a combination of waste generated from construction and building demolition and ease of recycling. The following judgement ratings have been assigned.
  - wood wall system assigned a value of one
  - steel wall system assigned a value of four.

The above indices do not provide an easy way to assess relative environmental performance. We can provide a better indication of relative performance between the wood and steel whole-wall systems by normalizing the impact indices and summarizing graphically. This summarization is presented in Figure 2 as a bar chart. The horizontal bars in Figure 2 indicate relative environmental performance for the impact category. Overall, these results show that the wood wall system dominates the steel wall system in embodied energy content, global warming potential, and building energy use. The steel system is slightly better with regard to resource and ecosystem impacts and much better in reuse/recyclability. Both systems have insignificant indoor air quality impacts.

Conclusions

We have attempted to describe the development of a whole-wall sustainability index based on LCA principles. We illustrated our prototype index by highlighting two examples—a conventional wood-framed whole-wall system and a cold-formed steel system. Our intentions are to offer the index initially to manufacturers as part of whole-wall thermal performance testing, analysis and internet presentation. We expect that manufacturers will want to use the index to improve the environmental performance of their product. For example, the steel-framed wall system can be significantly improved in resource and ecosystem impacts, embodied energy, and global warming by taking steps to certify that a larger fraction of the steel content comes from recycled sources. Also, in the building use stage, manufacturers can take steps to eliminate the thermal bridging problem responsible for potentially relatively poor whole-wall thermal performance.

Although these examples are rather obvious, we are in the process of developing more detailed databases in order to discriminate more closely among specific materials in the wall assemblies (e.g., fasteners) and among sub-components of the impact categories. That is, the sustainability index will be designed to examine more marginal changes in whole-wall material usage and processes. To date, the Buildings Technology Center has performed thermal testing on nearly 40 whole-wall assemblies. We anticipate developing sustainability performance ratings for many of these advanced wall systems in the next year.

The paper also overlays the IEA Annex 32 Integral Building Envelope Performance Assessment Matrix for the Environmental performance requirements (E) in an attempt to offer some type of quantification methodology to help manufacturers, designers and building owners select exterior envelope materials that have a high sustainability index yet still provide "fit for use buildings."

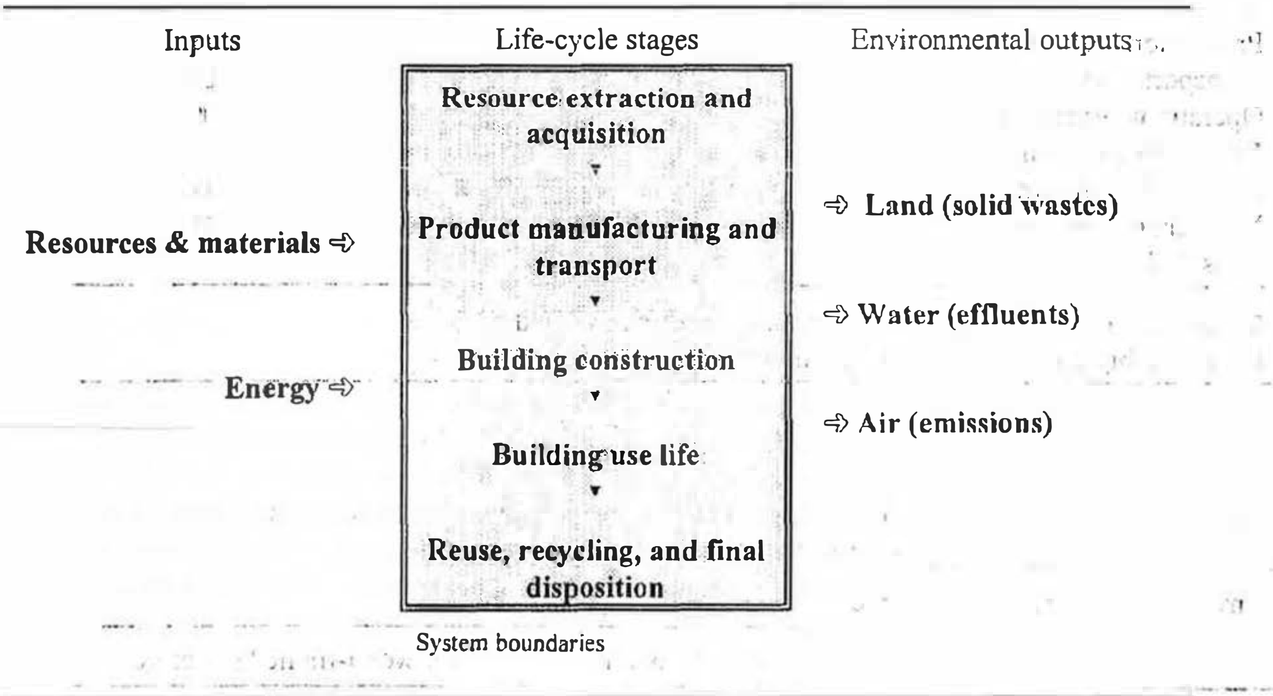

Figure 1. Definition of life-cycle stages, resource/energy inputs, and environmental outputs.

Table 1. AIA/ERG environmental performance comparison of wood and steel light framing systems.

Environmental performance	Wood framing	Steel framing	Steel with exterior XPS foam
Environment/ecosystems			
Air quality impacts	‖	‖	■
Water quality/availability	‖	‖	‖
Land soil quality/availability	▮	‖	‖
Virgin resource depletion	▮	‖	▌
Biodiversity/habitat loss	▮	‖	‖
Health and welfare			
Worker/installer health	□	‖	‖
Building occupant health	□	□	□
Community health /welfare	❒	‖	‖
Energy			
Production/manufacturing	□	‖	■
Transportation	❒	❒	❒
Operational energy use	□	▌	‖
Building operation			
Useful life/durability	❒	□	□
Maintenance requirements	‖	□	□
Reusability/recyclability	‖	□	‖

□ - good; ❒ - good to reasonably good; ‖ - reasonably good;
▌ - reasonably good to poor; ▮ - good to poor; ■ - poor

Table 2. Summary ATHENA environmental profile for a wood, steel, and concrete office building.

Environmental index	Wood	Steel	Concrete
		Multiplicative impact over wood-framed structure	
Total energy use	--	1.9	1.6
Greenhouse gas	--	1.45	1.81
Air pollution	--	1.42	1.67
Water pollution	--	120	1.9
Solid waste	--	1.36	1.96
Ecological resource use	--	1.16	1.97

Note: Example interpretation—the steel and concrete building required 1.9 and 1.6 times more energy for extraction, production, manufacturing, transportation, and construction than the wood-framed structure, respectively.

Table 3. Summary of LCA resource and energy inputs and environmental outputs applicable to whole-wall systems.

	Inputs - Resources and Energy		Outputs - Environmental		
Building wall life cycle stages	Resource & material consumption *(E2.1 & E2.2)*	Energy use *(E1.1.2)*	Land (solid wastes) *(E3.1)*	Water (effluents) *(E4.1)*	Air (emissions) *(E5.1)*
Resource extraction & acquisition	- Use of virgin or non-renewable materials - Use of old growth forests	- Energy intensity of extraction or acquisition - Renewable energy used - Transport fuels	- Soil erosion and compaction - Alteration of habitat and biodiversity loss - Solid wastes requiring disposal	- Sedimentation - Effluent impacts (nutrients, toxics, heavy metals, etc.) - Process water use	- Air emissions (CO, NO_x, SO_2, VOCs, PM) - Contributions to global warming, ozone depletion, acidification, local air quality...
Product manufacturing and transport	- Use of recycled or reused materials	- Process energy consumed - Renewable energy used or generated on-site - Transport fuels.	- Solid wastes requiring disposal - Reduced landfill space	- Sedimentation - Effluent impacts (nutrients, toxics, heavy metals, ...) - Process water use	- Air emissions (CO, NO_x, SO_2, VOCs, PM) - Contributions to global warming, ozone depletion, acidification, local air quality...
Building wall construction	- Recycling and reuse of construction materials	- Construction energy use considered not significant	- Solid wastes requiring disposal - Reduced landfill space	- Effluent runoff from construction sites not significant	- Air emissions from construction not significant
Building wall life cycle use	- Durability of materials during use phase	- Building energy use (whole-wall R value, thermal mass benefit, moisture tolerance, air-tightness)	- None expected	- None expected	- Indoor air emissions (e.g., VOCs and other chemicals)
Reuse, recycling, and disposal	- Ease of separation, reuse and recycling of component materials - Landfill requirements	- Energy used and recovered	- Solid wastes requiring disposal - Reduced landfill space	- Demolition effluents - Landfill leachates	- Air emissions (CO, NO_x, SO_2, VOCs, PM) - Contributions to global warming, ozone depletion, acidification, local air quality...

Table 4. Summary of major LCA resource and energy inputs and environmental outputs for 2x4 lumber-framed whole wall systems.

	Inputs - Resources and Energy		Outputs - Environmental		
Building wall life cycle stages	Resource & material consumption *(E2.1 & E2.2)*	Energy use *(E1.1.2)*	Land (solid wastes) *(E3.1)*	Water (effluents) *(E4.1)*	Air (emissions) *(E5.1)*
Material extraction & acquisition	- significant amounts of wood harvested from old growth forests, depletion a concern - 2.4 tons roundwood per ton lumber - one-third of supplies from sustainably grown sources	- moderate to low embodied energy consumption low - ~35% of waste wood recycled and used as fuel	- 0.45 tons bark/wood waste per ton lumber - extensive soil disturbance erosion especially if old growth forest stands - extensive habitat and biodiversity destruction from old growth	- sedimentation from runoff (site specific)	- small amounts of CO_2 produced from fuel use (0.83 tons per ton lumber) if grown sustainably - loss of CO_2 sinks - small amounts of CO, CH_4, NO_x, SO_2, VOCs, and PM from fuel use in logging
Product manufacturing and transport	- not significant	- transport energy potentially high	- not significant	- potential contamination from treated lumber manufacture	- small amounts of CO, CH_4, NO_x, SO_2, VOCs, and PM from fuel use in manufacturing
Building wall construction	- little if any recycling to extend resource during construction	- not significant	- moderate to large amounts of solid wastes produced requiring landfilling	- not significant	- not significant
Homeowner use	- not significant - high durability if protected	- potentially higher whole-wall R-value	- not significant	- not significant	- Indoor air quality not affected
Building wall demolition, reuse, recycling, and disposal	- little recycling practiced to extend wood resources	- energy use not significant during final disposition	- moderate to large amounts of solid wastes (25% of demolition wastes) requiring landfilling	- not significant	- air emissions not significant during final disposition

Sources: AIA, EBN, CWC, and Christian and Kosny.

Table 5. Summary of major LCA resource and energy inputs and environmental outputs for cold-formed steel whole-wall systems.

	Inputs - Resources and Energy		**Outputs - Environmental**		
Building wall life cycle stages	Resource & material consumption *(E2.1 & E2.2)*	Energy use *(E1.1.2)*	Land (solid wastes) *(E3.1)*	Water (effluents) *(E4.1)*	Air (emissions) *(E5.1)*
Material extraction & acquisition	- large quantities of materials (2.4 tons iron ore, 0.16 tons zinc, 0.36 tons of limestone per ton galv. steel) - large quantities of process water	- moderate to high energy use during extraction	- moderate amounts of waste materials (0.4 tons slag per ton galv. steel) and mine tailings - intensive land disturbance from ore and coal strip and pit mining	- mine runoff and wastewater from mining and manufacturing operations - sedimentation from erosion	- energy intensive with large amounts of CO_2 generated (3.9 tons per ton galv. steel)
Product manufacturing and transport	- large amounts of steel recycled (66%) in manufacturing	- high embodied energy (21 - 38 MMBtu per ton galv. steel).	- potentially significant erosion from ore and mineral mining sites	- contaminated runoff from mining	- large air emissions (46 lbs CO, 13.6 lbs SO_2, 6.6 lbs VOCs, 2.8 lbs PM per ton galv. steel)
Building wall construction	- steel cutoffs highly recyclable	- not significant	- small amount of waste during construction	- not significant	- not significant
Homeowner use	- not significant - high durability if protected	- whole-wall R-value potentially low due to thermal shorts	- not significant	- not significant	- not significant (indoor air quality not affected by off-gasing)
Building wall demolition, reuse, recycling, and disposal	- steel framing components highly separable from waste stream and recyclable	- energy use not significant during final disposition	- galvanized steel recyclable - much smaller amounts of solid wastes produced requiring landfilling	- not significant	- air emissions not significant during final disposition

Sources: AIA, EBN, CWC, and Christian and Kosny.

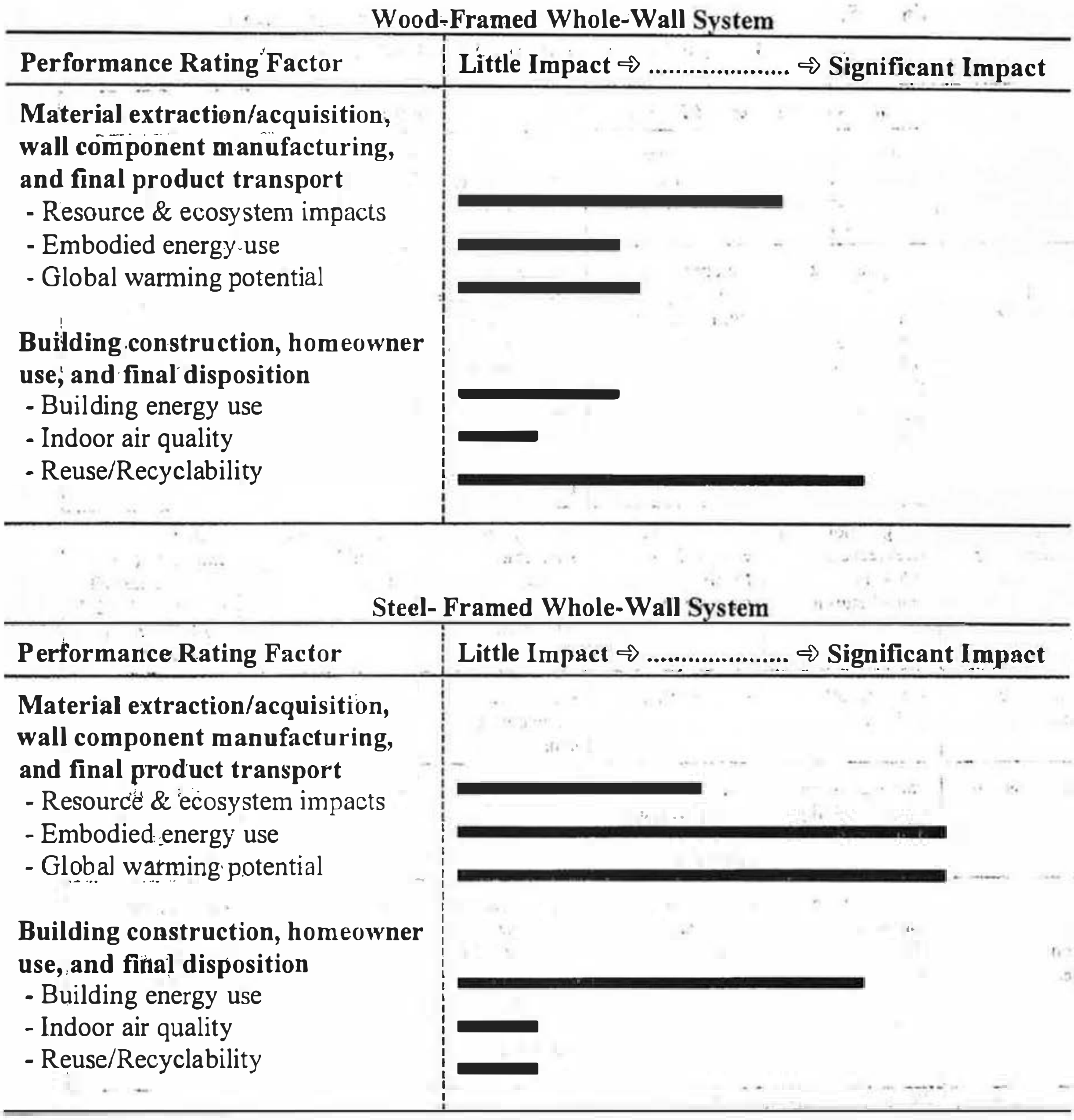

Figure 2. Whole-wall Sustainability Index.

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