SUSTAINABILITY MATRIX APPROACH

A SUSTAINABILITY MATRIX APPROACH TO BUILDING MATERIAL SELECTION AND ASSEMBLY DESIGN

By

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Abstract

The sustainable design of buildings, notably material and assembly selection is beginning to be embraced by design professionals. However, the environmental considerations of building design and material selection often rely on time-consuming, costly approaches such as life cycle analysis which often do not provide adequate information for designers to effect preventive engineering approaches in the early design stages. Less time-consuming approaches are available, but their application to design is often difficult due to their subjective nature. The Sustainability Matrix Approach, based upon the work of Graedel and Allenby offers guidance to the building designer in the preliminary design stages through a combination of streamlined life cycle assessment and a series of check-lists.

The series of checklists based upon core sustainability principles alerts the designer to environmental hotspots and can serve as a guide to redirect product and material choices to those that are environmentally preferable. To supplement the decision–making process, life cycle inventory data are used.

Using this approach to preliminary design, four wall systems were investigated: steel stud, wood stud, concrete block and strawbale. The results indicated that the environmental impact of the strawbale wall assembly was greater than anticipated largely due to the nature and amount of exterior and interior plasters used. The steel and wood stud wall assemblies, using the selected criteria, were found to be environmentally preferable to the strawbale wall assembly.

The sustainability matrix approach is a useful preliminary design tool for assessing the net environmental burdens of not only walls but other building elements as well. However, the sustainability matrix does not explicitly consider other important sustainability parameters that are not governed by material or system properties such as building durability. Nevertheless, the Sustainability Matrix Approach is a useful tool for learning about the difficult decisions required in designing environmentally preferable buildings.

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I am grateful to everyone in the Department of Civil Engineering, as they helped and supported me on this journey. If it weren't for the faith and guidance that my supervisor, Bob Korol had in me and gave me, none of this work would have been possible. Thank you for letting me explore my own path. Thank you Bill for your mentorship. I especially owe my appreciation to my family and friends for helping me along the way. Sara, thank you for sacrificing your time to be apart from me during the last months of this endeavour.

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1.0 Introduction

The construction industry is a major contributor to the material throughput and energy use within current developed economies. While these flows of matter and energy are essential for the modern human habitat, economy and culture, the current rate and quantity of these flows stress the earth's functions to act as a source and sink for energy and materials. Material flows that exceed the regenerative and assimilative capacity of ecosystems threaten the current economy that is based upon the services provided by healthy ecosystems.

The long-term availability of non-renewable energy sources will be a prime concern as the scarcity of non-renewables increases. However, of greater concern are the emissions and pollutants generated as a result of the conversion of energy forms. These are primarily evidenced as pollutants from fossil fuel combustion, ecological damage from generating stations, and direct pollutant loading as a result of nuclear processes. These stresses are not limited to ecosystems. The human physical, psychological and cultural ramifications of this excessive throughput are already evidenced by increased rates of cancer, elevated stress levels and largely a detachment from nature.

The material and energy flows within the construction industry can be characterised as relating to either the buildings or the infrastructure required to support the activities within them. Together, buildings and infrastructure material flows account for the largest flow of materials globally (Roodman & Lensson, 1995). In the past, these material flows, while substantial, were relatively benign and composed of abundant and local resources such as stone, mud, clay and wood. However, with the advent of modern economies, the resources used for construction have expanded beyond the use of locally available and unprocessed materials to those limited only by the available energy required to extract, process, manufacture, and ship materials.

In addition to material flows, buildings significantly contribute to both Canadian and world-wide energy consumption. For both production of building materials and operation of buildings, buildings account for one third of the total energy use worldwide (Roodman & Lensson, 1995). In Canada, for the commercial and residential sectors, most of the energy usage is directly influenced by the choice of building materials and the design of the building. For example, space heating alone (directly influenced by building design and choice of materials) accounts for 53% of commercial energy usage and 61% of residential energy use, totalling 13% of total energy use in Canada (Office of Energy Efficiency [OEE], 1998).

The modern materials of concrete, steel, plastics and glass were instrumental in creating economical, safe, and culturally rich cities that often define a nation's state of progress. The role of architecture and engineering was to ensure that this built environment was aesthetically pleasing, functional and safe. The issue of safety and a "duty to the public" is still believed to be the credo of today's engineers.

However, this view of safety is largely deficient in that it fails to recognise dangers posed to human health other than those of direct physical harm from structural collapse, fire and the elements. Equally important human safety issues, though less obvious, are those arising from the persistent exposure to anthropogenic emissions related to the construction industry.

The harm caused from anthropogenic emissions show up as increased cancer rates, endocrinological disruptions, infertility, asthma and mutagenic-related diseases. The reason modern building materials threaten human health is simple: building materials increasingly incorporate and generate through their production, toxic substances that nature is incapable of breaking down. Furthermore, the production of building materials generates large quantities of waste that may be considered natural, but that exceed natural cycles of assimilation.

To further aggravate the problem, the quantity of natural sinks is decreasing with declining biodiversity by habitat destruction, monoculture farming, tree plantations, strip mining and clearcutting, and pollution of the air water and land as a result of the production of materials and products. Thus the quantity and toxicity of materials flowing into the biosphere increases, while at the same time the biosphere's ability to process these wastes diminishes.

A slightly decreased ecological health might be considered a small price to pay for the material "progress" of humanity. However, since the ecological and human health burdens resulting from building materials are largely a result of inefficient material cycles that produce unusable and harmful wastes both during production and at disposal. Thus, the impacts are not simply the "nature of the beast" but rather– poor design.

At disposal, construction and demolition wastes account for 20 to 30% by volume of municipal landfills (Allenby, 1999, p. 89), roughly equivalent to the volume of household waste. During the extraction of raw materials, the wastes, or emissions to the environment, are seen as process wastes such as waste rock from mining raw material from stock (non-renewable) sources. For instance, one tonne of waste overburden material is produced for every tonne of steel produced in the steel-making process (ATHENA™, 2000a). Similar wastes occur throughout the manufacturing process. The result is a linear throughput of material cycles from the economy to the biosphere. Since the waste materials are generally not reintegrated with natural material cycles (and if they are, they are not readily assimilated due to their toxicity or concentration), this flow of materials is not sustainable. The result is both a decline in available resources and natural sinks.

The building industry to some degree has responded to the above-mentioned environmental problems, but the net material throughput and net energy use from non-renewable sources is largely untouched by current approaches to "green building".

Green building concepts follow the premise that the most pressing issues should be addressed first. This thesis agrees with the notion that greenhouse gases, ozone depletion and indoor air quality concerns are important design parameters. However, if reductions in the above mentioned areas result in increased burdens at another time in the future or to another area, they merely shift the problem with questionable net gains.

Bombarded with a host of "green" products, materials and techniques the building designer is often faced with many decisions that appear to require trade-offs of performance, price, aesthetics or ease of construction. Many of these strategies are presented as "environmental solutions." However, before assessing these solutions, it is necessary to ask oneself: "What is the problem with current methods? Can current approaches be improved or should they be abandoned?" It is often tempting to abandon old techniques, in favour of technological, new or innovative solutions. However, it is essential that the root problem be fully understood first.

This thesis will outline a preventive framework for the preliminary design of sustainable buildings. The framework is preliminary in the sense that it serves as a "map" of the issues relevant to sustainable buildings, rather than solutions themselves. It is hoped that by beginning to understand the complex interactions between building materials, elements, systems and the accompanying site and infrastructure, and the areas of the environment, culture and human health, that the "hotspots" impeding a sustainable future can be quenched.

Chapter 2 introduces the concepts of industrial ecology and the application of the precautionary principle with the goal of creating a circular economy. The concept of life cycle design is introduced. The material and energy flows are characterised as they relate to buildings to help understand the root problems involved.

The limitations of some current design approaches are reviewed in Chapter 3 with the aim of leading into the requirements of a framework necessary to guide sustainability-oriented design.

Chapter 4 outlines the sustainability matrix tool that can be used to map the significant environmental "hot spots" associated with building materials. The stages of a building material's life cycle are discussed in detail in addition to the corresponding emissions and ecological impacts.

Chapter 5 describes four wall systems (strawbale, wood stud, steel stud, and concrete block) that will be analysed using the sustainability matrix to demonstrate the usefulness of the design approach. A description of strawbale wall construction is included as background material in Appendix A.

Chapter 6 provides a summary of the major hotspots that were identified using the developed approach and suggests a few improvements for one wall system. The limitations of the sustainability matrix approach are discussed.

Chapter 7 provides conclusions and recommendations on both the wall systems analysed and the sustainability matrix in general.

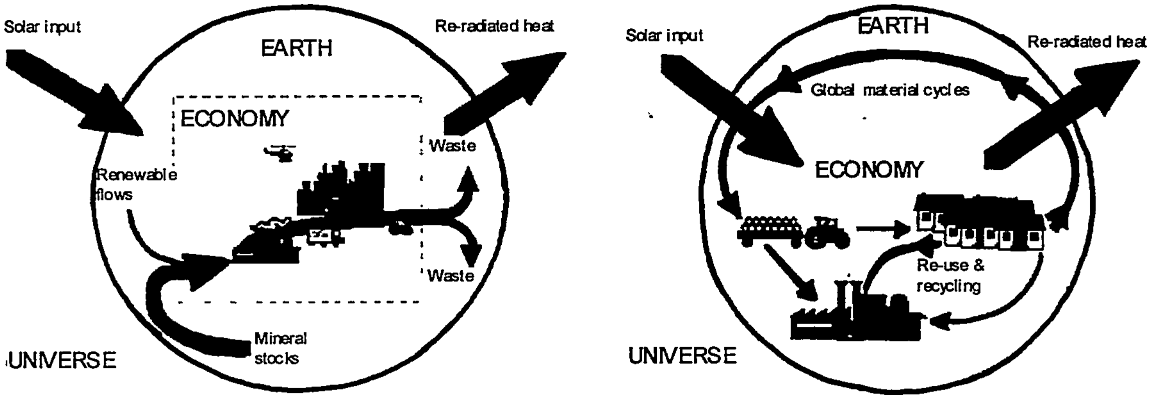
2.0 Industrial Ecology and the Precautionary Principle

In order to reduce the net impact of buildings on the biosphere, it is important to first understand how the associated materials and energy flow from the biosphere, circulate throughout the economy and eventually return back to the biosphere. To map these flows, various tools are available that operate on different levels of analysis. Using the concept of industrial ecology, applying life cycle thinking and guided by the precautionary principle, this chapter will establish the requirements of a streamlined mapping procedure that can be applied to various elements of a building.

2.1 Industrial Ecology: from linear to circular flow of materials

Natural ecosystems for the most part operate in closed cycles with the wastes of one organism or system becoming the food for another. Conversely, the throughput of materials within the economy can be best described as a linear system whereby raw materials originate from the biosphere, are transformed into useful products with the help of additional materials and energy, used for their intended function, and finally return degraded to the biosphere (Figure 2.1a). The nature and quantity of these flows is such that the scale of these flows is larger than the biosphere can handle. In addition, the composition of many of these material flows is such that the material flows cannot partake in natural cycles and hence become pollutants.

Industrial ecology views industrial processes as similar to those of natural ecosystems. This is achieved by making material flows more circular within an economy. In creating a more cyclical flow of materials, the use of the biosphere as source and sink for matter is decreased since product wastes are eventually recycled or reused as an input into another product or process, thus reducing the stress placed on the biosphere as a sink for wastes. Theoretically this also reduces the need for virgin materials, since products themselves are manufactured from the pool of wastes instead of from virgin sources (Figure 2.1b). The two types of flows are illustrated in Figure 2.1.



a) Linear Flow

b) Circular Flow

Figure 2-1 Linear and circular interactions of materials within the biosphere (Jackson, 1996, p. 19; 83)

In practice, however, many wastes occur as a result of leakage within the industrial system. This leakage dissipates to the biosphere either inherently or for practicality reasons (Ayres, 1994). For example, the use of zinc as a sacrificial coating on steel (galvanizing) is inherently dissipative since zinc coatings serve their function by oxidizing, thus rendering material recovery difficult. The use of paints and adhesives are dissipative for practical reasons. Although they can theoretically be recycled into new products, it is difficult with today's formulations to separate paints and adhesives from painted or bonded material. Whenever a waste is dissipative, the losses within the network of material flows must eventually be made up from virgin sources (Ayres, 1994), and the corresponding environmental impact must be dealt with.

Tim Jackson suggests that it is necessary to "improve the material efficiency of providing different services," such that the amount of matter flowing to the biosphere is greatly reduced (1996, p. 56). However, it is not only the amount of matter that flows into the biosphere that must be reduced. Since the composition of many anthropogenic material flows is not natural to ecosystems, the substitution of toxic substances with environmentally preferable materials must also be practiced (Jackson, 1996).

There is strong evidence to suggest that the recent rise in cancers and mutagenic diseases is ultimately a result of the increased load and symbiotic effects of anthropogenic discharges to the environment (Steingraber, 1998). It is clear that engineers need to look beyond conventional approaches if they are to take their most important ethical obligation seriously. Indeed, professional engineering bodies indicate that their members "shall regard the practitioner's duty to the public welfare as paramount" (Ontario Regulation 538/84, Sect. 91). A sustainability ethic is therefore needed for the practice of engineering that links engineering activity to human health and the well-being of the environment.

In addition to a net reduction in anthropogenic loads upon the biosphere and the substitution of toxic substances with environmentally preferable materials and processes, a change in the network of energy flows is also required. This is needed since the use of energy creates waste material flows through production and use of fuel sources, in addition to the construction and maintenance of the supporting energy infrastructure.

In essence, industrial ecology recognises that the capability of the earth to assimilate anthropogenic wastes is not infinite (Ayres 1993). By replacing the linear throughput of materials with a circular system, industrial ecology strives to reduce the impact of industrial processes on the biosphere.

In order to apply the concepts of industrial ecology to building materials, it is important to know when and where materials flow across the biosphere/society boundary and how energy is used to drive these processes.

2.2 Life Cycle Thinking

Life cycle thinking attempts to account for the flow of materials and energy, and their resulting burden on the environment, throughout a product or system's life. This life cycle is typically defined as the series of events from raw material extraction through product retirement, or cradle to grave. Industrial ecology promotes the notion of shifting towards a cradle-to-cradle concept which attempts to "close the loop" on anthropogenic emissions through reuse and recycling of material flows.

A life cycle approach recognises that each product and process is interconnected with the biosphere via flows of matter and energy at many stages in its life, from conception, design, raw material extraction, production, product use and end of product use. Each life cycle stage has inputs and outputs corresponding to raw material and energy requirements, emissions (wastes) and products/materials passed to the next life cycle stage. By identifying the respective location and nature of these connections, it is possible to guide the design process to one that will result in fewer impacts on natural systems.

The importance of a life cycle approach is to show the relationship between the various phases of a product or system and the environment. By investigating the flow of materials and energy throughout a product's life cycle, the effect of "problem shifting" can be identified. Problem shifting or end-of-pipe solutions often involve treating the symptom of environmental burden, while not addressing the root problem. For example reducing industrial air emissions by way of scrubbers shifts the problem from one of airborne emissions to that of land or water born. The above examples illustrate how a problem can be shifted from one location to another, from one stage to another, or as the next example illustrates, a perceived solution can result in a shift from one form of problem to another.

Historically, the production of soda or lye involved large emissions of hydrogen chloride gas that created corrosive local conditions as the gas reacted with moisture in the air. To alleviate the problem, manufacturers installed end of pipe devices to convert the gas into a more manageable form, hydrochloric acid that could then be disposed of in a receiving body of water. This worked for a time until the local aquatic environment suffered and regulations were again put in place to prevent the liquid release of hydrochloric acid. The manufacturers then found a market for chlorine gas, and recaptured most of their process effluent for sale to produce newly developed chlorine compounds. These compounds are well known for their environmental and human health impacts: CFCs, PVC, and the class of organo-chlorines. The problem of hydrogen chloride gas then had the consequences of ozone depletion, cancer and hormonal disruption, not only from the chlorine in the new products, but other compounds that made them possible (vinyl, plasticizers, etc)(Faber, Mansetten, & Proops, 1996).

Another example of problem shifting is related to indoor air quality. The response to indoor air quality problems is typically met with the substitution of a different, manufactured product, one that may potentially be more harmful overall, albeit through a less causal effect. For example the formaldehyde glues used in particle board (that emit formaldehyde during use phase) may be substituted with methylene diphenyl diisocyanate (MDI) glues that do not create harmful emissions while in service. However, these same glues are extremely toxic before they are cured, during the manufacturing stage posing a threat to workers (Wilson & Malin, November, 1999). Accidental exposure to toxic compounds from MDI glues can occur even in newer production facilities (Jimerson[1], personal communication, October 2000). Thus the indoor air quality problem is shifted from end users to plant workers. In order to overcome this transferring of pollutants from one area to another, the interactions between material and energy need to be investigated.

2.3 Material And Energy Flows

This section will show how the flows of materials and energy relate to buildings and their materials. The nature and relative quantity of these flows will be discussed to highlight relevant concerns.

2.3.1 Energy Flows

Much of the discussion in current research on the environmental impact of buildings, has focussed on the energy flows related to buildings, materials, and their resulting ecological burden. The ecological burdens associated with energy are largely a result of the emis-

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[1] Production Manager, The Collins Companies.

sions generated from the combustion of fossil fuels for the production of building materials and the operation of a building. The resulting impacts on the biosphere have both local effects (e.g. acidification from SO_x, smog from VOCs and NO_x) and global impacts (global warming from CO_2). Since energy use correlates to the above mentioned impacts, energy–based indicators are typically used to assess the environmental burdens associated with buildings. However, as will be shown, these impacts are only part of the picture.

The energy flows for a building can be broken down into four primary categories:

- initial or *embodied energy* used for the production and installation of the material (construction of the building which includes raw material extraction, transportation, manufacturing, installation, including site work, etc.)
- *recurring embodied energy* which is the energy used for the production and installation of replacement materials (finishes, etc.)
- *operating energy:* energy that is used for the operation of the building; to provide lighting, heating cooling, hot water and to power devices and other services,
- energy used at the end of the building life cycle (includes demolition, disposal, etc.) (Cole 1996, p. 307).

In addition, energy flows for a facility should also include the indirect energy contributions that result from the transportation of products and occupants, site operations and the energy required to support these activities throughout their life cycle stages. This includes the energy used to produce the machinery to produce the materials, the energy used to produce the supporting transportation infrastructure such as asphalt and concrete plants and the associated construction equipment. However, studies of this gross energy requirement (GER) indicate that as the boundary of analysis for energy extends away from the system under study, the indirect contributions of energy are on the order of three to ten times less than the preceding level (Vanderburg, personal communication, September 2000). Thus, the energy requirements to make the processing equipment and the supporting transportation infrastructure can be assumed to be from 1 to 10% of the total GER of the product, in this case building materials. Thus, some methodologies ignore the indirect energy contributions altogether (Boustead, 1999a).

The above energy flows act upon different phases throughout the life cycle of a building (material production, construction, use, end-of-life) as well as on different aspects of the facility itself (building structure, skin and services and facility operations). Figure 2-2 represents the energy flows into a typical facility.

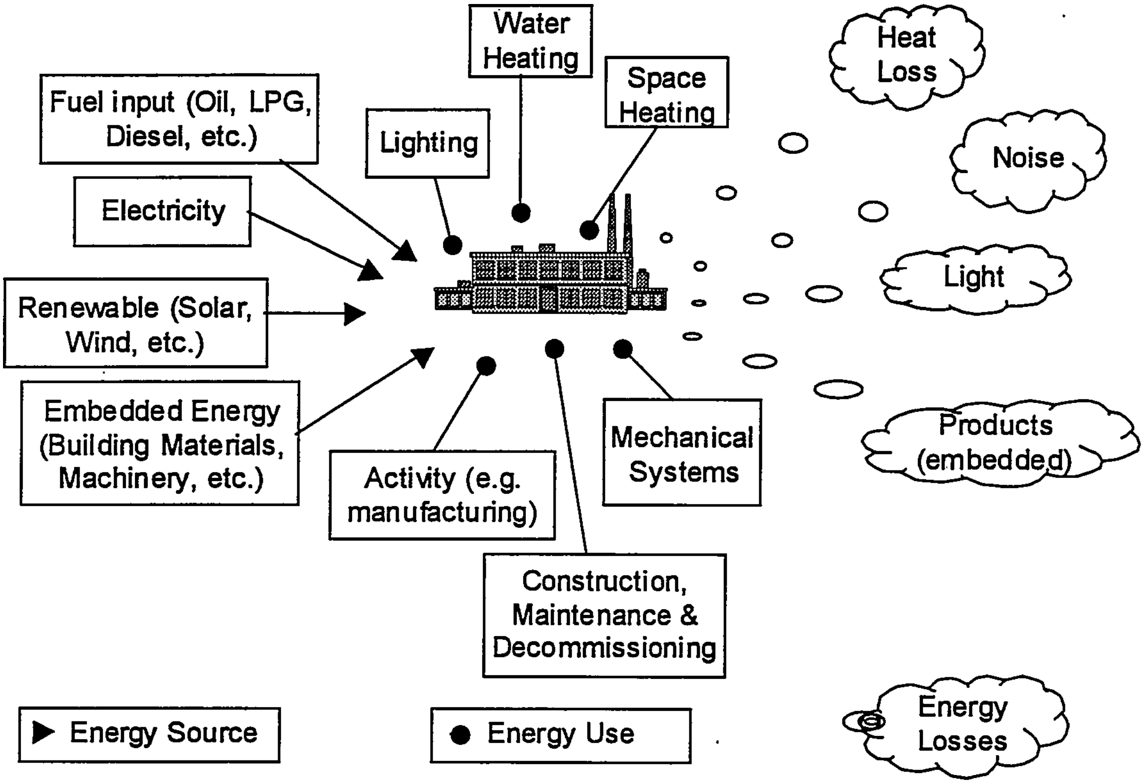

Figure 2-2 Typical energy flows for a building

Cole and Kernan (1996) examined the distribution of energy flows for three alternative designs of a three-storey office building. The designs had either wood, steel or concrete as the dominant structural material. Including finish materials and services (which were common for the three buildings), the following distribution of energy was found for a 50-year building life:

Table 2-1 Life Cycle Energy Use - Current

	Steel GJ/m^2 (50yrs)	%	Wood GJ/m^2 (50yrs)	%	Concrete GJ/m^2 (50yrs)	%
Initial embodied energy	4.11	4	4.66	5	4.63	5
replacement and repair	6.33	7	6.63	7	6.44	7
operating energy (50 years)	81.8	89	81.8	88	81.8	88
Total	92.24	100	93.09	100	92.87	101

(Cole and Kernan, 1996)

This assumed an operating energy of 1.64 GJ/m^2, which can feasibly be reduced by 50% using conventionally available techniques (Cole, 1996). Assuming a reduction of 75%, which should be achievable in the near future (Weizsäcker, Lovins, & Lovins, 1997), the distribution would be as follows:

Table 2-2 Life Cycle Enegry Use -Future

	Steel GJ/m^2 (50yrs)	%	Wood GJ/m^2 (50yrs)	%	Con-crete GJ/m^2 (50yrs)	%
Initial embodied energy	4.11	13	4.66	15	4.63	15
Replacement and repair	6.33	20	6.63	21	6.44	20
Operating energy (50 years)	20.45	66	20.45	64	20.45	65
Total	30.89	100	31.74	100	31.52	100

(Cole and Kernan, 1996)

As the operating energy of a building decreases, the proportion of life cycle energy costs for initial and recurring embodied energy increases. Of course, the absolute energy embodied in the materials remains the same. Since the energy used during the operation stage greatly exceeds the energy used in the other life cycle stages, the greatest potential for reducing the environmental burdens due to energy is to reduce the operating energy requirements. Looking more closely at the initial embodied energy of the building, Cole and Kernan found that the structural components of the initial embodied energy comprise only 16%, 25% and 21% of the initial embodied energy of the wood, steel and concrete buildings respectively (1996). Thus structural materials themselves seem to contribute little to the overall energy budget of a building. In fact, the renewal and replacement of finish material and envelope components contribute more than the initial embodied energy, over a 50-year building life (Environmental Research Group, 1994).

The upgrading of services, partitions and interior finishes is due to physical obsolescence of services, functional obsolescence of spaces and changing fashions (Brand, 1994). This may occur as frequently as five years, which is long before certain materials degrade. Thus, the simply specifying durable materials for components that will be replaced (i.e. finish, services, envelope) does not guarantee longevity, unless it can be guaranteed that longevity is solely based upon physical degradation.

Based upon this, it is not surprising that many so-called "green building" efforts strive at improving the energy efficiency as opposed to reducing the embodied energy of materials.

The energy distribution for the operation of a commercial building in Canada is as follows:

Space Heating:	53%
Lighting:	14%
Motive Power: (for pumping, ventilation, etc.)	12%
Water Heating, Space Cooling and Electric Plug Load:	21%

(OEE, 1998, p. 29)

Of these end uses, space heating and lighting are directly influenced by the design of the building through building layout, assembly design and material choices. Higher levels of thermal insulation and airtight building assemblies can reduce the operating energy of a building. Thus, while the embodied energy of the materials themselves do not contribute much to the overall life cycle energy use in a building, they indirectly affect the operating energy requirements. Blanchard and Reppe found that a minor increase in the embodied energy attributed to energy efficient building design can greatly reduce the operating energy (1998).

Strategies such as passive solar design, efficient heating systems and the use of daylighting are other strategies that can be used to reduce operating energy. The impacts of operating energy with respect to the analysis in this thesis will be discussed in Chapter 4.

2.3.1.1 End of life energy implications

Energy consumption for demolition varies widely depending upon the ultimate fate of the building material. The demolition energy for reuse is similar to the energy required for demolition if materials are separated for recycling in the case of wood and concrete. For steel however, the demolition of the structure for reuse of structural members is nearly twice the energy required if the same material were to be sent for recycling. (M. Gordon Engineering, 1996). The relative amount of energy required for demolition for recycling can be approximated as 10% of the initial embodied energy for steel and concrete structures, and 20% of the initial embodied energy of wood construction. However, these figures vary widely depending on actual fuel consumption for demolition equipment due to age of equipment and variable idle/use times. In addition weather conditions impact the energy required for demolition (M. Gordon Engineering, 1996). These figures refine previous estimates that suggested the energy for demolition is as low as 1% of the total initial embodied energy (Environmental Research Group, 1994). Putting these figures into perspective, the highest figure for demolition energy, 20%, in the case where initial embodied energy is highest (15% of total life cycle energy use), results in 3% of total life cycle energy use for demolition. Thus, it can be assumed that the energy used for demolition is only a small portion of the total energy budget. However, this does not include the energy used for recycling and reuse activities.

If a building material is reused, the embodied energy should be spread out over not only the initial use, but subsequent uses as well. The implications of multiple product life cycles are discussed in Section 4.4.1.1.

2.3.1.2 Energy Concerns in a Broader Perspective

From the above discussion, the operation phase of a building uses the largest amount of energy, though this can be substantially reduced through energy efficiency measures directly related to material selection.

Thus, the embodied energy of a given building material should be analysed over the life cycle of the building, not just on the basis of the material itself. Over the life cycle of a building the embodied energy attributed to materials may be reduced in various ways such as increasing the durability of materials or decreasing the embodied energy of the materials.

In the first case, materials and assemblies are selected according to durability. Assuming all other performance factors are met, one might choose slate over asphalt shingles, ceramic tile over vinyl, or masonry over synthetic stucco. The goal in such material substitutions is to reduce or eliminate the replacement interval, thus achieving a greater utility over a given time period.

Alternatively, materials may be selected to have a lower embodied energy, though perhaps sacrificing long-term durability. Low embodied energy materials are frequently local materials that are not overly processed from their natural state. Examples might include local timber, clay brick, earth, and straw, with construction by trades in the vicinity. Even if equivalent lower embodied energy materials are less durable, the net energy budget for the building materials may still be equivalent over a building's life span. This would occur because the resulting gains in initial embodied energy may be offset by increased energy expended during replacement. Mathematically, it would appear that an ideal material would incorporate high durability and low-embodied energy.

However, viewing buildings from such a narrow perspective implies that the longevity of a building is inherently linked to the durability of its materials. Brand

> (1994) explains that the longevity of a building depends not only on the durability and maintenance of its building systems but also the degree to which buildings are adaptable, both functionally and physically. It is not uncommon today to see a 20- to 30-year old building torn down, not because it is physically worn out but because some component or aspect of its original design hinders its continued use. Even more troublesome for sustainability is consumer society attitudes in which the finishes in homes, shops, and offices become expendable fashion items replaced before they have physically failed.
>
> This leads to another question– namely, whether buildings should be made to endure generations or whether they should be razed to the ground every 20 years. With traditional designs and materials, durability was not only a requirement but also an asset. However, today, the use of durable synthetic materials on buildings that can barely survive 30 years becomes a liability at replacement time because they do not readily biodegrade into harmless substances (Abush, 2000).

From the preceding discussion, the embodied energy of materials in a building are significantly less than the operating energy of a building over its entire life cycle. Nevertheless, it is important to consider the energy impacts of materials. These impacts can be reduced through energy efficiency strategies or by using renewable energy sources.

Energy efficiency strategies can be achieved either on an individual product/material level or on the whole building level:

- Product level: improve the energy efficiency of the material extraction through production process and reduce energy requirements for demolition and disposal.
- Building level: reduce the total quantity of energy intensive materials throughout a product's life cycle.

To reduce the impact from energy related activities, the source of energy can be chosen to be appropriate for its intended use (use fuel instead of electricity for heating), or select renewable energy sources.

2.3.2 Material Flows

Within the available literature on the sustainability of building materials, there is a larger degree of uncertainty as to the nature and amount of material outflows than there is with energy flows.

Energy flows, and material inputs are typically accounted for by corporations and utility companies when they directly affect profitability. In addition, most flows reported as inputs are easily tracked since they are primary constituents of a purchased or extracted raw material. However, material outflows are less documented for the following reasons:

- uncertainty as to the composition of inputs/outputs,
- lack of desire/need to record/report material discharges, unless required by legislation such as National pollutant Release Inventory (NPRI) or as in the United States, Chemical Right to Know (CRTK) acts,
- typically only material flows that are of particular concern (at a given time) are reported: i.e. Global Warming Gases, Ozone depleting chemicals, smog forming gases, land and water acidifying releases, etc.

The uncertainty of the composition of the inputs and outputs of a given process or system are chiefly a result of the variability of the input material. Synthetic, as well as natural materials, may contain trace amounts of substances that cause environmental burdens. These generally result from natural deposits found in ores, or residues from reaction processes. Examples of this include trace amounts of cadmium present in all zinc products, as cadmium is naturally present in zinc ores (Graedel & Allenby, 1996). During a particular process, it is possible that these harmful substances may be concentrated. Alternatively, these may also be concentrated by natural means such as bioaccumulation. While this may be less of a burden in relation to reported values of discharges, this uncertainty should be reported. In some cases, the variability of the input material, such as clay for brick making, can significantly alter the composition of emissions (Cole & Rousseau, 1992). Thus two plants may have different emissions, despite using identical equipment.

In addition, there remains also a degree of uncertainty as to the environmental impact of a particular discharged material. For instance, where the impact is unknown, or where no direct cause and effect relationships are known, the material flow may not be accounted for. For instance, consider a particular waste that contains less than 1% by weight or volume of a particular chemical. In cases where guidelines exist for effluents, these would likely be reported however small the quantity, since a small amount of a toxic substance such as gasoline, arsenic,, or heavy metals may have a devastating effect on the local environment. However, the impact of most anthropogenic substances is not known. Of the 77% of substances known to be of potential toxic concern, there is no toxicological data (U.S. National Academy of Science, cited in Vanderburg, 2000). There always exists the possibility that an unknown impact may occur due to an unforeseen interaction with other trace chemicals, or on its own under unanticipated conditions. The previously unforeseen impacts of CFCs and DDT should remind one of unanticipated consequences of chemicals. The current research on the release of estrogen mimicking chemicals or endocrine disrupters further illustrates this point (Steingraber, 1998).

Material flows may also be less well studied because of the potential liability and economic loss that corporations may face, should toxic or burdensome material flows be discovered. For instance, until an in-depth study is performed on the discharges (or effects) of wastes, a manufacturer could claim that they have little knowledge of the environmental burden of their product. From a liability perspective, providing due diligence has been followed; the lack of material flow studies limits a manufacturer's liability. More likely however, is that there is little incentive for manufacturers to perform costly assessments of their processes, unless prompted by consumer demand, legislation or a deep concern for sustainability.

Fortunately, major classes of pollutants have been identified and their gross discharge, accidental or intentional, must be reported under chemical right-to-know legislation, Toxic Release Inventories (TRI) from the United States Environmental Protection Agency (USEPA) and the National Pollutant Release Index (NPRI) from Environment Canada. However, the reporting guidelines may allow discharges from smaller firms to go unreported. Collectively, the sum of smaller firms may overwhelm the contribution from larger ones. In addition many industries, such as those involved certain mining activities are exempt from these requirements (AQUAMIN, 1996).

Only materials of a generally accepted concern are identified and reported. These materials are those with a *known* cause-effect relationship on the environment or human health. Since the effects of combined, low doses of pollutants can never fully be scientifically concluded as cause-effect, low, combined exposure to chemical pollutants can not be regulated by specific "safe-discharge" levels.

The above-mentioned issues with respect to material flows of building materials occur during all phases of a building's life cycle. There appears to be no clearly identifiable stage where burdens are the greatest, as is the case with energy. This is largely due to the uncertainty and inadequate knowledge of both the time lag and the unknown synergistic effects of building materials. For example, the effect of a building material may occur during the extraction phase and may be exhibited primarily as ecological disruption. During the manufacturing and construction stages, the effects of materials may show up as threats to worker health. During operation, the greatest threat may be poor indoor air quality on the occupants. During disposal, the effects of materials depends upon their final resting place, but are closely tied to ecological impacts. Since materials do not stress the same environment throughout their life cycle, the number of potential exposure routes is numerous. Thus a common indicator, as used in energy is difficult to apply to materials. Some strategies however, such as Eco-Indicator '99, attempt a complex normalization to equate health, ecosystem and resource degradation (Goedkoop & Spriensma, 2000). Such weightings are beyond the scope of this work.

2.4 Material and Energy Concerns

It is chiefly the treatment of material concerns that the proposed methodology attempts to address. While the impacts from energy are significant, the largest burden due to energy occurs during the operation stage of a building's life cycle. Since energy cost savings are directly linked to operating energy consumption, this energy use is already being addressed through energy conservation measures. For instance, energy efficiency is readily realisable to such an extent that through proper design and construction, buildings may be designed to eliminate heating devices entirely (Weizsäcker, et al., 1997). This trend of energy efficiency will likely continue with rising fuel prices.

As previously mentioned, the energy flows only account for one dimension of sustainability. If energy efficiency improvements do not consider the material flows other than from energy use (and their associated burden), there is a great risk that in saving energy, ecological and human health is compromised. An example of when this scenario may occur is where materials for insulation contain products that affect indoor air quality such as glass fibre insulation, or contain ozone-depleting substances such as extruded polystyrene. In these cases, a gain in energy efficiency may be offset by an increased burden elsewhere.

Another example involves the use of industrial wastes to make building materials. One such example is the use of manufactured wood products such as I-joists or oriented strand board (OSB) that use waste material from sawmills. In addition to the potential health concerns due to the binders like urea-formaldehyde and MDI used in these products (Wilson & Malin, November, 1999), these materials may pose an environmental burden at the end of their life cycle, despite already having become a diverted waste from another industry. The caution here is that as much as one can make material cycles circular, their ultimate fate may still pose an environmental or health threat. Thus, as much as novel uses for waste materials can forestall their return to the biosphere, the production of new materials from wastes does not justify their substitution for natural capital. For example, the production of composite wood lumber that embodies the waste plastics of industrial and consumer activity can be viewed as a short term solution to unsustainable forestry practices, but its use alone solves neither the problem of the production of wastes, nor the inability to sustainably harvest and use wood. Furthermore, it is a replacement of a known natural product with one that has an uncertain future. Thus, the true environmental burden of both the donor (waste) material and the resulting product made from this waste, should be reflected in a life cycle approach.

In order to overcome the potential environmental and health burdens associated with materials, there should be a reduction in the overall use of toxic substances, and a net reduction in the quantity of flows associated with material production. Furthermore, the nature of the discharges should be characterised to reflect any potential reuse and reintegration into the economy. This reflects a shift from linear to circular throughput of materials.

2.5 Precautionary Principle

Since the interactions between industrial activities and the biosphere are not only complex and in constant flux, they may never be fully understood to the point where one can say with certainty that a given process is innocent. The precautionary principle was developed as a means of addressing the limitation of environmental policies that are based upon the assimilative capacity of the environment in question (Dethlefson, Jackson, & Taylor, 1993).

Environmental management based on the premise that there is a threshold of acceptable pollution without causing unacceptable harm may be useful as a conceptual tool for understanding that ecosystems do have a certain ability to tolerate stresses. This can be evidenced by the natural tendency of ecosystems to not exhibit completely closed material cycles, especially in younger ecosystems (Odum, cited in Jackson, 1996). This extends to the fact that no natural ecosystem actually exhibits zero emissions (Jackson, 1996).

However, the emissions from anthropogenic activities are clearly non-natural stressors and have often exceeded even upper limits of acceptable doses for human exposure. Chemical leaching at Love Canal, Niagara Falls, New York and mercury poisoning at Minamata Bay, Japan, are obvious, though extreme examples of the failure of approaches that assume nature has a certain tolerance for anthropogenic emissions. In the case of Love Canal, it was assumed that toxic substances could be contained, yet they continue to this day to leach into the groundwater and evaporate into the air. At Minamata Bay, a presumed safe form of mercury was dispersed into the sea and was transformed into a more harmful compound by methanogenic bacteria present in the water (Jackson, 1996). Conventional approaches rely on the development of monitoring and assessment technologies to assess compliance with set standards based upon causal relationships that may have little resemblance to actual interactions with nature.

The argument for the precautionary principle is that toxic substance should be reduced by as much as possible and that this should be the approached within the design stage to avoid end-of-pipe solutions (Dethlefson, et al., 1993). Some authors argue that this transition to very low toxic releases should be achieved by using not only the best available technology not entailing excessive cost (BATNEEC), but preferably, the best available technology (BAT) (O'Riordan & Cameron, 1994).

The precautionary principle attempts to address the problem that even though there may be extensive observations with respect to the innocence of a given substance on the environment, there always remains the possibility that a critical pathway may have been overlooked. It thus tries to resolve the error in simplistic cause-effect relationships between technology and the environment, since these simplified approaches fail to consider the complexity and flux of the technology-society-biosphere interactions. Operationally, this translates to a mentality of 'no regrets' (Dethlefson, et al., 1993) with respect to the direction of individual technologies or choices made within the context of the precautionary principle.

In the best case, the precautionary principle avoids environmental degradation. In the worst case scenario, where it is shown that no harm would have occurred, the technology is still less likely to interfere with the environment or society at a later date since development occurred based upon prevention. The methods for realising the precautionary principle essentially translate into a useful ignorance towards the complexity of the interactions of technology and the environment. Using the precautionary principle, the transition to very low toxic releases may be achieved (Dethlefson, et al., 1993).

2.6 Strategies for Sustainability

From a whole building perspective, energy flows alone do not capture the ecological impacts associated with non-energy related releases. An investigation of material flows indicates that the complex interactions of materials with affected ecosystems and impacts on human health are not well understood and that an element of precaution should be applied. Thus it is essential to characterise both energy and material aspects of building materials to include ecological and human health considerations..

From this chapter, the following key strategies for reducing the impact of the flows of matter and energy for buildings can be identified.

- Reduce the total amount of material flows that participate in linear cycles.
- Eliminate the use of toxic substances contained in or used in the production of building materials.
- Use energy efficient techniques on either a material level or whole-building level to achieve net reductions in energy use.
- Use appropriate and where possible, renewable energy sources.

In addition to the above-mentioned strategies, an ecological dimension will be added in Chapter 4 that captures the direct impacts associated with raw material extraction and material disposal.

The next chapter will outline the requirements for a methodology that can be used to apply these principles. The remainder of this thesis will explore the application for some typical (and one not so typical) wall assemblies.

3.0 Current Design and Assessment Tools

This section outlines some limitations of currently available design and assessment tools used to improve the sustainability of buildings. Sustainability principles are introduced in Section 3.3.

3.1 Life Cycle Analysis

To solve some of the problem addressed in Chapter 2 with respect to problem shifting and uncertainty in material and energy flows, various quantitative tools have been developed. The most notable of these is termed life cycle analysis (LCA). The life cycle approach introduced in Section 2.2 is at the heart of life cycle analysis, which quantitatively tracks the inputs and outputs of matter and energy throughout a product's life cycle from material extraction to its end-use.

As a design or product improvement tool for the construction industry, LCA approaches are often difficult to apply since quantitative valuation, essential to LCA, is often not known until designs are finalised. At a final design stage, improvements identified by LCA approaches can only improve the design in minor ways that fit the original building plan. For example with minor material substitution that does not severely affect the integrity of other building systems (e.g. finish materials). However, the greatest material savings occur from early design choices such as building footprint (size), orientation, and structural materials. It is quite difficult (and costly) to alter the original design, for example, of a load-bearing wall from masonry to steel, wood or strawbale once plans are finalised.

It is widely believed that with increased computerization, it will soon be possible to have a database with an inventory of every material used in a building such that environmental choices could finally be made with scientific precision. Various models are being developed and tailored to buildings including ATHENA™ (ATHENA™ Sustainable Materials Institute, 2000a) and OPTIMIZE (Canada Mortgage and housing Corporation [CMHC], 1991).

However, there are a few limitations to this approach:

- every scientific model is an abstraction of reality and thus makes an assumption about the nature of the system studied (by quantifying it),
- there always remains the possibility that an unforeseen impact or pathway exists,
- the "grave" portion of buildings is uncertain, and
- the potential risks of aggregation.

Life cycle analysis approaches require that the system under study be adequately reduced to a scientifically manageable size. The first limitation in LCA approaches involves defining the boundaries of analysis. For energy related flows, the boundaries are often set when the contribution is deemed small enough not to affect the overall outcome. However, these same boundaries may be inadequate for capturing the relevant material flows (Lave, Cobas-Flores, Hendrickson, & McMichael, 1995).

The second limitation is significant since LCA will always impose a limit on the boundary of analysis and the "limiting amount" of concentrations. That is, even though LCA models are adaptable, it is possible that an emission previously undetected, or perceived as benign may in fact turn out to seriously compromise human life (e.g. CFCs, endocrine disrupters). This problem affects all stages of an LCA since the discovery of a new ecological burden demands a reassessment of the boundaries of analysis, inventory, assessment and necessarily, improvement. There is no element of precaution inherent in the application of LCA. It is not sufficient on its own to address unforeseen risks, or account for the social and cultural effects of materials and products.

The *third limitation* of LCA stems from the traditionally long service lives of buildings. This makes it difficult to predict future attitudes towards buildings constructed today, future recycling/reuse infrastructure, and whether a product (the building) will be sent to its grave as a result of functional or physical obsolescence.[2] As such, a very important life cycle stage is not well addressed: end-use.

The omission of end-use has seriously skewed LCA research into concentrating on the flows of energy during a building's operation phase, with the assumption that landfill space is abundant and recycling infrastructure will become available with time and technology. It is also assumed that landfill transport and raw material extraction will continue at the same (if not less) energy consumption levels. However, as buildings are replaced, and materials are mined from further afar, the future of waste and resource extraction may dominate energy consumption throughout a building's life cycle.

The fourth limitation is the most transparent of all. LCA is an aggregated procedure, in that an LCA of a building would necessarily be the summation of LCAs of all of the in-

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[2] In many cases, buildings are replaced before the structure physically wears out. This functional obsolescence is often due to aesthetics and when the building cannot be adapted to new uses. Physical obsolescence occurs when services are difficult to update (i.e. when they are cast into concrete), and when the building physically decays from lack of maintenance. Both of these are preventable but not always through material or assembly selection (Brand, 1994).

dividual materials, accounting for the material and energy flows from the epoxy on reinforcing rod to the chlorine compounds in the roofing membrane. Aggregation is necessary to some degree to manage large quantities of data. However, the underlying assumptions in the data accumulation are hidden from the user by way of quantification and summation of impacts. Thus instead of presenting a full view of environmental impacts, only summary information is available to the end user. The seduction of computing may lead to an aggregation and trust that any result obtained is valuable and valid. Computers are inestimably efficient and useful at storing and retrieving information. However, computers cannot interpret, create, nor realise the potential impacts on humanity and culture, except as can be defined through quantitative analysis and logic. Thus, a computer software tool will never know the balance of protecting human health versus ecological health versus the economy, except as defined by logic.

The tool used for this research attempts to overcome some of the inherent difficulties in the application of LCA for the design of sustainable building systems, namely:

- system boundaries,
- uncertainty in data collection,
- time, costs (linked to complexity),
- poor link to environmental impact/overall sustainability,
- type and nature of data collection, and
- base reserves available.

The issues with respect to system boundaries essentially hinder the useful application of LCA as an impact tool since the boundary is often drawn when contributions are deemed small and the resulting impacts assumed negligible. This may be acceptable for energy but this fails to account for the symbiotic effects of materials within our environment. These symbiotic, persistent and cumulative effects pass typical boundary analysis.

In addition, the current convention of LCA is ill–suited for design purposes. The first stage of inventory analysis is critical for an LCA, yet is burdened by high costs, time and uncertainties. Whole building assessment tools such as GBTool and ATHENA™ overcome some of these limitations.

3.2 Other Approaches

GBTool, developed as part of the international Green Building Challenge (GBC) in 1998 is an extensive computer software tool that compares the environmental performance of existing buildings relative to a reference building. However, the section concerning material flows and impacts is brief. The ATHENA™ computer software program attempts to fill this gap using industry-specific LCA analysis (ATHENA™ Sustainable Materials Institute, 2000a). ATHENA™ computes the material and energy flows for common materials in the context of the whole building. Coupled together, the two tools are satisfactory for decision making for conventional designs that use conventional materials.

However, these tools for assessment provide insufficient information to guide alternative designs, or those incorporating unstudied materials. Since these tools also require that the design be fairly complete as far as layout and materials selection, they defeat the purpose of preventive design. The greatest potential for reduction of environmental burden occurs in the very initial stages of design, before building size, wall type, layout and materials are laid out and quantified (Allenby, 1999).

The United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) provides an alternative assessment and design framework that uses a credit system for guiding the design of whole buildings including site, operational energy and the effects of materials (USGBC, 2000).

However, the material assessment component in LEED, GBTool and ATHENA™ do not directly capture the degree to which a building design meets the principles of sustainability related to industrial ecology mentioned in Chapters 2 and 3. Instead, ATHENA™ and GBTool focus largely on quantifiable flows of matter and the impacts due to energy consumption, with GBTool adding site context issues. The non-quantifiable effects of ecosystem impacts are in some expert's opinion equally if not more important than the quantifiable measures as derived from a full life cycle analysis (Wayne B. Trusty & Associates, & Environmental Policy Research, 1994).

The sustainability matrix framework shown in the next chapter fills the gap of specifically identifying the impacts not directly tied to quantitative flows, but related to the industrial ecology and ecological dimensions. Cole and Rousseau suggest that the less quantifiable non-energy related impacts, including those to the air, are more easily characterised (Cole & Rousseau, 1992). Thus, the framework presented here is a characterization of the material and energy impacts as they relate to industrial ecology.

3.3 Sustainability Principles for Design

The extension of industrial ecology principles to materials and products is encompassed in the Design for Environment (DfE) approach. In Design for Environment, the goal is to reduce the ecological burden by rethinking each aspect of the design. This often entails a paradigm shift in thinking not only about the systems of a building, but the systems of nature and how they interact with the intended purpose and goal of buildings.

Four principles emerge from the study of industrial ecology and energy that serve to reduce the intensity per unit throughput of the economy:

- minimise the amount of toxic materials present and as a result of the manufacturing, use and end use of a material,
- ensure that all toxic, resource and energy intensive materials that are used are closed loop within the industrial system,
- minimise the amount of energy transformations required in producing, maintaining and recycling a product such that energy usage is minimised,
- use renewable energy and ensure that this practice is sustainable (Vanderburg, 2000).

A methodology for designing buildings sustainably that embraces these principles is lacking at present. In choosing such a framework it is suggested that the following requirements be included:

- ***straightforward to use:*** The concepts and principles for sustainable design should not be concentrated in the hands of few. On the other hand, the approach should not be simplified by omission.
- ***instructive:*** The required approach must help designers, owners and occupants develop a culture or ethic of sustainability through enlightenment.
- ***adaptive:*** When environmental concerns deepen and priorities change to newly discovered concerns, minor corrections in the methodology should be tolerated within the framework.
- ***objective:*** The approach needed should limit bias or prejudice. Objectivity does not necessarily need to be quantitative.
- ***include a life cycle thinking approach:*** The entire life cycle should be investigated.
- ***systems-based:*** The entire system of interactions should be considered and not simply the abstraction

The purpose of the remainder of this thesis is to develop and apply the above needs and principles into a working preliminary tool for assessing the sustainability of various building assemblies.

4.0 A Proposed Sustainability Matrix System Approach

The approach investigated in this thesis follows that of Graedel and Allenby (1996; 1998), adapted for the particulars of buildings and their component parts. This abridged life cycle assessment uses a matrix approach to accomplish the objective of proposing a preliminary design based on sustainability principles. In the formulation being proposed, matrix rows are used to differentiate the various stages in the life cycle of a process or product, while the matrix columns delineate the specific context being addressed. The intersection of a particular row and column, i.e. an element of the matrix, is linked to a set of checklists that characterise how the material or product adheres to the principles set out in Chapters 2 and 3. A numerical score is assigned to each element based upon the answers to the checklists. For this thesis, a scale of zero to four was chosen, with a score of four being the ultimate goal for sustainability and zero representing the worst possible scenario. An overall rating can then be determined as the summation of all the elements in the matrix. This allows for a straightforward comparison of similar products, providing that the same criteria are used in the determination of the matrix elements (Graedel, Allenby & Comrie, 1995).

Mass and energy inventory data, from various sources such as the DEAM database (Ecobalance Inc., 1999), product inventory reports (Venta, 1998; Demkin, 1996), building material inventory software (ATHENA™ Sustainable Materials Institute, 1999a) and personal communication with experts in material production processes were used to support the checklists.

4.1 Differentiation of levels

The way in which the materials, assemblies and the facility itself interact on different levels is a key point to how the sustainability matrix is developed. The performance of a building material, and its resultant environmental burdens, depends upon its application. For example, wood materials have different maintenance requirements whether they are used in the interior or exterior of the building. Exterior uses of wood require frequent application of preservative or protective coatings whereas this requirement may be waived for interior applications. Thus, the same material, for the same life cycle stage, will have different burdens depending upon the context of the material's application.

In addition, looking at an individual material in isolation does not incorporate issues of the scale of application. For example, the nature of the environmental impacts of many building materials in the context of an assembly may be relatively benign for a particular life cycle phase (e.g. disposal), per unit of assembly. This would be the case for concrete, brick, sand and gravel which are relatively inert. However, when these materials are used in large quantities throughout society, the impacts are multiplied (Allenby, 1999). For example, the judicial use of wood for the construction of a few houses may be sustainable without proper harvesting methods, but when it is multiplied by the total use throughout society it no longer becomes sustainable. Thus when looking at a material for an assembly, it is important that the broader context of the building.

To capture these contextual issues, it is useful to distinguish between the various levels of material and energy flows for a building and in turn the facility as shown in Figure 4-1.

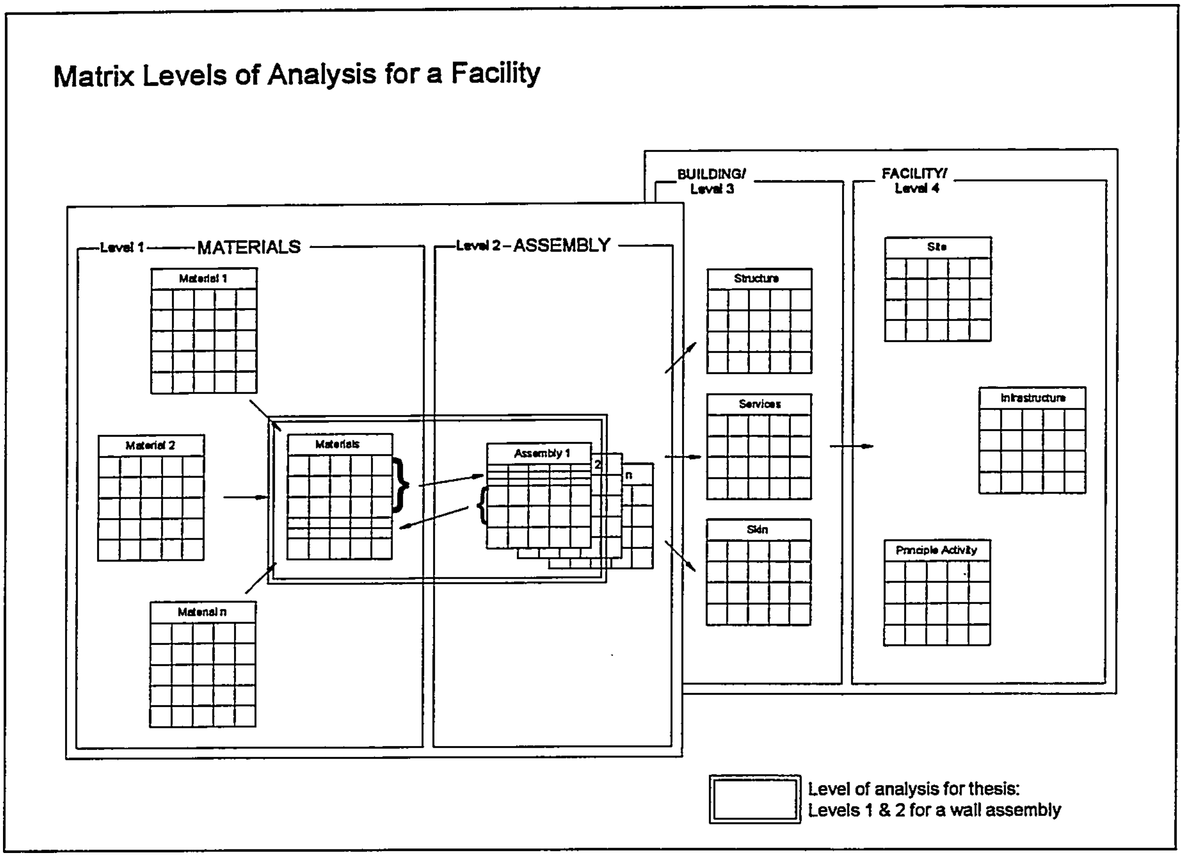
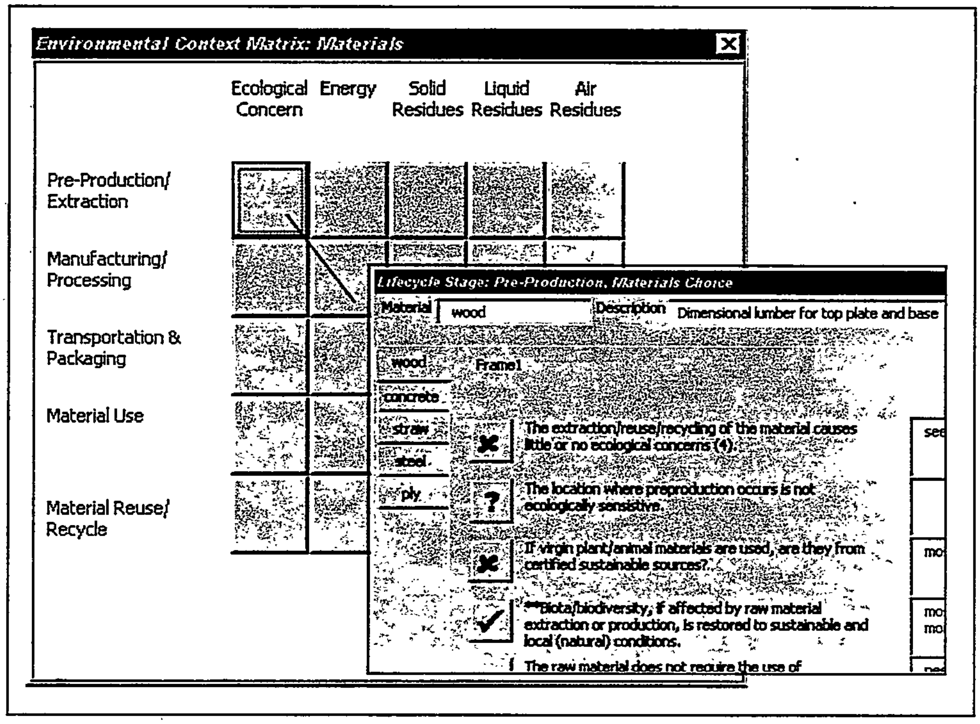


Figure 4-1 Matrix system for a facility identifying sub matrices.

In Figure 4-1, individual materials (Level 1) form part of a larger building assembly, for example a wall (Level 2). A wall is in turn combined with other assemblies such as the foundation and roof (also Level 2). Together they form the structural assemblies of Level 3. Also on Level 3 are the physical services (plumbing, electrical, HVAC) and envelope (skin & finishes). The matrices of Level 3 form the physical aspects of the building. The physical aspects are in turn part coupled with the matrices of infrastructure, site and activity (residence, commercial, etc.) to form a matrix for the entire facility. Thus, each level contains constituent lower level matrices and is itself part of a larger picture.

A sample Level 1 matrix is shown in Figure 4-2, which illustrates the various life cycle stages and burdens considered for a building material with a sample checklist. The figure shown is a screen capture from the visual basic program developed as part of this research. The full set of checklists used in the analysis can be found in Appendix E.



Material: wood

Description: Dimensional lumber for top plate and base

☒ The extraction/reuse/recycling of the material causes little or no ecological concerns (4).

? The location where preproduction occurs is not ecologically sensitive.

☒ If virgin plant/animal materials are used, are they from certified sustainable sources?

✓ **Biota/biodiversity, if affected by raw material extraction or production, is restored to sustainable and local (natural) conditions.

The raw material does not require the use of

Figure 4-2 Matrix for a building material, with checklist shown for Level 1.

The scope of this thesis is the materials (Level 1) and their intended function (Level 2) for wall systems. The interaction of these two levels will be discussed next.

4.2 Combined Matrix for Materials and Wall Systems

The interaction between Levels 1 and 2 can be captured by combining matrices from Level 1 and Level 2. The combined matrix showing the relevant life cycle stages for both materials and their use within the wall system (Levels 1 & 2) is illustrated in Figure 4-3.

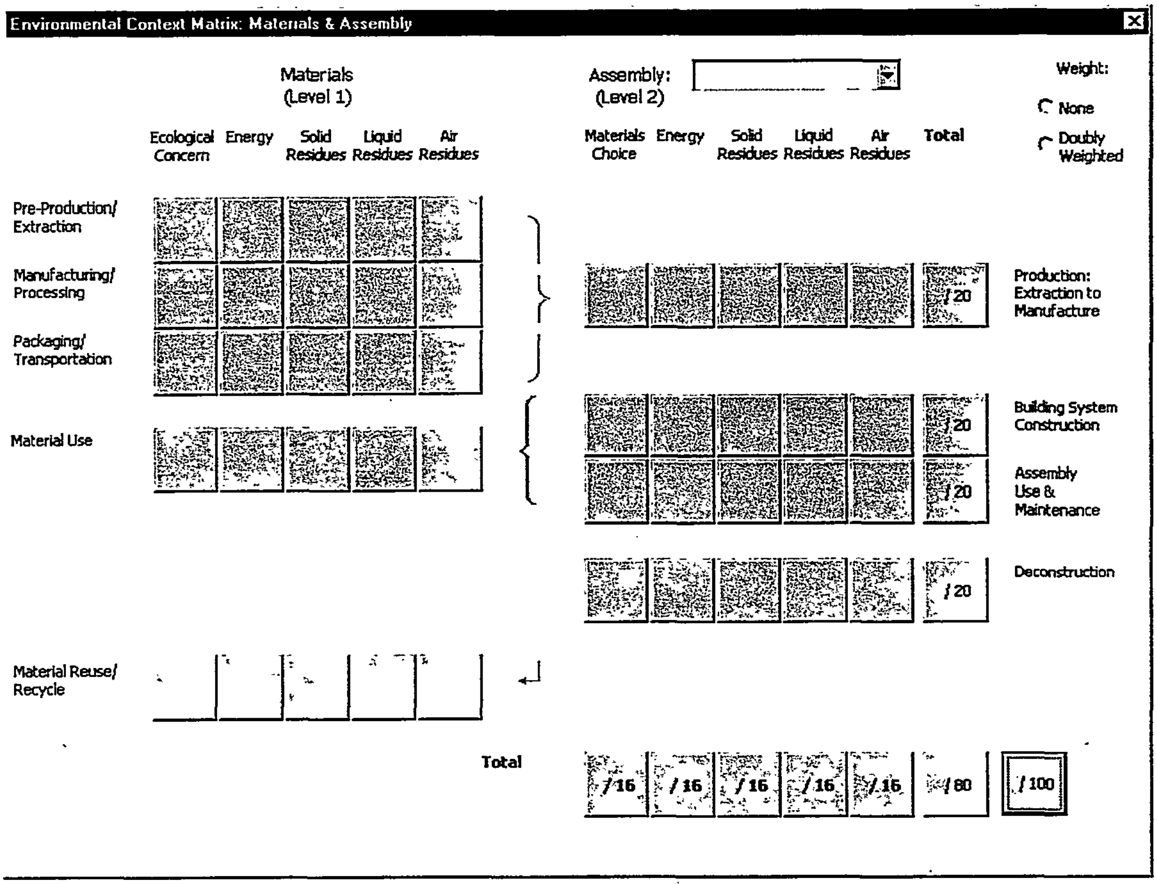


Figure 4-3 Combined Material and Assembly Matrix.

In the following sections, the issues relevant to each row and column in the matrix will be discussed.

4.3 Matrix Columns

This section provides a brief overview of the general impacts common to each life cycle stage for materials and assemblies used in building construction. The checklist comments found in Appendix F elaborate on the specific details associated with each material, while Appendix G provides the checklist results for the wall assemblies.

4.3.1 Ecological Concern (Materials)

This column identifies the stresses on the ecosystem (local and global) for a given life cycle stage. As such, the burdens identified in this column are issues that are not easily assessed by quantified discharges to the land, water or air environments, nor from energy usage. For example, the effects of timber extraction such as deforestation, erosion and consequently river siltation cannot adequately be addressed in the solid, liquid, gas nor energy columns. Rather, the impacts described here recognise the limitations of an ecosystem to assimilate wastes due to the activities that occur in a particular stage and acknowledge the role of ecosystems to act as sources and sinks for human activity.

The degradation of an ecosystem affects the cycles of matter in a two-fold way, by reducing the capability of an ecosystem to produce renewable materials and to act as a sink for degraded materials.

The ecological burden column also recognises the global interaction between ecosystems in the cycling of materials. For instance the effect of deforestation not only affects the local environment through loss of productive land and waters, but also interrupts the global cycling of carbon, namely sequestration, incurring global impacts such as climate change.

The ecological burdens column identifies and characterises the impacts of a particular phase on the general ability of an ecosystem to provide services and accept anthropogenic wastes. The burdens considered here are generally those that physically alter, diminish or destroy this function.

4.3.2 Materials Choice (Assembly)

For Level 2 matrices, the first context column of the matrix changes from ecological burdens to materials choice. This change reflects that the environmental burden associated with a building element is dependent upon the choice of materials and the context in which they are used. For example, while virgin steel production may have significant ecological impacts, these burdens may be reduced by directly reusing steel members, using recycled steel, and minimising its usage.

Since the material level matrix is a component of the building system matrix, the ecological burdens associated with the constituent materials are carried forward and weighted according to their relative contribution, as described in the previous section. This carrying forward of the burdens serves as a basis for evaluating the major ecological burdens associated with the actual use of the material in the context of the building system. For a preliminary analysis, as performed in this thesis, the materials choice may be evaluated first to determine whether the quantity of material used justifies completing the detailed checklists for the ecological burdens.

4.3.3 Energy Use

This column characterises the environmental burden associated with the energy use during a particular stage (row). The environmental burdens associated with energy use are primarily due to the emissions from the combustion of fossil fuel. They include global warming gases (CO_2, etc.), acid gases (SO_x) and smog forming gases (N_2O and VOCs).

Summary indices of global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and embodied energy (EE) were used as indices for the production of materials. Smog potential was not investigated, due to the difficulty of assessing the interactions between VOCs, N_2O and regional effects. The emissions for these gases, however, are presented in Appendix D.

As previously discussed, the largest burden associated with energy use for a building occurs during the operation or use stage. For comparison purposes, the example assemblies chosen were nearly identical in terms of thermal energy performance, and are considered energy conserving by current building standards.

4.3.4 Solid, Liquid and Gaseous Emissions

The solid, liquid and gaseous emissions columns characterise the discharge (intentional or unintentional) of matter to the environment. The characterization follows with the goal of reducing the net load upon the environment. As such, the checklists for these columns indicate the extent to which materials loops are closed.

Toxic substances are of particular environmental concern and their use should be avoided where suitable alternatives exist. Owing to the complex nature of the interactions between pollutants themselves and with pollutants and the biosphere, it is difficult to predict a quantified ecological impact. Many pollutants in isolation, and at the point of release over a short period of time, may appear to have relatively little ecological burden. Furthermore, there is much debate over the toxicity of individual pollutants. What is certain is that the ultimate fate of anthropogenic pollutants that have reacted with other pollutants over time and through the biosphere is difficult to predict except in retrospect once the damage has been done.

Ecosystems have a natural tendency to break down and cycle wastes that are non-anthropogenic in nature, and to a certain degree anthropogenic substances. However, for the most part, microorganisms have a limited ability, in their natural ecosystem state, to breakdown hazardous anthropogenic wastes. While some success has been made at the biodegradation of hazardous wastes, this typically relies on the use of technology and associated energy to effect this process. Since the natural breakdown of hazardous substances is slow, and is unlikely to occur until after the release of the pollutant and ecosystem degradation, the assimilative capacity of the ecosystem for toxic substances is assumed to be small, given the current scale of industrial activities.

Many toxic substances tend to bioaccumulate in the tissues of species high on the food web. Thus, pollutant discharge levels aimed at protecting local ecosystem health, may not account for the effects of bioaccumulation on humans.

The toxicity of an emission to the biosphere depends not only on the nature of the substance, but the amount as well. Thus, the emission of particulate matter is not so much a problem because of the material itself but rather the inability of the receiving body to readily assimilate the waste. For instance, some silt is essential in aquatic systems for microorganisms. However, the heavy siltation that results from eroded lands, results in the blocking of available light for these same microorganisms to function. Similarly, a certain degree of particulate matter can be tolerated by the human respiratory system. However, a large quantity or prolonged exposure of particulate matter in the air can aggravate the bronchial cavities.

In scoring the burden of solid liquid and gaseous emissions, the focus is on mapping the nature and relative amount of pollutants released, with the aim of identifying strategies to reduce this loading. However, the actual reduction of the relative risk or toxicity of these emissions is more likely to be judged on policy or economic recommendations.

Thus, the checklists for the solid, liquid and gas emissions target the elimination of toxic emissions, the minimisation of wastes and the recycling of the remaining wastes back into the industrial ecosystem.

The liquid and airborne emissions of the sample wall assemblies were inventoried using available process inventories of building materials and emissions derived from fuel consumption. Airborne emissions are captured in the global warming potential and acidification potential indices for the assembly production. The calculations for these indices can be found in Appendix B. Airborne emissions of concern during the operation are those that affect indoor air quality. The largest contributors to poor indoor air quality are emissions of VOCs. These occur primarily from building materials that use organic resins and binders such as manufactured wood products and paints. In the wall assemblies analyzed, sources of VOCs (plywood) were isolated from the interior environment and thus do not pose a significant concern. Paints were not explicitly considered since low– or no–VOC alternatives are available. Other airborne emissions that were characterised are particulate matter and the potential of a building material to support harmful mould growth.

Quantitative data for liquid emissions occurring from raw material extraction were difficult to find and are thus not well represented for all materials studied. The impact of liquid emissions for the selected building products is captured in the eutrophication potential index, with the calculation shown in Appendix A. The liquid emissions were also screened for large emissions of key toxic substances such as heavy metals, cyanide, phenols and other hydrocarbons.

Solid waste was not easily characterised due to limitations of the reported data. However, for the materials investigated, this is not likely to influence the matrix significantly since the material production wastes from the investigated materials are not as significant as those from the production of other potential materials used in a building such as for carpets, paints and other petrochemical derived products.

As mentioned before, quantitative data was only available for extraction through production life cycle stages. Emissions occurring during construction and demolition of buildings were not quantified, since these flows are dependent upon the design and construction operations specific to builders. The impacts from construction and demolition can range from insignificant to extensive for similar materials, but leading practices suggest that construction related waste can be economically reduced (Fishbein, 1998).

4.4 Matrix Rows / Life cycle Stages

The matrix rows represent the differentiation of a material or system with respect to the product's life cycle. Each row represents as much as possible, a distinct life cycle stage. Five life cycle stages were chosen for the materials matrix, while four stages were identified for the assembly portion of the matrix.

For the materials portion, the following stages were chosen, recognising that intermediary links to get from one stage to the next may be required (such as transportation):

1. Raw material extraction / pre-manufacture
2. Processing/manufacture
3. Packaging/transportation
4. Use/maintenance
5. End-use (disposal, recycle, reuse)

For Level 2 (assembly) the following life cycle stages could be identified:

1. Material production (steps 1 to 3 for materials)
2. Assembly or system construction
3. Assembly use & maintenance
4. Deconstruction
5. End-use (disposal, recycle, reuse)

The final stage for Level 2 overlaps with and is identical to the fifth life cycle stage for materials.

The first and last stages for both materials and assemblies represent the bulk material flows from and to the biosphere, or in the case of recycled/reused/refurbished products, bulk material flows to/from the economy. The intermediate stages represent material and energy flows required to drive the product cycle.

4.4.1 Pre-Production (Raw material extraction / mining from waste streams)

The characterization of the product with respect to the first stage involves all activities beginning from raw material extraction up to and including the delivery of the material input (ingot, log, oil, etc.) for the manufacturing/processing stage. For some building materials that involve multiple refining/processing prior to manufacturing of the final product, this stage may need to be broken into two stages: extraction (ore) and refining (ingot).

The primary burdens concerned with the extraction of raw materials are due to mining of raw materials and timber extraction. Detailed descriptions of these activities are well documented for example in the American Institute of Architects' Environmental Resource Guide Subscription (Demkin, 1996). Additional references can be found in the checklist results in Appendix F and G.

4.4.1.1 Use of recycled materials

In general, the use of recycled material poses less of an environmental burden than an identical material produced from virgin sources. However, recycled materials require transportation, processing and an input of energy to render them into useful products. As material flows are recycled, they degrade in the process, and often require the addition of virgin material if they are to have the same properties as materials derived entirely from virgin sources. Thus, a recycled material would certainly reduce the impacts derived from the first stage (raw material), but the downstream implications may increase as a result. Furthermore, the use of recycled content may shift the burden into different columns. Thus, a weighting factor for the use of recycled content material would need to reflect this multidimensional issue. On a broader scale, even if using recycled content material did not reduce the environmental burden of the building material itself, the end-use stage of the "donor" most certainly would. Similarly, if the recycled content building material is not recyclable or remanufacturable in itself, the overall burden may increase.

Since the overall goal is to reduce the *net* impact on the biosphere by closing materials loops and reducing unsustainable energy use throughout a product's life cycle, specific weighting factors will not be used for the express consideration of using waste material unless this source material is environmentally preferable in itself; i.e. produces fewer emissions than an equivalent virgin material.

The reduction of the environmental burden of a product due to recycled and reused materials may be accounted for as suggested by Anderson and Borg (1997). They illustrate (Figure 4-4) that the production of a material or component from recycled materials may entail higher energy usage than identical products manufactured from virgin sources. However, subsequent remanufacturing and recycling activities are less for products designed to be recycled than products not specifically designed for recycling. Presumably, the initial higher energy burden is attributable to the design of a particular material/product for use of recycled content material.

As the number of product cycles increases, the energy use per product cycle decreases as a result of the decreased use of energy intensive primary activities. It is unclear from the literature the degree to which transportation energy affects the analysis, though it can be reasonably expected that the transport of materials to be recycled would consume less energy than a corresponding amount of raw material, assuming equal distances for both. Thus, even from an energy perspective, recycled and reused materials at the worst consume no more energy than the production of material from virgin sources (ores). In any event the material throughput and ecological impact is reduced since the use of virgin material is avoided.

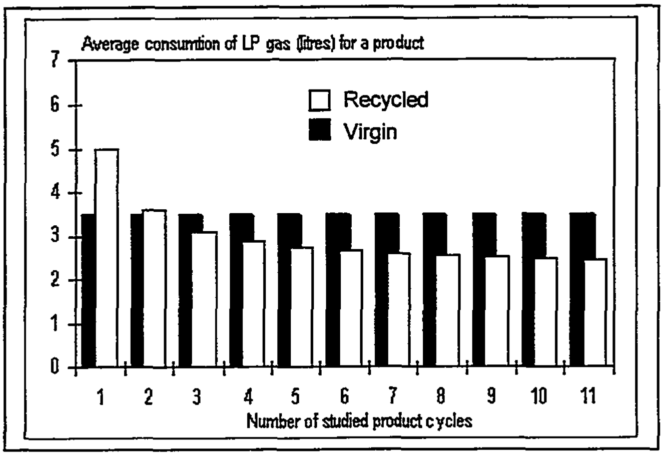


Figure 4-4: Energy consumption for multi-staged products. (Anderson and Borg, 1997)

Anderson and Borg propose a weighting method for assessing the environmental impact of using recycled materials (1997). However, they state that the original source material should be derived from similar products, that is, it assumes that no down-cycling exists. This is to avoid the simplifying assumption that the use of recycled material and the production of recyclable products is inherently environmentally preferable without regard to actual practices and net global impacts. However, the use of down-cycled materials for long-lived high design and high yield low-design products may in fact be preferable in building materials. As such, the checklists developed will explicitly consider the source of material, whether virgin, renewable, reused, or recycled but will not give further environmental "bonuses" for the potential at the end use, except as is currently practiced or reasonably anticipated.

4.4.2 Processing & Manufacturing

The next stage, manufacturing, processing, refining, defines the processes and activities that are required to produce a building material, as delivered to the construction site. Examples of this stage would include, rolling steel into structural shapes, sawing, planing and drying lumber, production of ready-mix concrete from raw materials and the production of blocks.

4.4.3 Product packaging, transportation, preparation

This life cycle stage investigates the degree to which packaging is used, and where possible, characterises the distance from manufacturer to building location and the form of transportation used. This life cycle stage highlights the impacts of imported versus local materials.

The packaging used for building materials is dependent upon the manufacturer, although some trends can be observed. Many packaging materials, such as cardboard are theoretically recyclable but are often disposed of instead. Some packaging materials, such as large tarpaulins are often reused on site as covering and protection for other materials.

Other types of packaging may consist of skids, metal banding and wood packing for structural materials and pails for liquid materials. The type of packaging depends upon the degree of protection required or anticipated from shipping. Materials that need to travel long distances and those that have aesthetic properties or tight tolerances typically have more packaging associated with their use.

Local materials reduce the need for packaging since the packaging can be selected based upon the site conditions and weather. In addition the use of local materials facilitates packaging take-back by the manufacturer (such as skids).

In addition to the packaging itself, the degree of preparation required to render the product usable should also be considered. For instance if a product is not packaged, or protected from the elements, it may require cleaning, or degreasing. The degree to which this is required should be considered, as a reduction in packaging requirements may increase the environmental impacts associated with preparation and installation.

4.4.4 Installation and construction

The installation and construction stage includes all aspects related to the assembly of the building system from the constituent materials. For the material matrix, residues specific to the material, independent of its application are identified. For the building system matrix, residues generated as a result of wastes, construction equipment and production processes are included.

4.4.5 Use, Operation and Maintenance

The environmental burdens associated with the use, operation and maintenance of buildings can be inherent to the material itself or a result of its particular application. Some burdens can clearly be identified as being directly related to the material itself. For example, the emission of a pollutant from a material is an inherent property of the material, whether it releases it to the indoor or outdoor environment. The impact however, depends upon the context of the application as described in Section 4.3.4 for Volatile Organic Compound (VOC) emitting materials.

The burdens associated with maintenance of building systems are limited in the analysis to cleaning, maintenance of protective coatings, and replacement or refurbishment of building systems due to wear. The replacement of building systems due to functional and physical obsolescence are not included on level one and two of the analysis, as they are more related to aesthetic and functional aspects on the level of facility design.

The cleaning of building systems such as walls, floors, and windows constitutes the largest proportion of day-to-day material throughput for a building. In addition to the often-toxic cleaning products that affect indoor air quality, large quantities of water may be used to maintain the cleanliness of building systems. The selection of materials in addition to the design of the building system in question affects the nature and frequency of cleaning operations.

Selecting materials that prevent the accumulation of dirt, or mask its presence can reduce cleaning operations. Smooth, non-porous surfaces resist the accumulation of dirt, and natural colours mask the accumulation. Non-porous surfaces also reduce the cleaning requirements. Protection of materials from sources of dirt, such as ledges, overhangs and selective wear surfaces (kick plates, etc) are also effective measures to reduce cleaning requirements.

The replacement or renewal of surface finishes depends largely upon the intended occupancy, whether it is commercial-industrial, commercial-retail, office, retail etc. For instance in a retail environment it is common for finish materials to be renewed or replaced for aesthetic reasons before wearing out. Similarly, entire assemblies such as interior partitions in offices may be replaced before their life expectancy as a result of functional obsolescence (Brand, 1994). These issues are not as relevant when the analysis focuses on the structural or building envelope, as these typically have longer life spans, regardless of the occupancy type. However, premature assembly or material replacement can be accounted for in the sustainability matrix qualitatively by favouring materials whose physical life span matches the functional/aesthetic life span. The matrix would need to be adequately weighted to reflect this "consumable" nature. A significantly reduced throughput of materials and energy would be required to compensate for this frequent replacement.

The environmental burdens associated with the maintenance of a building system analysed with the checklists assumes that maintenance is preventive in nature such that replacement/maintenance occurs *before* the material has failed and damage extends to other building materials or systems. The time difference between replacement before failure and at failure is assumed to be insignificant.

The use of energy for this phase is largely dependent upon the building system that is analysed. For a building envelope component such as a wall or roof, the thermal resistivity, reflectivity and heat capacity as well as air tightness of the assembly would affect the overall energy requirements, depending on temperature, insolation, diurnal temperature variation, and building design. The environmental burden associated with the energy use of the system is thus based upon the degree to which the building system minimises the use of energy, as required for the function of the assembly. Actual energy usage for the whole building cannot be calculated without knowing the layout, orientation and selection of materials and systems of the building. The systems analysed, and compared in this thesis were chosen to have similar thermal properties to reduce the operating energy impact variation between products.

4.4.6 Disassembly, reuse, recycling

Traditionally, building materials were reincorporated into new buildings when a building was torn down. Examples from Roman times include the reuse of slate from roofs and stone from walls. In more recent times, the reuse of timber was quite common. As buildings were torn down, heavy timbers were salvaged to be incorporated into new buildings.

The change from heavy timbers to light-gauge construction materials as well as the low-cost of new materials due to mechanized production, made the use of new material more attractive than reuse. However, the increased complexity (less materials but more different types) of newer wall systems makes separation of the constituent materials uneconomical. In addition, increased services such as electrical and plumbing in newer buildings often leave building materials unusable due to holes.

Given the ecological burden of virgin material production, coupled with a declining quality of certain materials such as timber, the reuse/recycling of materials is key to reducing the need for virgin materials and for lessening the burden on the biosphere as sink. In order to keep building materials in circulation within the economy for as long as possible, Manahan identifies important considerations in recycling, namely; simplicity, modularity, reparability, minimisation of kinds of materials, avoiding bonding between dissimilar materials, avoiding toxic materials, identification of toxic materials and avoiding plated metals (1999).

Theoretically, most materials are recyclable and many are reusable. However, reusing or recycling of individual materials is limited more by the ease of disassembly, the ability for separation into base materials and the transport to recycling and reuse centres, than by the material properties themselves. Thus, implicit in the life cycle stage: Deconstruction/End Use, is the consideration of material reuse and recyclability as it relates to the particular wall assembly.

4.4.6.1 Impacts from landfilling, lakefilling

The impacts that occur from landfilling of construction waste include land and groundwater contamination, loss of usable land, and disruption to the local environment during landfill operation (dumping) and monitoring costs.

Whether a material is recycled, reused, landfilled, lakefilled or incinerated, toxic materials pose a burden on the environment. That is, regardless of the fate of a building material, the toxic constituents will return to the environment, either through immediate disposal or disposal after reuse.

Since the practice of landfilling, lakefilling and incineration is not sustainable at current levels of production, the impacts and checklists investigated for this stage address the issues/barriers and practicality of recycling/reuse of building materials.

4.4.6.2 Impacts from recycling

The fact that a material is recyclable or even is recycled does not guarantee that this practice is either environmentally preferable or sustainable. For instance, while the recycling of aluminum is less energy intensive and less ecologically disruptive than producing the same from virgin ores, the same may not be true for other materials.

For instance, the steel industry has an extensive recycling infrastructure in place to deal with used, or scrap steel. It is estimated that most of the steel used in buildings is currently being diverted from landfills through steel recyclers (Kalin & Associates, & The Centre for Studies in Construction, 1993). While the recycling of steel is less energy intensive than producing the same product from virgin ores, the recycling process still consumes a significant amount of energy.

4.4.6.3 Impacts from reuse

The reuse of materials is often considered the most environmentally preferable option for material end-use. The impacts associated with reuse of materials involve the energy required to salvage building materials and the necessary preparation required to make the material serviceable again. For existing buildings not designed for disassembly, the energy required for deconstruction of steel and concrete structural elements is larger than that required for demolition for recycling or landfilling. This is largely due to the additional use of heavy machinery such as hoists, cranes and pneumatic tools, which are needed to perform an expedient deconstruction. If longer times were allowed for deconstruction, more time-consuming manual labour could be used, reducing the energy requirements for deconstruction of steel and concrete buildings. The energy requirements for manual labour are small compared to machinery energy requirements. Wood structural elements require less energy for deconstruction for reuse than for recycling since manual labour is predominantly used in deconstruction as opposed to heavy machinery (i.e. excavators) that is used for demolition for recycling. For wood, steel and concrete structural elements, the energy used for deconstruction is still significantly less than the initial embodied energy (<20%), suggesting that material reuse offers significant advantages over using virgin materials (M. Gordon Engineering, 1996).

4.4.6.4 Durability

For durability requirements, the sustainability matrix should address the functional durability of the building system vs. durability of material. In this case, the assessment should explicitly state an expected life-span and use equivalent replacement intervals and maintenance summed up over life-span. A benefit should be given to long-durability materials (past design life) only if used in an adaptable, reusable, reclaimable structure, or if in a building of historical significance that is likely to be preserved. This recognises that the durability of a building might be governed by the adaptability of the building, or it's historical or cultural significance, rather than the durability of the constituent materials.

Since the sustainability matrix is a preliminary design tool, rough estimates for the overall durability of a component or system can be used, bearing in mind that functional durability (use governed by adaptability), aesthetic issues, and future demographic distribution may overwhelm the considerations for physical durability. Thus, a building that is designed to be environmentally preferable based on a 100–year lifespan, hardly achieves this goal if future conditions govern that replacement (tear-down) will occur due to conditions other than material or building failure (i.e. aesthetics, change in function). However, should this route be chosen, higher-level matrices (above Level 2) need to be completed to ensure that the facility, infrastructure and site are also designed for these considerations. Further information on material selection for durability in accordance with a building's intended service life is available (Canadian Standards Association, 1995).

For the analysis performed in this thesis, wall assemblies were chosen such that they had similar durability. This reduces the complexity of equating dissimilar materials.

5.0 Analysis

5.1 Wall Systems considered in analysis

The sustainability matrix was applied to four infill (non load-bearing) wall systems. The primary wall system chosen for analysis was a strawbale infill wall as is commonly used in strawbale construction. This wall system was chosen since it is often promoted as a sustainable alternative to conventional wall assemblies. Thus, it was felt that it would be valuable to compare strawbale wall assemblies to wood stud, steel stud and concrete block wall assemblies using the sustainability matrix. Background information on strawbale construction can be found in Appendix A. The comparison wall assemblies were chosen to be as similar as possible to strawbale construction in terms of performance.

The primary qualities of a strawbale wall system that needed to be equivalent in the comparison wall assemblies were thermal resistance and surface finish. All of the wall assemblies were suitable structurally as infill walls with respect to in plane and out of plane loadings. Where the infill wall assembly cannot meet these structural requirements, modifications to the frame would be needed. While the assemblies tested are intended as non load-bearing construction, each assembly can be adapted to load-bearing applications with minimal changes in the material quantities. Load bearing applications were not considered since adequate design guidelines for load-bearing strawbale walls are not yet refined. As such, load-bearing strawbale designs often use excess materials to allow for uncertainties. It was felt that it would be unfair to compare designs based upon experience and rules of thumb (load-bearing strawbale) to those that have benefited from extensive optimization and testing in load-bearing applications (block, steel stud and wood). In addition, the analysis of load-bearing wall assemblies would require consideration of additional structural materials required to transfer loads over wall openings and at corners. These materials would be dependent more on building design and local conditions, rather than the wall assembly itself. Thus, non load-bearing applications were investigated.

Since strawbale walls are most frequently stuccoed, stucco-clad comparison wall assemblies were chosen. This form of construction is often termed exterior insulation and finish systems (EIFS) and consists of a cementitious base coat and polymer modified (PM) finish coat adhered to a substrate, commonly expanded or extruded polystyrene. To simplify the analysis, it was assumed that the stucco coating was similar in all four wall assemblies. Thus, the polymer in the EIFS systems was not considered. This is not expected to change the outcome of the results since strawbale walls are frequently coated with a similar coating. The total thickness of the EIFS stucco was selected to be 10 mm based upon Bomberg, Lstiburek and Nabhan (1997).

The supporting structure for the other EIFS systems chosen were wood stud, steel stud, and concrete block back-up walls. Further details on these types of construction are presented in Sections 5.3, 5.4 and 5.5 for wood, concrete block and steel stud walls respectively, while Section 5.2 describes the elements of a strawbale wall.

The wall assemblies were chosen to have similar thermal properties, based upon current test results for a two-string strawbale wall. The thermal resistivity of a strawbale wall is assumed to be RSI 4.6 $m^2 \cdot K/W$ (R 26) for the wall thickness given. Thermal bridging in the steel stud wall was reduced by using exterior insulation. However, the equivalent heat flow calculations used the parallel path heat flow method, which may overestimate the thermal resistance of steel stud walls. The total heat flow for a typical month in January with an average temperature difference of 25°C was calculated to determine the approximate difference in energy costs between the wall assemblies, assuming an energy cost of \$0.08 per kilowatt-hour. The heat flow calculations for the summary values found in Table 5-1 can be found in Appendix B.

Table 5-1 Thermal Properties of Wall Assemblies

Wall Type	RSI ($m^2 \cdot K$ / W)	Heat Flow / Month in January ($kW \cdot h/m^2$)	Heat Flow per Month in January per $120m^2$ of wall ($kW \cdot h$)	Cost per month due to heat loss (\$)
Wall #1 - Strawbale	4.60	4.04	485	38.82
Wall #2 - Wood Stud / EIFS	4.71	3.95	474	37.91
Wall #3 - Block / EIFS	4.45	4.18	502	40.13
Wall #4 - Steel Stud / EIFS	4.12	4.51	542	43.34

It was assumed for all wall assemblies that bulk water migration through the wall assemblies from the interior to the exterior would is largely due to air exfiltration. Water migration by vapour diffusion was assumed to be small and controlled by the permeability of the interior finish coating. Walls were assumed to dry to both the exterior and interior. Sheet vapour retarding membranes were therefore omitted from all four wall assemblies. The vapour flow through the strawbale wall assembly is still under investigation by other researchers.

The functional unit for the analysis of the four wall assemblies was a 1m long strip of wall, 3m high.

5.2 Wall Type 1: Strawbale

The strawbale wall chosen for analysis is illustrated in Figure 5-1 with material quantities and other characteristics shown in Table 5-1. Sample calculations for material quantities can be found in Appendix B.

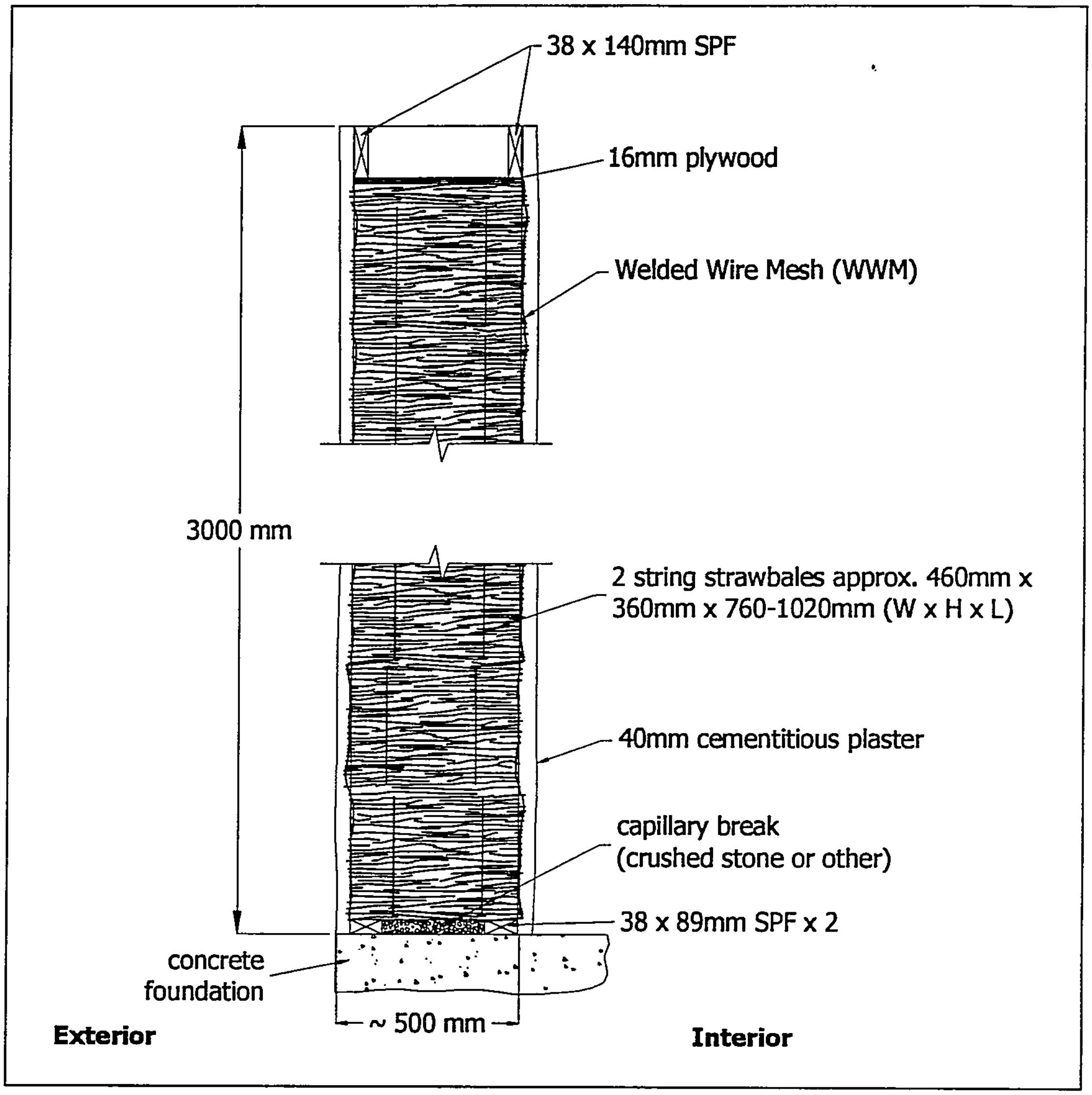


Figure 5-1 Wall #1 - Strawbale

Table 5-2 Material Quantities for Wall #1 - Strawbale

Material	Mass per 1m x 3m strip (kg)
Cement Stucco, (Interior & Exterior), 80mm	594.90
Reinforcing Mesh	5.20
Strawbales	165.60
38mm x 140mm x 1000mm S-P-F x 2 pcs.	2.23
38mm x 89mm x 1000mm S-P-F x 2 pcs.	2.84
16mm x 460mm x 1000mm Plywood	3.84

The strawbale wall shown in Figure 5-1 is typical of a strawbale wall that is used in Ontario. The only portion of a load-bearing strawbale structure included in the analysis is the top box-beam since it also functions as an attachment for stucco wire mesh and also serves to protect the top of the bales from potential moisture, and animals. In addition it serves as a fire stop.

The bottom 38 x 89 mm framing members at the bottom of the wall assembly serve as an attachment point for the stucco wire mesh and to contain the capillary break, composed of crushed stone or other material capable of providing a capillary break.

The stucco netting is provided only for crack control and is comprised of 14 gauge, 50 x 10mm welded wire mesh. A Portland cement based plaster was chosen for the exterior and interior of the bale walls since this is currently one of the few code compliant finishes in Canada. The ratio investigated was a cement:lime:sand mixture of 1:1:6 as is commonly used in Canada (Magwood & Mack, 2000).

5.3 Wall Type 2: Wood/EIFS

In order to match the thermal properties of a strawbale wall, 140mm of cavity insulation was required. To achieve this 38 x 140mm softwood lumber was selected. Since the same wall could be constructed from 38 x 89mm members at 400mm on centre (o.c.), the 38 x 140mm members were spaced at 600mm o.c. to reduce the amount of lumber. This wall assembly is shown in Figure 5-2 and the wall system properties are shown in Table 5-2. Sample calculations for material quantities can be found in Appendix B.

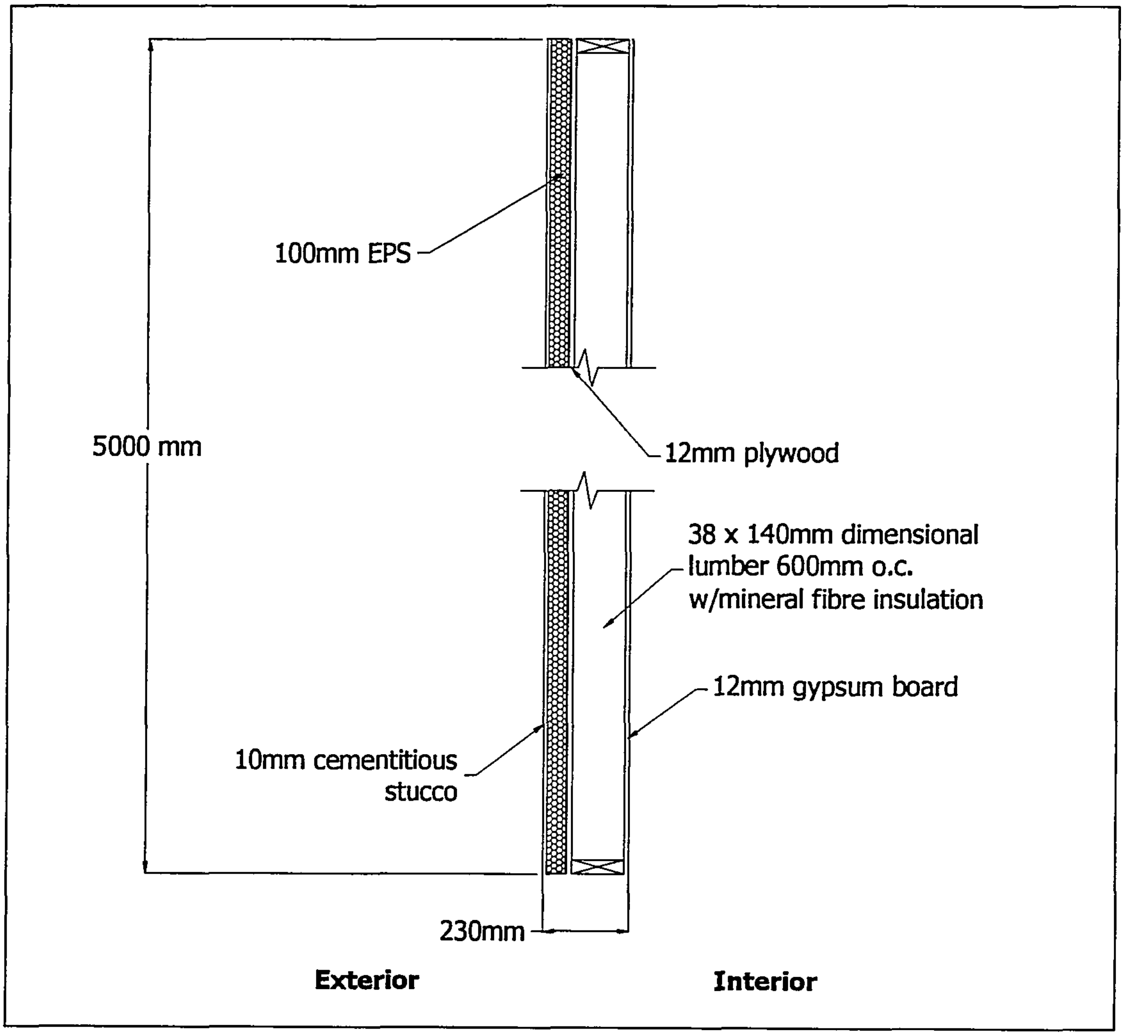


Figure 5-2 Wall #2 - Wood Stud / EIFS

Table 5-3 Material Quantities for Wall #2 - Wood Stud / EIFS

Material	Mass per 1m x 3m strip (kg)
Cement Stucco, 10mm	59.49
Expanded Polystyrene (EPS), 50mm	2.40
Plywood, 12mm	27.90
38mm x 140mm S-P-F .	30.70
Mineral Wool Batt, 140mm (Cavity)	4.03
Gypsum Wallboard, 12mm	28.80

5.4 Wall Type 3: Concrete Block / EIFS

The masonry infill wall consists of 140 mm concrete block, expanded type II polystyrene insulation, and a 10mm stucco layer as in the wood wall. The interior wall requires strapping (metal or wood) to provide support for drywall and also includes a thin layer (50mm) of mineral fibre insulation between the strapping to increase the overall thermal resistivity. This wall assembly is shown in Figure 5-3 and the wall system properties are shown in Table 5-3.

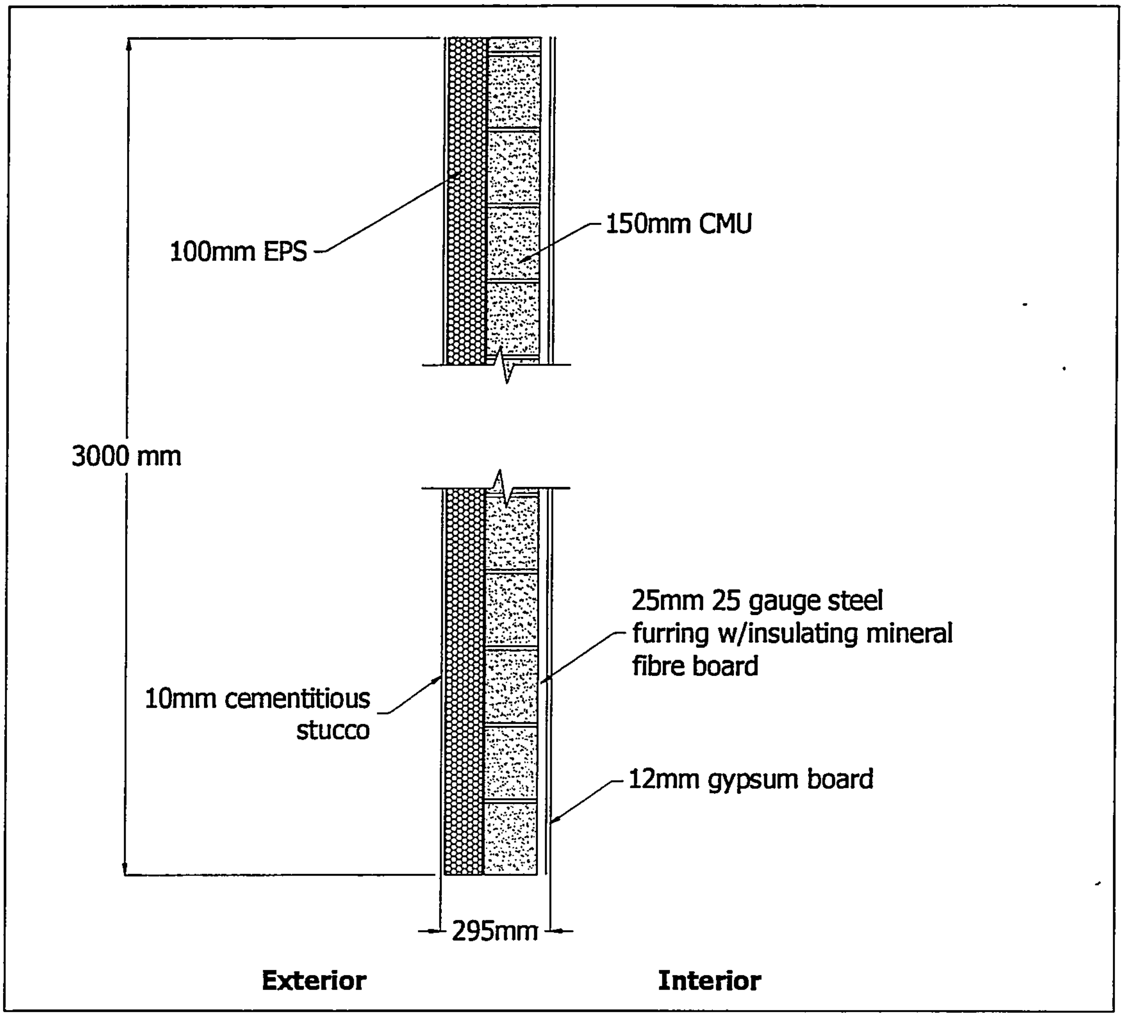


Figure 5-3 Wall #3 - Concrete Block / EIFS

Table 5-4 Material Quantities for Wall #3: Concrete Block / EIFS

Material	Mass per 1m x 3m strip (kg)
Cement Stucco, 10mm	59.49
Expanded Polystyrene (EPS), 100mm	10.50
Concrete block, 15cm	511.20
Steel Strapping	5.00
Mineral fibre board, 25mm (Cavity)	0.72
Gypsum Wallboard, 12mm	28.80

5.5 Wall Type 4: Steel Stud / EIFS

The steel stud wall was constructed similar to the wood stud wall, except out of 20 Ga. steel studs measuring 38 x 152mm and spaced 600mm on centre. Figure 5-4 illustrates the wall cross-section properties, and material quantities per functional unit are listed in Table 5-5.

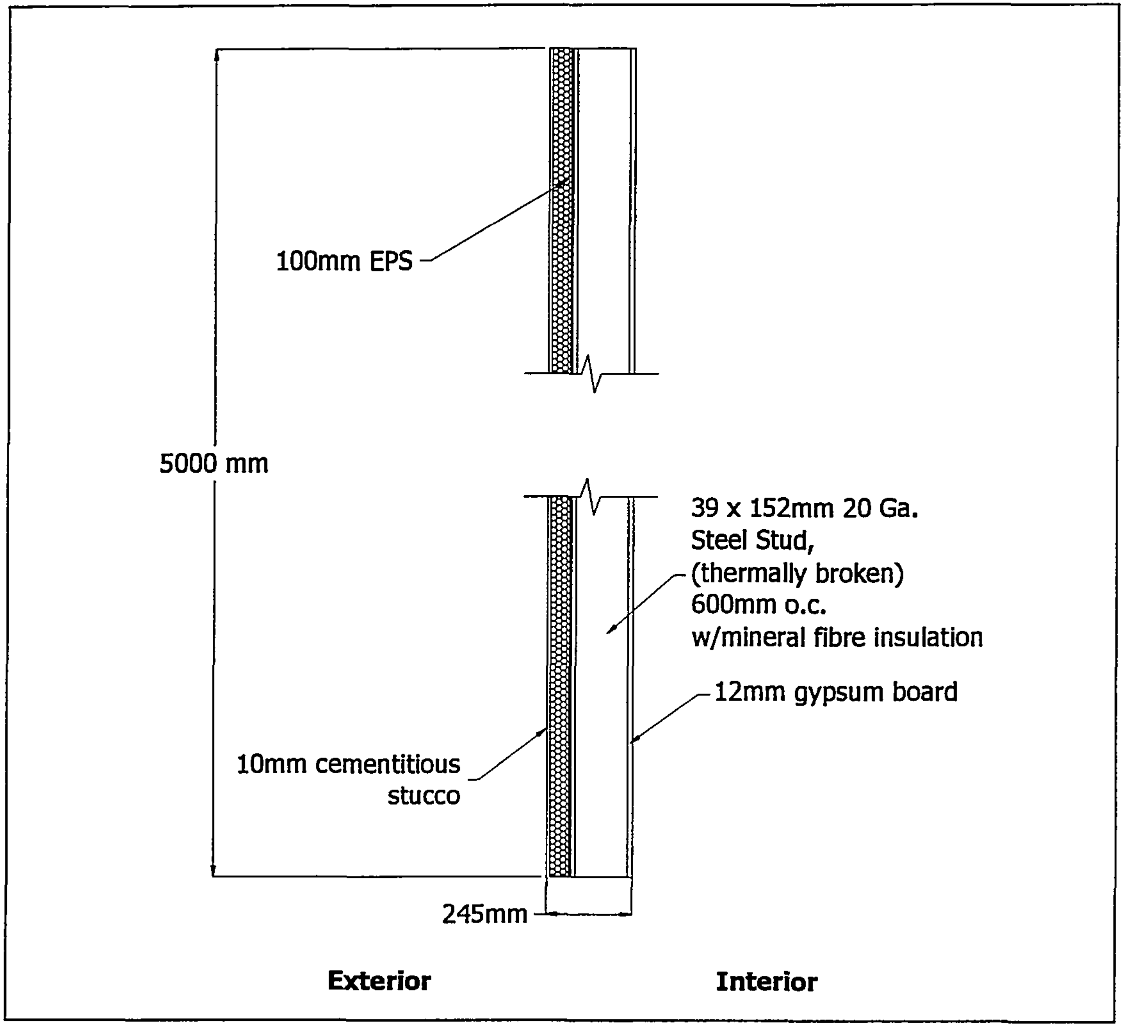


Figure 5-4 Wall #4 - Concrete Block / EIFS

Table 5-5 Material Quantities for Wall #4: Steel Stud / EIFS

Material	Mass per 1m x 3m strip (kg)
Cement Stucco, 10mm	59.49
Expanded Polystyrene (EPS), 50mm	2.40
39mm x 152mm 20Ga. Steel Stud	13.40
Mineral Wool Batt, 152mm (Cavity)	4.03
Gypsum Wallboard, 12mm	28.80

5.6 Checklists

Using the principles outlined in Chapters 2 and 3 and the categorisation of impacts in Chapter 4, checklists were adapted from Graedel and Allenby (1996; 1998) and supplemented with additional checklists developed in this thesis specifically for building assemblies. Using this approach, the environmental "hot spots" of the four wall assemblies can be identified, with the aim of designing out the problem areas.

The detail of the checklists decreases as one moves throughout a product's life cycle. This reflects the fact that while one can be fairly certain of a product's origin, one is less certain of how the assembly will be handled far into the future. For example, one can design a product to be recyclable, but unless it is supported by top-down initiatives such as legislation, financial incentives and a cultural shift, one cannot guarantee that the intended fate of an assembly will be realised. In the last case, that of culture, the uncertainty with respect to end-use is most significant. For instance, durable materials are often suggested as an option for extending a product's life cycle and thus reducing the net life cycle burdens. However, if a product is discarded because it is no longer "aesthetically pleasing" or has fallen out of fashion, durability becomes a liability rather than an asset. It is not plausible to design for durability without satisfying or changing the cultural prerequisites of culture. Since satisfying the issues of durability is more dependent upon the design of the building as a whole, rather than the particular assemblies, these issues are better characterised on the level of the building itself. Since this work focuses on materials and their assemblies, the end use cannot be characterised with great precision. Stewart Brand (1994) provides a comprehensive investigation into these issues.

Since the current state of knowledge with respect to the materials in buildings is focussed on the environmental impacts of material production, most of the information required to complete the checklists for the production stages is available. However, there is less research on, and certainty of, the impacts of building materials at the end of their life. In addition less information is available on the non-energy related impacts from building operation, maintenance, and repair, except when it comes to indoor air quality. Even then, the research is not conclusive in assessing what constitutes a risk to the human and ecological environments. The checklists are therefore less detailed as one progresses through the life cycle stages.

To organize the results and comments from the checklists and to present them in the form of a sustainability matrix, a Visual Basic for Applications interface was developed for an Excel spreadsheet that contained the checklists, scoring and comments.

5.7 Sources of Information

A variety of information sources was consulted for the evaluation of the matrix. These include process specific life cycle inventories and summaries such as those published by the ATHENA™ Sustainable Materials Institute, product reviews and life cycle reviews such as those featured in Environmental Building News, company product literature, the

American Institute of Architect's Environmental Resource Guide (Demkin, 1996), Material Safety and Data Sheets (MSDS) and personal communication with industry experts.

5.8 Scoring

Numerical scoring is the most problematic aspect of any impact study since equating a quality to a numerical scale always incorporates some value judgements. Since even quantitative life cycle assessment involves value judgements to determine which pollutants or emissions are to be measured, or are of concern to be measured. The sustainability matrix approach also incorporates value judgements that rely on the skill of the practitioner. However, since the sustainability matrix tool is not intended for absolute product rankings, but rather to guide and improve design for alternative products, the assignment of numerical scores to qualitative aspects of materials is not considered to be a hindrance, except when basing decisions on the summary scores alone.

The purpose of the scoring in the sustainability matrix is to indicate to the designer where potential burdens exist. Since the scoring per matrix element is "coarse" i.e. from 0 to 4, the numerical scores serve as "red flags" with the numerical score indicating the degree of "redness" or concern.

In general, the scoring for each element is assigned as follows, although the distinction is less defined for some matrix elements:

For a score of 0:

> The product or assembly violates the principles set out in Section 3.3 and makes no attempt to minimise the impact. Other strategies exist that are environmentally preferable.

For a score of 1,2 or 3, depending on the degree to which:

> The assembly minimises the use of materials whose burdens are significant (i.e. wasteful use of materials).
>
> The material minimises its associated burdens.
>
> Preferable or suitable alternative materials exist.

For a score of 4:

> The burdens associated with the product cause insignificant ecological or human health impacts.

5.9 Weighting of Life Cycle Stages and Environmental Concerns

The sustainability matrix was weighted to reflect the both the degree of environmental concern and the most significant life cycle stages. It was decided for the 4 wall assemblies that the material selection aspects were most significant since the bulk of material flows can be controlled by the choice and application of materials. Thus, the product extraction through manufacturing stages were deemed most significant for material flows. However, since most of the energy use occurs during the use phase of an assembly, it was necessary to increase the weighting of this stage as well. Consequently, this led to a life cycle stage weighting that reduced the overall weight of the construction, and end of life stages while increasing the weight of the product extraction through manufacturing and use and operation stages. The weighting factors for the life cycle stages are shown in Table 5-6.

Table 5-6 Life Cycle Stage Weights

Life Cycle Stage	Weight (%)
Extraction Manufacturing Packaging and Transport	50
Construction	7.5
Use / Operation	30
Deconstruction / End-use	12.5

In addition to weighting the life cycle stages, the environmental concerns (columns) of the sustainability matrix were also weighted. The weights for the environmental concerns were chosen to reflect the fact that for the wall assemblies investigated, the most significant concern was felt to be the ecological concern and the energy concern. This reflects the fact that while the impact of emissions to land are significant, the current priorities that need to be addressed globally are those of global warming and ecological destruction. If different materials or wall assemblies were selected, the weightings should be changed so that toxic emissions are not underrepresented.

The weights for the environmental concerns are shown in Table 5-7.

Table 5-7 Environmental Concern Weights

Environmental Concern	Weight (%)
Ecological Burden / Materials Choice	40
Energy	40
Solid Emissions	4
Liquid Emissions	8
Airborne Emissions	8

Combining the two sets of weights results in a doubly weighted matrix, which when multiplied by the maximum score of four for each cell in the un-weighted matrix, results in the matrix shown in Table 5-8, with a total maximum score of 80. The score was later normalized to 100.

Table 5-8 Doubly-Weighted Sustainability Matrix

		Ecological Concern / Materials Choice	Energy	Solid	Liquid	Air	Total
	Weight (%)	40	40	4	8	8	100
Extraction ➔ Manufacturing	50	16	16	1.6	3.2	3.2	40
Construction	7.5	2.4	2.4	0.24	0.48	0.48	6
Use / Maintenance	30	9.6	9.6	0.96	1.92	1.92	24
Deconstruction / End - Use	12.5	4	4	0.4	0.8	0.8	10
Total	100	32	32	3.2	6.4	6.4	80

6.0 Results and Discussion

6.1 Assessment of impacts

The overall score for the material extraction through manufacture for the respective matrix elements was based upon the life cycle inventory (LCI) data presented in Appendix D. Life cycle inventories for the wall assemblies can be found in Appendix C. Since the LCI data does not represent impacts that can't be quantified, nor does it embody the principles set out in Chapter 2, the analysis was supported through the use of the checklists presented in Appendix E. The results of the checklists for materials are listed in Appendix F and the results of the four wall assemblies are shown in Appendix G.

6.2 LCI Indices

Summary indices of embodied energy, global warming potential (GWP), acidification and eutrophication were calculated based upon the LCI data for each wall assembly. The summary indices for the four wall assemblies are shown in Table 6–1 for Wall #1 (straw-bale), Table 6–2 for Wall #2 (wood stud), Table 6–3 for Wall #3 (concrete block), and Table 6–4 for Wall #4 (steel stud). Sample calculations for the indices can be found in Appendix B.

Table 6-1 Wall #1 - Strawbale

	Energy (MJ/m)		GWP (kg CO_2)		Acidification (H^+ equiv.)		Eutrophication	
Material	Value	% of total	Value	% of total	Value	% of total	Value	% of total
Strawbale	121.9	12.8	15.2	9.4	2.0	16.5	12.8	25.2
Softwood	19.9	2.1	3.1	1.9	0.3	2.6	1.0	2.0
Plywood	25.7	2.7	2.5	1.5	0.3	2.3	1.2	2.3
Cement Plaster	577.7	60.5	112.4	69.6	5.7	47.8	30.2	59.6
WWM	210.2	22.0	28.3	17.5	3.6	30.8	5.5	10.8
Total	955.4	100.1	161.4	99.9	11.8	100.0	50.7	99.9

Table 6-2 Wall #2 - Wood Stud / EIFS

	Energy (MJ/m)		GWP (kg CO_2)		Acidification (H^+ equiv.)		Eutrophication	
Material	Value	% of total	Value	% of total	Value	% of total	Value	% of total
Softwood	120.4	15.7	18.7	27.6	1.9	28.1	6.3	26.9
Plywood	186.5	24.4	18.0	26.6	2.0	29.2	8.5	36.5
Polystyrene	200.8	26.2	11.1	16.4	1.3	19.8	3.6	15.6
Mineral Wool	57.4	7.5	3.6	5.3	0.5	6.7	1.1	4.7
Cement Plaster	72.2	9.4	14.0	20.7	0.7	10.5	3.8	16.2
Drywall	128.3	16.8	2.3	3.4	0.4	5.7	0.0	0.0
Total	765.6	100.0	67.7	100.0	6.7	100.0	23.2	100.0

Table 6-3 Wall #3 - Concrete Block / EIFS

	Energy (MJ/m)		GWP (kg CO_2)		Acidification (H^+ equiv.)		Eutrophication	
Material	Value	% of total	Value	% of total	Value	% of total	Value	% of total
Concrete block	666.6	47.3	124.6	67.7	13.1	66.3	42.5	72.4
Steel Stud	131.8	9.3	20.3	11.0	2.8	14.2	5.0	8.5
Polystyrene	401.5	28.5	22.2	12.1	2.7	13.5	7.2	12.3
Mineral Wool	10.2	0.7	0.6	0.3	0.08	0.4	0.2	0.3
Cement Plaster	72.2	5.1	14.0	7.6	0.7	3.6	3.8	6.4
Drywall	128	9	2	1	0	2	0	0
Total	1410.6	100.0	184.0	100.0	19.8	100.0	58.7	100.0

Table 6-4 Wall #4 - Steel Stud / EIFS

Material	Energy (MJ/m) Value	Energy (MJ/m) % of total	GWP (kg CO_2) Value	GWP (kg CO_2) % of total	Acidification (H^+ equiv.) Value	Acidification (H^+ equiv.) % of total	Eutrophication Value	Eutrophication % of total
Steel Stud	353.2	43.5	54.3	63.7	7.6	72.4	13.4	61.3
Polystyrene	200.8	24.7	11.1	13.0	1.3	12.8	3.6	16.5
Mineral Wool	57.4	7.1	3.6	4.2	0.5	4.3	1.1	5.0
Cement Plaster	72.2	8.9	14.0	16.5	0.7	6.8	3.8	17.2
Drywall	128	16	2	3	0	4	0	0
Total	811.9	100.0	85.4	100.0	10.4	100.0	21.9	100.0

Based upon these results alone, Wall #2, the wood stud wall, performs the best in terms of energy, GWP, acidification potential (AP) and comparable to Wall #4, the steel stud wall, in terms of the eutrophication potential (EP).

In terms of the summary indices, the concrete block wall (Wall #3) had the highest environmental impact of the four assemblies. The major contributor to its poor performance is the cement content of the concrete blocks. Next to the cement content, the polystyrene and the steel stud strapping were the next largest contributors to all of the indices.

Surprisingly, the strawbale wall did not perform as well as anticipated from an environmental standpoint, based on the LCI data. From Table 6-1 it is clear that the primary reason for this is due to the cement plaster and the welded wire mesh, which accounted for 60% and 22% of the overall embodied energy of the wall assembly. The GWP, AP and EP follow in similar proportions, as they are largely due to energy related emissions.

Comparing the strawbale wall to Wall #2, the wood stud wall, one notes that the embodied energy required to produce a one metre long strip of strawbales, three metres high, is equivalent to the energy required to sustain the harvesting of wood. This is surprising since strawbale is often assumed as being low in embodied energy. The reasoning behind this assumption is that straw is a waste material and hence any use derived from it would have a low (or negative as some suggest) embodied energy. However, straw is not an agricultural waste material, in Ontario. Thus, if there is no need for strawbales, either for livestock bedding or other commercial purposes, the straw is not harvested for baling. Rather, it is cut into chaff and left to return nutrients to the soil.

The reason behind the high embodied energy of strawbales, is due to the inefficiency of farm equipment. The fuel consumption figures obtained were typical of small farming operation (<1200 ha) of which most strawbales for construction would be obtained. The age of the machinery might be a significant factor in the excess fuel consumption. However, it is unlikely that small scale farming operations, especially organic farms would be able to afford newer, potentially more efficient farm machinery. The emissions derived from the fuel consumption were underestimated as they were derived from diesel transport truck conversion efficiencies.

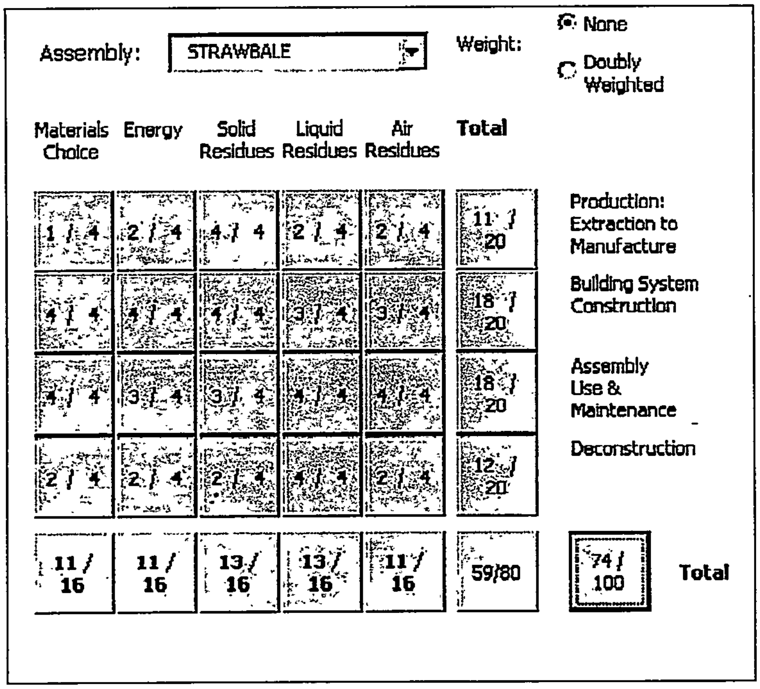
Despite the contribution of cement to the overall embodied energy of the strawbale wall assembly, the overall impacts derived from the LCI data (with the exception of global warming potential) are low for typical construction methods (compared to Wall #3) and thus compare favourably overall with Wall #2 and Wall #4, within the estimated accuracy of the LCI data.

From the LCI data and the summary indices, it is difficult to draw conclusions on the overall environmental performance of three of the wall assemblies; Walls #1, #2 and #4. The concrete block wall is clearly a poor performer in terms of the LCI data.

6.3 Sustainability Matrices

To further qualify the environmental performance of the four wall assemblies, the checklists were applied to further define the environmental considerations. The material component of the combined material/assembly matrix was not scored, due to difficulties in determining how to weight the total scores for aggregate materials. This limitation is further discussed in the next section. Despite this limitation, it was felt that it was more effective to view the performance of the constituent materials by how they interact within the wall assemblies, as opposed to attempting to assign a context score based on a difficult to realise metric, for example one tonne of material. Consequently, no scores are shown for the material section of the matrix, but checklist comments were made to further clarify the scoring of the assembly portion of the matrix.

Two matrices were computed for each wall assembly; one not weighted and the other weighted according to the weights previously outlined and are shown in Figure 6-1 through Figure 6-8.

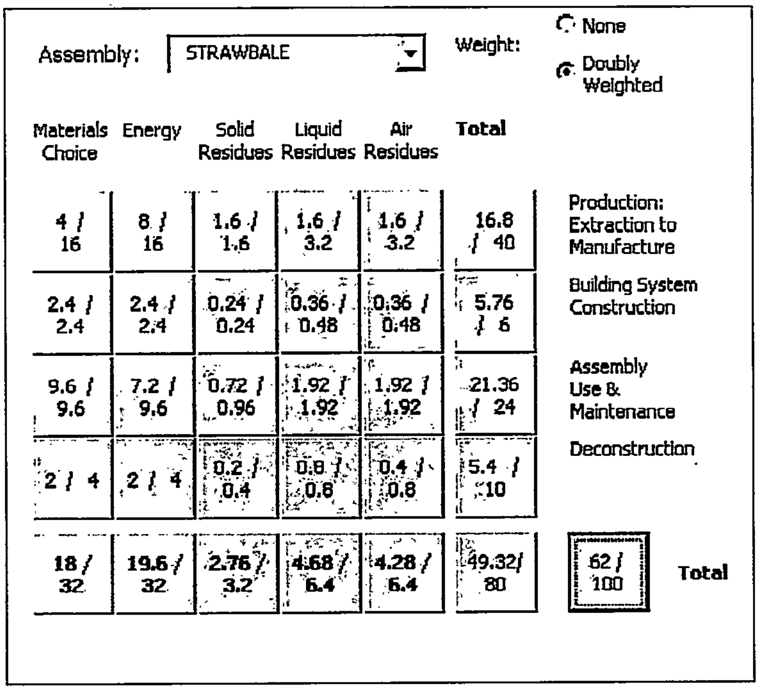


Assembly: STRAWBALE

Weight: ● None ○ Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	Total	
1 / 4	2 / 4	4 / 4	2 / 4	2 / 4	11 / 20	Production: Extraction to Manufacture
4 / 4	4 / 4	4 / 4	3 / 4	3 / 4	18 / 20	Building System Construction
4 / 4	3 / 4	3 / 4	4 / 4	4 / 4	18 / 20	Assembly Use & Maintenance
2 / 4	2 / 4	2 / 4	4 / 4	2 / 4	12 / 20	Deconstruction
11 / 16	11 / 16	13 / 16	13 / 16	11 / 16	59/80	74 / 100 Total

Figure 6-1 Sustainability Matrix for Wall #1 - Strawbale (unweighted)

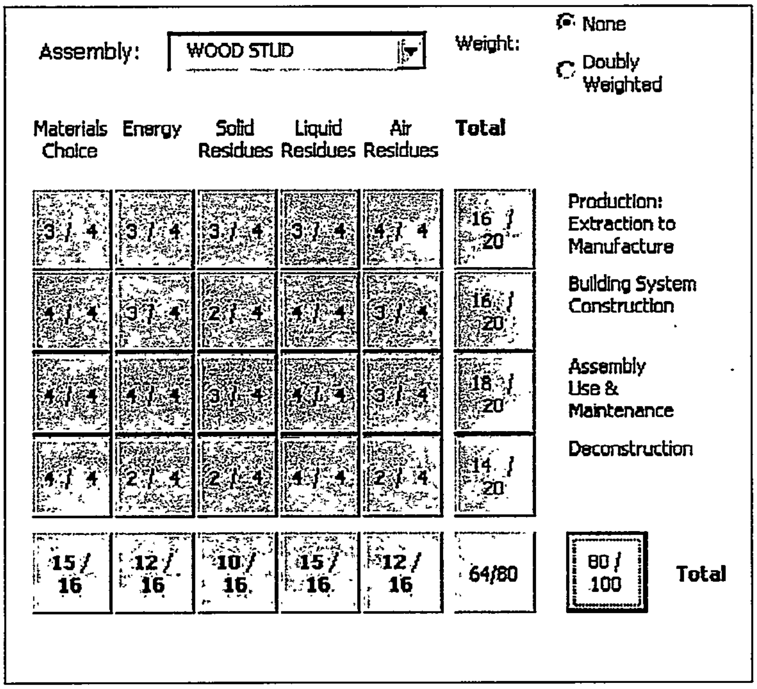


Assembly: STRAWBALE

Weight: ○ None ● Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	Total	
4 / 16	8 / 16	1.6 / 1.6	1.6 / 3.2	1.6 / 3.2	16.8 / 40	Production: Extraction to Manufacture
2.4 / 2.4	2.4 / 2.4	0.24 / 0.24	0.36 / 0.48	0.36 / 0.48	5.76 / 6	Building System Construction
9.6 / 9.6	7.2 / 9.6	0.72 / 0.96	1.92 / 1.92	1.92 / 1.92	21.36 / 24	Assembly Use & Maintenance
2 / 4	2 / 4	0.2 / 0.4	0.8 / 0.8	0.4 / 0.8	5.4 / 10	Deconstruction
18 / 32	19.6 / 32	2.76 / 3.2	4.68 / 6.4	4.28 / 6.4	49.32/ 80	62 / 100 Total

Figure 6-2 Sustainability Matrix for Wall #1 - Strawbale (weighted)

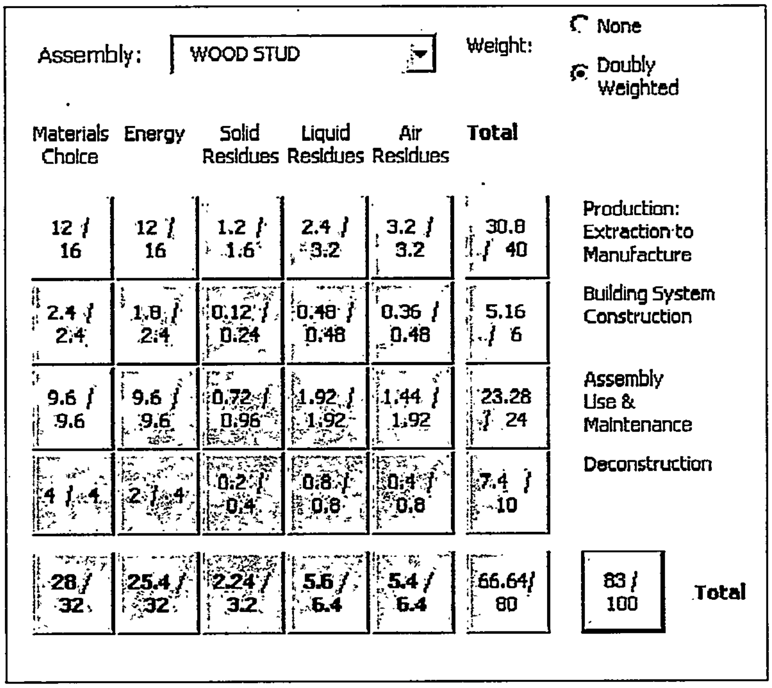


Assembly: WOOD STUD

Weight: ● None ○ Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	Total	
3 / 4	3 / 4	3 / 4	3 / 4	4 / 4	16 / 20	Production: Extraction to Manufacture
4 / 4	3 / 4	2 / 4	4 / 4	3 / 4	16 / 20	Building System Construction
4 / 4	4 / 4	3 / 4	4 / 4	3 / 4	18 / 20	Assembly Use & Maintenance
4 / 4	2 / 4	2 / 4	4 / 4	2 / 4	14 / 20	Deconstruction
15 / 16	12 / 16	10 / 16	15 / 16	12 / 16	64/80	80 / 100 Total

Figure 6-3 Sustainability Matrix for Wall #2 - Wood Stud / EIFS (unweighted)

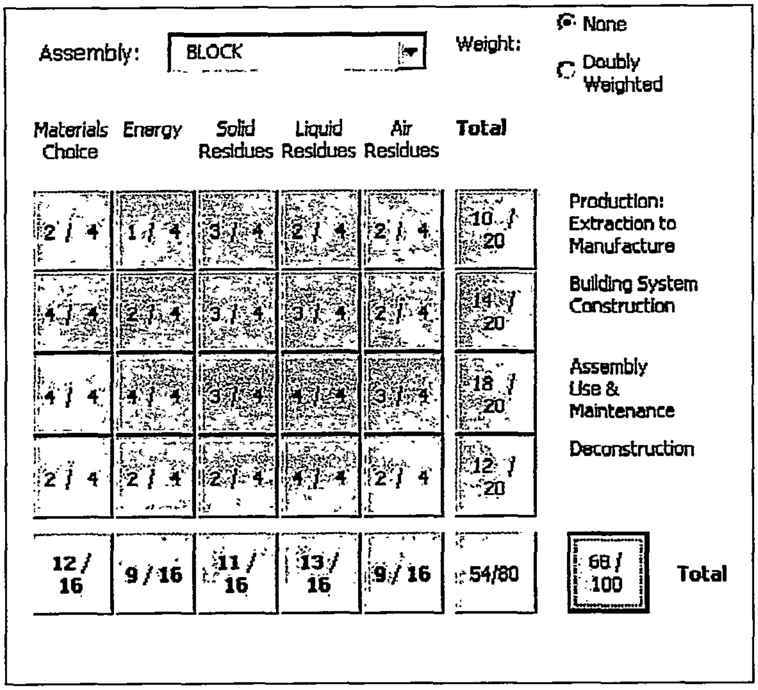


Assembly: WOOD STUD

Weight: ○ None ● Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	Total	
12 / 16	12 / 16	1.2 / 1.6	2.4 / 3.2	3.2 / 3.2	30.8 / 40	Production: Extraction to Manufacture
2.4 / 2.4	1.8 / 2.4	0.12 / 0.24	0.48 / 0.48	0.36 / 0.48	5.16 / 6	Building System Construction
9.6 / 9.6	9.6 / 9.6	0.72 / 0.96	1.92 / 1.92	1.44 / 1.92	23.28 / 24	Assembly Use & Maintenance
4 / 4	2 / 4	0.2 / 0.4	0.8 / 0.8	0.4 / 0.8	7.4 / 10	Deconstruction
28 / 32	25.4 / 32	2.24 / 3.2	5.6 / 6.4	5.4 / 6.4	66.64/ 80	83 / 100 Total

Figure 6-4 Sustainability Matrix for Wall #2 - Wood Stud / EIFS (weighted)

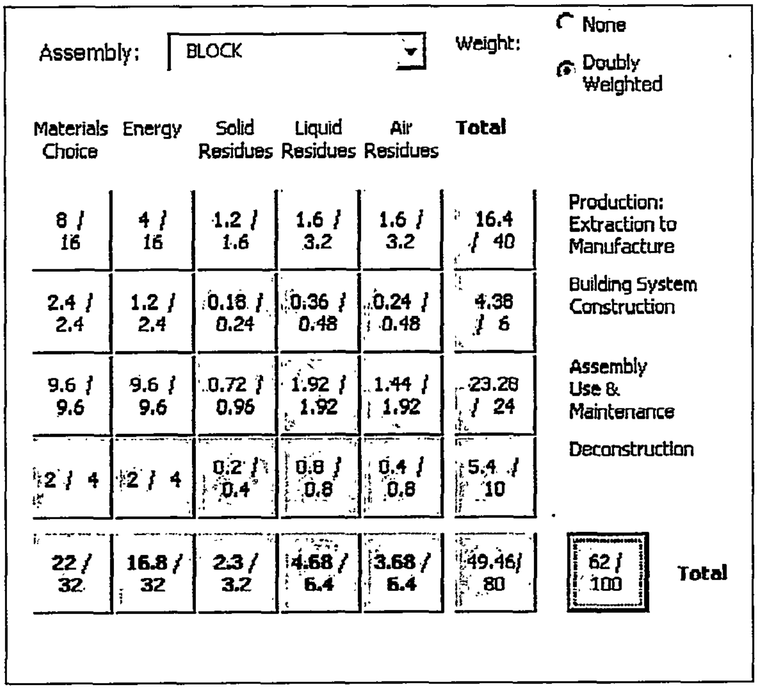


Assembly: BLOCK

Weight: ● None ○ Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	Total	
2 / 4	1 / 4	3 / 4	2 / 4	2 / 4	10 / 20	Production: Extraction to Manufacture
4 / 4	2 / 4	3 / 4	3 / 4	2 / 4	14 / 20	Building System Construction
4 / 4	4 / 4	3 / 4	4 / 4	3 / 4	18 / 20	Assembly Use & Maintenance
2 / 4	2 / 4	2 / 4	4 / 4	2 / 4	12 / 20	Deconstruction
12 / 16	9 / 16	11 / 16	13 / 16	9 / 16	54/80	68 / 100 Total

Figure 6-5 Sustainability Matrix for Wall #3 - Concrete Block / EIFS (unweighted)

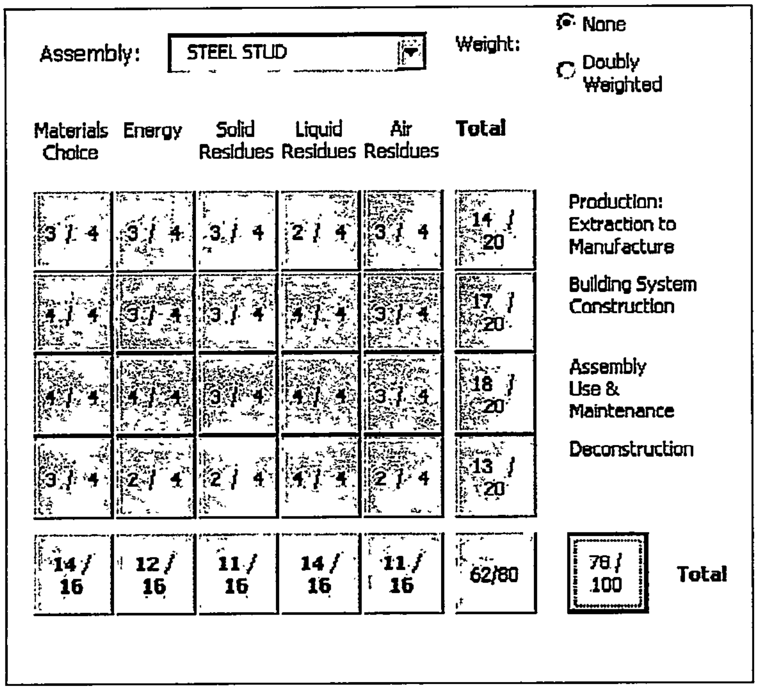


Assembly: BLOCK

Weight: ○ None ● Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	Total	
8 / 16	4 / 16	1.2 / 1.6	1.6 / 3.2	1.6 / 3.2	16.4 / 40	Production: Extraction to Manufacture
2.4 / 2.4	1.2 / 2.4	0.18 / 0.24	0.36 / 0.48	0.24 / 0.48	4.38 / 6	Building System Construction
9.6 / 9.6	9.6 / 9.6	0.72 / 0.96	1.92 / 1.92	1.44 / 1.92	23.28 / 24	Assembly Use & Maintenance
2 / 4	2 / 4	0.2 / 0.4	0.8 / 0.8	0.4 / 0.8	5.4 / 10	Deconstruction
22 / 32	16.8 / 32	2.3 / 3.2	4.68 / 6.4	3.68 / 6.4	49.46/ 80	62 / 100 Total

Figure 6-6 Sustainability Matrix for Wall #3 - Concrete Block / EIFS (weighted)

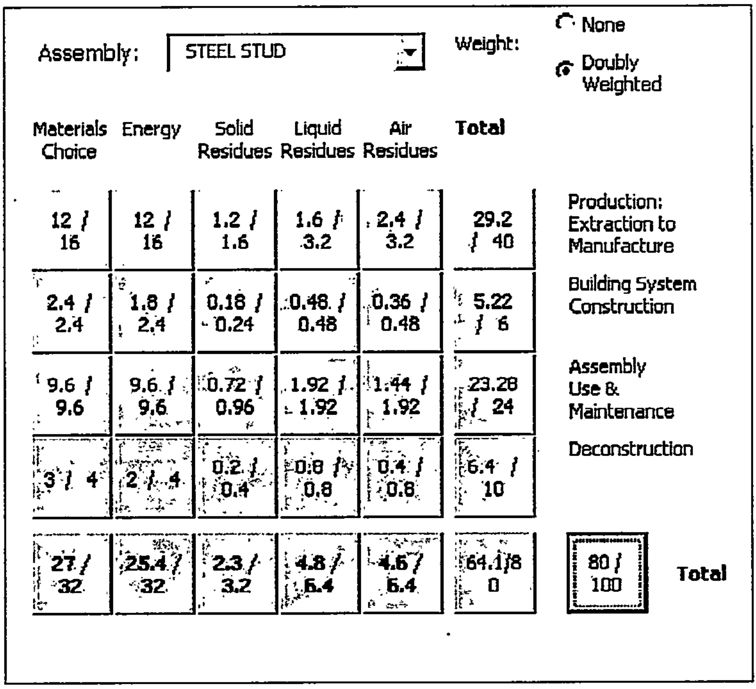


Assembly: STEEL STUD

Weight: ● None ○ Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	**Total**	
3 / 4	3 / 4	3 / 4	2 / 4	3 / 4	14 / 20	Production: Extraction to Manufacture
4 / 4	3 / 4	3 / 4	4 / 4	3 / 4	17 / 20	Building System Construction
4 / 4	4 / 4	3 / 4	4 / 4	3 / 4	18 / 20	Assembly Use & Maintenance
3 / 4	2 / 4	2 / 4	4 / 4	2 / 4	13 / 20	Deconstruction
14 / 16	12 / 16	11 / 16	14 / 16	11 / 16	62/80	78 / 100 **Total**

Figure 6-7 Sustainability Matrix for Wall #4 - Steel Stud / EIFS (unweighted)



Assembly: STEEL STUD

Weight: ○ None ● Doubly Weighted

Materials Choice	Energy	Solid Residues	Liquid Residues	Air Residues	**Total**	
12 / 16	12 / 16	1.2 / 1.6	1.6 / 3.2	2.4 / 3.2	29.2 / 40	Production: Extraction to Manufacture
2.4 / 2.4	1.8 / 2.4	0.18 / 0.24	0.48 / 0.48	0.36 / 0.48	5.22 / 6	Building System Construction
9.6 / 9.6	9.6 / 9.6	0.72 / 0.96	1.92 / 1.92	1.44 / 1.92	23.28 / 24	Assembly Use & Maintenance
3 / 4	2 / 4	0.2 / 0.4	0.8 / 0.8	0.4 / 0.8	6.4 / 10	Deconstruction
27 / 32	25.4 / 32	2.3 / 3.2	4.8 / 6.4	4.6 / 6.4	64.1/80	80 / 100 **Total**

Figure 6-8 Sustainability Matrix for Wall #4 - Steel Stud / EIFS (weighted)

The above matrices show that the environmental performance of the steel stud wall (Wall #4) and the wood stud wall (Wall #2) is essentially the same, in both the weighted and not weighted cases. This is primarily due to both walls having similar system properties, and in fact sharing most of the same materials. With the exception of the structural elements of steel wood and plywood, they both have the same quantities of mineral wool, polystyrene, and cement, explaining the relative similar environmental performance.

For the strawbale and concrete block wall, the difference between the un-weighted matrix and the weighted matrix was large, significantly reducing the overall score such that both wall assemblies had the same value of 62 in the weighted case.

While it is tempting to draw a conclusion based upon the checklists, it is more useful to use the matrices to ask oneself not "Which wall system should I choose?" but rather, "How can I make the wall system that I choose, the most preferable?" Answering the first question based upon the matrices, one could with some confidence that the wood stud wall is a better performer than the concrete block or strawbale wall, given the assumptions made in the checklists. In all cases, it was assumed that the most environmentally preferable technologies and techniques were used. That is, selective harvesting of timber, organic farming of straw, responsible use of recycled content material (e.g. in steel, mineral wool, gypsum). Should these assumptions not be correct, the analysis will likely change.

Answering the second question, one should be reminded that the ultimate purpose of the matrix type approach, namely Design for Environment (DfE) or product improvement.

Using the results of the analysis, one could go through the checklists and redesign the strawbale wall so that it is perhaps more preferable.

For instance, three possible solutions could be developed to overcome the burden from cement-based plasters:

1. Reduce the amount of cement plaster used non-structurally (most of it is used as "filler" for uneven walls).
2. Substitute fly-ash for cement, thus reducing the energy intensity and associated emissions due to cement production.
3. Substitute cement itself: possible use earthen-based plasters or lime or gypsum.

Similar strategies can be used with respect to the block, steel and wood wall. For example, rigid mineral fibre insulation could replace the energy intensive (and un–recyclable once stuccoed) polystyrene insulation. Similarly, the block could be used directly as either the inside or outside finish surface, reducing the need for either drywall or the stucco layer.

Thus, while the numbers tend to indicate a near equivalence among the environmental performance of comparison wall assemblies using LCI data, the checklists tell a different story, one of a path of potential improvement.

6.4 Limitations

The major limitation of the streamlined approach, or sustainability matrix as it is referred to in this work, is the extensive knowledge required to achieve meaningful results. It is extremely difficult to make an objective decision on qualitative data without being criticized of being subjective. The best ammunition against this danger is understanding how little one really knows, and that even the quantitative life cycle inventory data itself, is at best approximate. In this light, the sustainability matrix is perhaps best used as a tool for finding out what is not known, that is, as a learning tool.

The concept of a rough scoring guide for each matrix element is a useful concept that can increase the speed at which design decisions can be made, without going through time consuming LCA. It is also useful to recognise the interconnection of the various levels of matrices as defined previously. This can help the designer realise where he or she should devote their time as opposed to tweaking out the minutiae. For instance, relating the assembly matrices to the building matrices, one realises that the overall contributions of the embodied energy of a wall, with respect to both the operating energy and the embodied energy of furnishings and other equipment, is relatively small as was discussed in Section 2.3.1.

Some difficulties arose in trying to aggregate the scoring of the material level matrix into the assembly matrix. It was originally hoped to link the burdens to a common unit such as weight of material per wall. However, it was found that the impacts are not always related to this functional unit. For instance one could aggregate the material scores based upon the weight of materials used in the wall assembly. For the end-use, this would capture the effects due to toxic emissions that might result from leaching in a landfill for example. However, this would not take into consideration the volume of space occupied by low density materials. Using a volume-based aggregation would result in the opposite effect, favouring high-density materials that take up less landfill space.

To overcome this difficulty, aggregation was based upon the weight of the materials, with the final score being adjusted where necessary after aggregation. It was found that this was necessary only in some cases where experience showed the final aggregate score to be misleading as in the case where only a small quantity of a toxic material was used, but the burden was significant. In these cases the wall system level checklists (Level 2) served as a final check on the suitability of the weighting. For most of the building elements analysed, the toxicity was low.

It is possible to increase the weight of certain life cycle stages and specific burdens to reflect a particular concern that needs to be addressed. For instance, the energy column weight was increased to reflect global warming concerns. If a healthful indoor environment was to be highlighted, one could increase the weight of the operation stage, and perhaps the air column. Care should be taken in interpreting these results however, since the weighting may not correspond to actual impacts. For instance, doubling the weight of the energy column, and reducing the impacts accordingly by product redesign to improve the score by twice the amount, may not result in a net twofold improvement. This results since the scoring is not linear.

Despite the above limitations of aggregation and weighting, the matrix approach is still successful in identifying potential problem areas. The weighting and scoring problems mentioned above do not hinder the overall goal of locating problem areas, with the goal of redesign.

6.5 Comparing and Integrating Other Approaches

The checklists characterize the nature and amount of emissions that occur throughout a material's life cycle. The emissions generated during the extraction through transportation and packaging stages is process specific, though general trends can be found. The characterization of emissions can be supported by quantitative data that is available through various databases and software packages that perform inventory analysis. Alternatively, the major releases can be identified based upon experience, with the checklists serving as a guide to ensure that specific emissions are not neglected. Currently, the data on building material emissions during the extraction through delivery stages is not comprehensive. The available data is limited to specific types of assembly construction, and often neglects the characterization of raw waste material flows that occur from raw material extraction. Some programs such as ATHENA™ report material flows based upon largest contributions by mass. Emissions that do not constitute a large fraction of the waste stream are reported as "other materials". While the quantity of these flows may be small, their toxicity is not known.

ATHENA™ reports specific classes of emissions that occur during production of the materials for a building assembly. However, not all pollutants of potential concern are reported. For instance in the production of steel, there is no characterization of the solid, liquid or particulate emissions of metals. The metal wastes are reported as ferrous and non-ferrous for liquid effluents, with the user left to distinguish the proportion that is toxic. For instance in the production of a 25 Ga. steel stud wall, 3 m. high and 10 m. long, the metal related effluents are reported as follows:

Table 6-5 Solid Liquid and Air Emissions for Production of a 25 Ga. Steel Stud Wall, 10m long, 3m high, 600mm o.c. (ATHENA™ Sustainable Materials Institute, 2000a)

	Water Emissions				Air Emissions		Solid Emissions
Stage	Non-ferrous (mg)	Iron (mg)	Other Metals (mg)	Toxicity index	Metals (mg)	Toxicity Index	Steel (mg)
Extraction	not reported			5	70	0	0
Production	431	7369	839	32	180	12	0

To some degree, the air and water toxicity indices capture the ecological impacts, but these indices are based upon the critical volume (ATHENA™, 2000b), which is not linked to actual ecological damages, but instead is based upon an assumed assimilative capacity of the receiving body (air or water), and does not consider the possibility of synergistic effects of emissions.

The eco-indicator approach is more closely tied to ecological impacts. This is done by using a damage-based model that scores ecological impact based upon aggregated indices such as fatalities, health impairment and ecosystem impairment (Goedkoop & Spriensma, 2000).

The eco-indicator approach does not consider whether a material is from renewable or non-renewable resources since raw material depletion does not directly affect either human or ecosystem health. In addition, toxic substances that occur in the workplace, whether during production or the use phase are also not considered since it is argued that while local concentrations may be high, once they are released to the outside environment, they are diluted and the relative ecological impact is thus small (Goedkoop & Spriensma, 2000).

The results obtained through the sustainability matrix are subjective if they are assigned a scoring, weighted, and then aggregated into a single indicator that is used for comparison between dissimilar products.

Boustead (1999b) explains that the validity and meaning of a single aggregated environmental index is dependent upon whether the user has access to appropriate data on the full life cycle in interpreting the aggregated index. For example, looking only at the final score, a difference of 10 points between two dissimilar wall assemblies may not provide enough information to guide alternative designs. However, if the user can then find out *why* a product received a particular indicator (as in the case of the sustainability matrix), the indicator approach then becomes meaningful since it can identify where and why the impacts occur, and possibly suggest alternatives.

A similar problem occurs with whole building assessment systems such as LEED, created by the United States Green Building Council (USGBC) (USGBC, 2000). The LEED approach evaluates a building's "greenness" by given "credits" for satisfying different green building strategies. For example a credit might be given for the reuse of materials or for on-site greywater recycling. The total credits are then added up and the building is assigned a rating of Platinum, Gold, Silver or Bronze, according to a prescribed total of credits. While there are certain prerequisites in each category of analysis (e.g. energy, water, site, materials), it is possible to obtain a "Platinum" rating without having achieved any credits in a given area. For example a platinum level can be achieved without even considering water conservation.

With the lack of a similar rating system or approach, it is difficult to compare the results of the sustainability matrix for the selected wall assemblies. This does not however, reduce the meaningfulness of the results. The real test is whether the application of the sustainability matrix is successful in identifying the major environmental burdens of a building system throughout its life cycle. This is largely dependent upon the knowledge and skill of the user, and the nature of the specific burdens.

The burdens that are more easily quantified, such as energy consumption, are easily found for common building materials, though often in aggregated form. While the embodied energy values can vary by an order of magnitude, they can still be used to assess the relative burdens associated from energy use throughout a building's life cycle.

While a rigorous life cycle inventory (LCI) would provide quantitative data on the emissions of general processes, it cannot identify company-specific operations or regional variations. Since the sustainability matrix poses questions that relate directly to the local ecology, and addresses company-specific operations it is better suited for initial design rather than final product assessment. However, with the sustainability matrix, it is often difficult for an inexperienced professional or designer to assess with any meaning whether, for example "The location of the raw material extraction is ecologically sensitive." What this does highlight is how little designers may know about the origins and fate of their designs.

In addition, the use of LCI data, as used for the four sample wall assemblies does not always give a clear indication of the environmental preference of a particular wall system. For instance, the impacts that are most significant for the strawbale wall assembly are due to the extensive use of cement-based plaster. The LCI data do not expressly indicate that the use of concrete is not minimised. From the LCI data, it is difficult do draw conclusions of the overall environmental preference of strawbale construction compared to Wall #3, which is constructed from concrete block, even though the summary indices are lower for the strawbale wall. It is difficult to conclude that Wall #1 is preferable to Wall #3 since Wall #1 represents an inefficient use of a resource (cement), whereas the block wall minimises the use of cement. The strawbale wall is an example of an inefficient resource since much of the cement used ends up filling gaps created by the irregular surface of strawbales. If less of the concrete were used as "gap filler", and instead as structure, the situation would change. The sustainability matrix reflects this consideration by ranking the two wall assemblies as nearly equal for the energy column due to the inappropriate use of an energy intensive material, even though the strawbale wall uses less overall energy than the block wall.

The goal of streamlined assessment tools, in general, is to simplify the life cycle analysis of a product such that the designer can focus on creating solutions as opposed to analysis of impact. Software tools are promoted as freeing the designer from the tedious task of familiarizing themselves with ecological impacts of materials. Since full rigorous LCAs often neglect to characterize non-quantitative impacts such as human health or non-quantifiable ecological impact, the sustainability matrix was presented as a possible solution to this problem.

In applying the sustainability matrix to four sample wall assemblies, it was found that the task of assessment requires a great deal of knowledge and experience to have any meaning. In addition, the approach highlighted that it is difficult to answer with any certainty or credibility many of the questions presented. However, the approach does not hide these uncertainties as would occur in a quantified approach where value judgments are hidden from the user. This is the primary advantage of the sustainability matrix, so long as the information is not presented in aggregated form. Highlighting these uncertainties can also be termed a "useful ignorance." If, as some experts concluded, the non-quantifiable impacts due to building materials, are as important as the quantifiable impacts (Wayne B. Trusty & Associates, & Environmental Policy Research, 1994), and we know very little about these impacts, there is not only much work to be done, but a change in the education of designers is also required.

This thesis focussed on the areas that are deficient in current methodologies, namely the characterization of the ecological impacts during extraction through end-use and the specific emissions that occur from construction through to end-use. As such, a piece of the picture is missing. Further research should integrate the nature and amount of non-energy related emissions.

7.0 Conclusions and Recommendations

The use of the sustainability matrix as applied to four sample wall assemblies is valuable as a conceptual tool that designers can use to develop a sense of the major impacts associated with a given set of materials. The specific examples illustrate the depth and complexity of the issues surrounding the selection of sustainable building materials.

7.1 Wall Assemblies

This work began as an investigation into the merits of strawbale construction. The merits of this type of construction were touted as being far superior to conventional construction for many reasons, energy efficiency being the most notable. Upon viewing first-hand some notable examples of strawbale construction, the initial question was raised: "If strawbale is the answer, what is the question?"

Three wall assemblies, wood stud, concrete block and steel stud, each clad with an EIFS were selected to be comparable in performance to the strawbale assembly in terms of thermal resistivity and finish appearance. The four wall assemblies were then used to demonstrate the effectiveness of the sustainability matrix approach.

From the life cycle inventory of the four wall assemblies, indices for the embodied energy, GWP, acidification and eutrophication potential were determined. Based upon these indices, the concrete block wall was found to be the worst performer in all of the LCI indices. The wood stud and steel stud wall assemblies were lowest in terms of the indices, with the difference between the two assemblies being insignificant.

The results from the LCI of the straw bale wall indicated that the energy used for the harvesting and processing of the straw bales is equivalent to that of harvesting the wood as used in the wood stud wall. This result was surprising given that strawbales are often assumed to be low in embodied energy, but is understandable when the energy intensiveness of farm operations is considered. The largest impact from the strawbale wall assembly was due to the cement plaster and wire reinforcement that is used in the rendering or stuccoing of the bales, accounting for 70% to 87% of the contribution to the summary indices. Conclusions on the overall environmental performance of the strawbale wall assembly based upon the summary indices was difficult since there was not a marked difference from the other wall assemblies for all of the indices except that the strawbale wall was closer in performance to the concrete block wall assembly.

The sustainability matrix was used for the four wall assemblies to get a better picture of the environmental performance of each wall assembly. Using the LCI data as a guide or yardstick for assessing the material and energy flows, the degree to which the wall assemblies met the requirements for sustainability (presented in Section 3.3) was determined using checklists. Two cases were given for each wall assembly: one unweighted and the other doubly weighted to increase the importance of early life cycle stages, energy, and ecological concern/materials choice.

For the unweighted case, the overall scores ranged from a score of 68 in the case of the concrete block wall to a score of 80 in the case of the wood stud wall. Since the scoring guidelines are coarse and not all impacts should be weighted equally, conclusions from these matrices were not meaningful.

The doubly weighted matrices revealed that the strawbale and concrete block wall are significantly worse performers than both the wood and steel stud walls. This was mostly attributable to low scores achieved in the materials choice and energy categories during the production stage. The checklists in these categories highlighted the inefficient and wasteful use of energy intensive cement products in both wall assemblies. In the strawbale wall assembly, there is a heavy use of energy intensive materials from virgin sources which is not minimised in the wall assembly. Essentially, the cement was inefficiently being used to smooth out the bale walls. In the case of the concrete block wall, the major hotspot was due to the use of energy intensive cement for the blocks and the polystyrene insulation needed to overcome the poor thermal performance of the block wall. Other differences between the environmental performance of the wall assemblies existed, but the overall contribution to the total score was small.

It was found that the wood and steel stud wall assemblies were good choices compared to the concrete block and strawbale walls. Both wall assemblies minimised the use of energy intensive cement by minimising the total amount used by choosing a smooth substrate to apply the plaster to. The impact from other materials was reduced by selection of recycled and waste materials.

The prime conclusion that can be drawn from applying the sustainability matrix to the strawbale wall is that any material must be viewed in the context of its assembly. For instance, while a strawbale itself is a natural, locally available, rapidly renewable material, the amount of cement plaster that is required to make the wall assembly (in Ontario) results in an unneeded and excessive throughput of materials and use of energy. Alternative cladding materials for strawbales (appropriate to the climate in Ontario) should be investigated.

With respect to the concrete block wall assembly, the wall could be redesigned to utilise the surface of the block as a finish material, eliminating either the interior or exterior finishing materials. In addition the use of alternative insulation materials and substrates for the plaster, such as mineral fibre could be used to reduce the environmental impacts.

The steel and wood stud walls as designed represent a good choice for sustainable wall assemblies compared to the strawbale and concrete block wall assemblies.

7.2 Sustainability Matrix

The logistics of answering 100-plus questions per material, for the first time, is a daunting task for any individual entering the field of sustainable materials selection for green buildings. The checklists, numerous as they are, serve to reinforce how much information is hidden by the quantitative methods of Life Cycle Analysis. It is tempting to summarise the resulting LCI information and reduce it to a single performance value for a material, or even a type of assembly. However, while this would ease the comparison of generic assemblies, it does not aid in the understanding of the impacts that occur during the life cycle of a material. This was found to be the case when looking solely at the LCI data. The results obtained by such an analysis do not provide the proper feedback necessary to correct the course of sustainable design. For instance, if a designer knew that generic product A was three times more damaging than generic product B based upon a single indicator, he or she would be missing the requisite knowledge to know why.

In using a checklist type approach that is not tied to any specific target, except to the principles outlined in Chapter 2, the designer can revisit the checklists and determine why a material or assembly is not a sustainable choice. The examples used showed some potential improvements based upon the checklists.

The sustainability matrix is useful for assessing preliminary designs to screen out poor choices and to select an appropriate "rough cut" for further design and analysis. In the case of the wall assemblies investigated, the design of the strawbale and concrete block wall assemblies should be red-flagged as not meeting the requirements of sustainability presented in Section 3.3, which are:

- minimise the amount of toxic materials present and as a result of the manufacturing, use and end use of a material,
- ensure that all toxic, resource and energy intensive materials that are used are closed loop within the industrial system,
- minimise the amount of energy transformations required in producing, maintaining and recycling a product such that energy usage is minimised,
- use renewable energy and ensure that this practice is sustainable.

Based upon the results of the checklists in Appendix F, the strawbale and concrete block wall assembly designs should be seriously reconsidered.

Since the major hotspots in the strawbale and concrete block wall assemblies were attributed to the inefficient use of energy intensive cement-based products and welded wire mesh (in the strawbale wall), the following options for redesign should be considered in the next iteration:

- reduce the total amount of energy intensive plaster used, and/or
- substitute cement-based plaster for less energy intensive materials such as clay or pozzolons (fly-ash).

If these strategies were to be implemented, the amount and type of welded wire mesh could also be reduced since there would be less of a need for shrinkage control.

7.3 Future Work

While the sustainability matrix approach was found useful in identifying major environmental hotspots, further development of the approach is required.

The weightings of the life cycle stages and environmental burdens should be revisited to investigate the degree to which different weighting scenarios affect the targeting of hotspots. A form of sensitivity analysis is recommended to determine the variability of the results. In addition, it is suggested that the scoring guidelines be investigated to determine the degree to which users with different backgrounds affect the results.

A second or even third iteration is suggested, especially with the strawbale wall assembly, to determine how the wall systems would compare when the recommendations outlined in Section 6.3 are followed.

Numerical integration between the different levels of analysis (materials and assembly) is recommended. One possibility is to adjust the scoring based upon absolute emissions and impacts as opposed to relative scoring between the assemblies. To help with this, more wall assemblies should be investigated using the sustainability matrix such that the user has a better feel of what constitutes a significant burden. For instance, the concrete block wall assembly fared poorly relative to the other wall assemblies and thus received a low overall score. However, the concrete block wall may be preferable to other wall assemblies not investigated. A baseline of other wall assemblies would thus help in determining what constitutes an average or reference wall assembly.

Looking at materials and assemblies in context with the broader impacts of the building, its neighbourhood, the surrounding community and ultimately the biosphere requires an extension of the type of checklists for sustainability presented here. This will ensure that instead of asking whether we should use strawbale, wood stud, concrete block or steel stud, one is asking whether the building needs to be built anew from the ground up or whether a top-down conversion of an existing building is equally suitable. Extending this framework to consider the time required for transportation and the qualities of the work or activity within the building and one begins to realise that "green building" is more than the sum of its materials.

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Appendix A Strawbale Construction

A1 History

The use of straw as a building material is not new. Straw has been used in the construction of buildings for many centuries, especially throughout Asia and Europe, using a variety of techniques. These range from using the straw as an additive to earthen walls, in bundle form embedded in mortar, or compacted and plastered with clay (Steen, Steen & Bainbridge, 1994).

However, the use of baled grasses in North America did not occur until the development of the steam or horse-driven mechanised balers in the late 1800's. With the relative sparseness of timber, and the need to quickly erect temporary shelter, early settlers looked to locally available materials for construction. These included sod houses or "soddies" in the plains of Canada and the United States, and later baled grasses in Nebraska. The bale structures were easier to build than sod structures, with the added advantage of not removing productive soil. It was also discovered that these "temporary structures", when plastered, were more than adequate as permanent structures to survive the climate of Nebraska (Steen, Steen & Bainbridge, 1994).

The Nebraska-style bale buildings used baled grasses that directly supported the roof above. The earliest bale structure known is a one room schoolhouse built in 1886 or 1887 in Nebraska, measuring sixteen feet by twelve feet and seven feet in height (Welsch cited in Steen, Steen & Bainbridge). However, this structure was constructed of baled hay and was unplastered and reportedly only lasted a few years before being eaten by cows (Myhrman & MacDonald, 1998).

It is important to distinguish the difference between hay and straw. Straw is the stalk that remains after grain has been harvested and is available once a year in Canada, ranging from late July to late August, when the grain crops are harvested. The stalk has little food value. Hay on the other hand, is considered a grass, contains seed heads and is used as feed. Thus, a bale structure made from hay would be prone to composting, while providing both a home and food to insects, rodents and other animals. The predominant varieties used in strawbale construction are wheat, rye, rice and barley straw.

Early strawbale houses still in existence today include some from the early 1900s. Many of these are still being used in the Southwest United States (Myhrman & MacDonald, 1998). In Canada, the first permitted strawbale structure was a two-story load bearing house designed by Kim Thompson, in Ship's Harbour, Nova Scotia. Since then, numerous structures have been built in almost every province, with a number being built in Ontario.

A2 Description

The strawbale wall assembly analysed in this thesis consists of two-string bales laid flat in a running-bond fashion, similar to concrete block except that they are laid together without mortar. Average bale dimensions are shown in Figure A–1

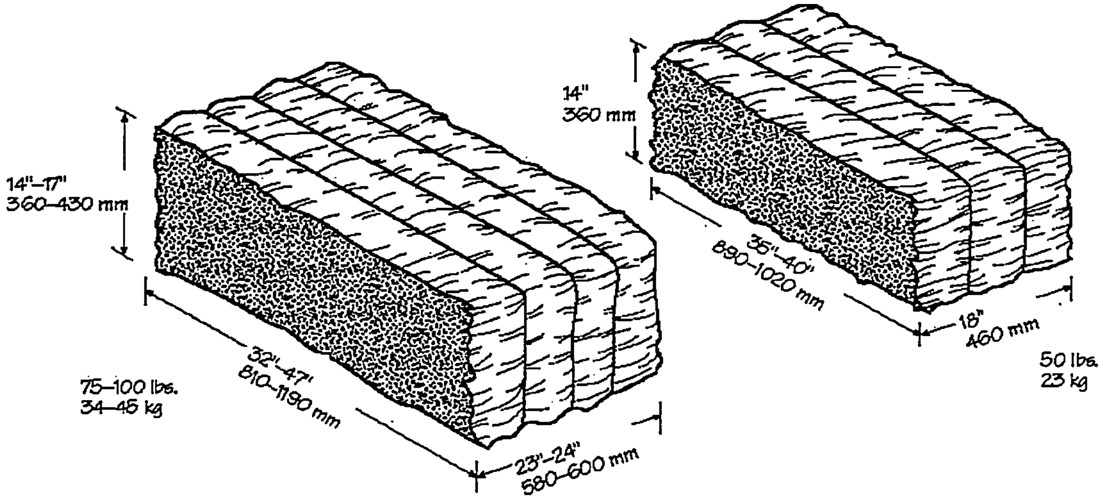

Figure A-1 Average Bale Dimensions (Steen, Steen, & Bainbridge as cited in Wilson, May/June, 1995, p.11)

Various types of wall assemblies have been successfully tried with strawbales including load bearing, non-loadbearing and hybrid designs. Literature that details the various combinations of strawbale wall assemblies can be found elsewhere (Steen, Steen, and Bainbridge, 1994; Myhrman & MacDonald, 1998; Magwood & Mack, 2000). Structural properties and requirements are well described in King (1996).

A3 Fire Concerns

It is often presumed that a strawbale structure is inherently flammable, and perhaps much of this is attributed to the notion of burning bundles of straw in fields. While straw is flammable, in a bale wall, a critical component for combustion is removed from the combustion equation: oxygen. A strawbale wall, once fully plastered, severely restricts the natural convective flow of air that typically supports fire spread in a building. The straw, being tightly packed together and effectively encased in plaster becomes a monolithic firestop. A useful analogy between the fire resistance of straw versus a strawbale wall, would be to compare burning a single sheet of paper versus lighting a closed telephone book on fire (King, personal communication, March 4, 1999). Thus a strawbale wall tends to char instead of burn. Fire tests performed by SHB Agra indicate that plastered strawbale walls can have up to a 2–hour fire rating (Simons, 1993).

A4 Moisture

The extreme longevity of strawbale buildings in warm arid climates is well documented. However, being an organic material, straw can rapidly decompose given the proper conditions of moisture and temperature. Canadian climate, especially that of Ontario, poses a unique challenge to the design of strawbale buildings since the climate can range from hot and humid to cold and dry with extremely wet periods throughout. The prime concern with strawbale construction in Canada is the prolonged accumulation of moisture within strawbale walls.

The extended accumulation of moisture within building elements is not an issue specific to strawbale. All building assemblies are vulnerable to the effects of moisture to some degree. For example wood framed walls easily rot where moisture seeps in around windows sills and projections, where subject to capillary action and where trapped after being transported by vapour diffusion or air leakage. Steel stud walls have been found to corrode if not protected adequately. EIFS (Stucco based) systems have notoriously been the subject of ongoing concerns with respect to moisture damage. Concrete and masonry walls are prone to spalling from bulk moisture migration and freeze-thaw action. Yet, natural materials such as thatch perform well to shed rain on roofs. Thus, while straw is a natural material, it shares the vulnerabilities of nearly all building materials: water.

One advantage of strawbale walls with respect to moisture is that when straw gets wet and *begins* to rot, it smells – one knows where the problem is and can readily repair it. In wood framed walls, this problem goes on undetected for long periods of time. The bales have a quality that is ideal for the durability of buildings: materials that look or smell bad before they're bad (Brand, 1994).

Given the same level of detail and attention as in Exterior Insulation and Finish Systems (EIFS), that is, attention to drip edges, flashing and protection from long periods of wetting, straw can be expected to perform as well or better than current EIFS walls. Recent reports however, suggest that the optimum surface finish with respect to moisture, may not be cement based plasters as analysed in this thesis, but rather more permeable finishes such as lime, gypsum, or earth-based plasters (Straube, 2000).

A5 Insulation

Published tests on the thermal resistance of strawbales have ranged from be 0.054W/m°C to 0.18 W/m°C. Joseph McCabe performed the first thermal testing on individual bales laid flat and on edge, and determined the resistance to be 0.054W/m°C for bales laid on edge (heat flow ⊥ to straw) and 0.061 W/m°C laid flat (heat flow || straw) (McCabe, 1993). This originally published figure showed great promise for energy efficiency, especially in northern climates.

However, since then, further tests have revealed varying results including 0.18 W/m°C (Watts et. al, 1995), 0.15 W/m°C (ORNL, 1996 as cited in "R-Value," 1998), to (0.13-0.17w/m°C) (CEC, 1997 as cited in "R-Value," 1998) and most recently 0.099 W/m°C

(Commins & Stone, 1998). The variability in the test results were attributable to air gaps and moisture. The air gaps found between the drywall and the bales and the plaster and bales presumably allowed convective loops to establish themselves within the bale wall, reducing the thermal resistivity. Moisture still present from construction was also found to lower the resistivity of strawbale walls ("R-Value," 1998).

Even though these walls were constructed in a laboratory environment, unfamiliarity with this construction technique may have resulted in less than perfect specimens. Nevertheless, it shows the importance of proper application of bale plasters to reduce the possibility of natural convective loops. McCabe has also suggested wind driven pressure differentials set up across bale walls may lead to insulation blow-through, where gross air movement greatly reduces the thermal resistivity (McCabe, personal communication, March 7, 2000). However, this effect also occurs within conventional wall systems that use air permeable insulation such as fibreglass and loose fill cellulose coupled with poor air barriers.

While the thermal resistivity of strawbales is significantly less than previously thought, a strawbale wall using two-string bales still provides a favourable level of insulation.

The thermal mass is often cited as a benefit to strawbale housing. The effect of thermal mass is that of tempering ability. That is a wall with a high thermal mass can store heat over a long period of time and gradually release it when temperatures fall. This tempering ability is most seen with adobe structures in the South-western United States. There, the building mass heats up during the hot days and releases the stored heat throughout the cold nights. By daybreak, the thermal mass is cool and keeps the building cool until it warms up throughout the day. The result is that night temperatures appear warmer while it is sensibly cooler during the day. However, this effect is minimal in climates with low-diurnal temperature fluctuations such as in Ontario. While the thermal mass benefits can be beneficial for heat storage applications, such as in passive solar design, the thermal mass of strawbale and the comparison wall assemblies analysed in this thesis is ignored.

A6 Summary

Strawbale wall assemblies provide a unique method of construction that might have positive environmental benefits. However, given that the thermal benefits of strawbale are not exceptionally higher per unit thickness of material, and the above-mentioned cautions with moisture, it is important to discuss the relevant environmental burdens pertaining to straw itself, and then to the building material usage specific to strawbale construction.

Appendix B Sample Calculations

The following appendix provides sample calculations for the determination of heat flow through the four wall assemblies, embodied energy calculations for strawbales, and material quantities per unit of wall assembly for the cement plaster and welded wire mesh in the strawbale wall, and mineral wool insulation quantities for the wood stud wall.

B1 Calculations for Heat Flow Through Wall Assemblies

The sample calculations that follow show the effective thermal resistance of the four selected wall assemblies. Thermal resistances were calculated based upon ASHRAE values (cited in Hutcheon & Handegord, 1995, tbl. 8.1) using the parallel path method. The heat flow for a 1m^2 section is given for average conditions in January for Southern Ontario. To gauge the relative difference between the heat flows, the energy lost during one month was calculated for a 200m^2 section of wall, which would be representative of an average sized building.

The heat flow through a building section is given by:

Heat Flow = 1/R ΔT (W/m^2)

Where R is the thermal resistance of the building assembly and
ΔT is the temperature difference between the inside and outside.

The heat flow per month (kWh) is obtained by multiplying the above value by (24hours x 30days).

Wall 1: Strawbale

Material	Thickness (mm)	R (m^{2}K/W) Framing	R (m^{2}K/W) Cavity
Air Film		Measured value used ("R-Value", 1998)	
Cement:Lime:Sand Stucco	50		
Reinforcing Mesh			
Strawbales	460		
Framing			
Reinforcing mesh			
Cement:Lime:Sand Stucco	50		
Air Film	560		

RSI Effective (Measured) 4.6 m^2 K/W

Heat flow through 1m^2 of wall in winter (ΔT = 25 °C) =

(1/4.6)*25 = 5.4 W/m^2

= 783 kWh per month for 200 m^2 of wall

Wall 2: Wood Stud, EIFS

Material	Thickness (mm)	R (m^2K/W)	
		Framing	Cavity
Air Film		0.03	0.03
Polymer modified stucco	10	0.014	0.014
Glass fibre mesh			
EPS Type II	50	1.316	1.316
Vapour permeable felt	0.25	0.011	0.011
plywood	12.7	0.109	0.109
2 x 6 wood stud (S-P-F)	140	1.077	
Mineral Wool batt (Cavity)	140		3.256
Gypsum Sheathing	12	0.075	0.075
Air Film		0.120	0.120
Total		2.751	4.930
	%	10	90

RSI Effective =	4.71	m^2 K/W
Heat flow through 1m^2 of wall in winter (ΔT = 25 °C) =	5.3	W/m^2
	764	kWh per month for 200 m^2 of wall

Wall 3: Concrete Block, EIFS

Material	Thickness (mm)	R (m^2K/W)	
		Framing	Cavity
Air Film		0.03	0.03
Stucco	10	0.014	0.014
EPS- HD	100	3.448	3.448
Concrete block, 15cm	140	0.213	0.213
Strapping	25	0.000	
Mineral fibre board (Cavity)	25		0.595
gypsum Sheathing	12	0.075	0.075
Air Film		0.120	0.120
Total		3.899	4.495
	%	10	90

RSI Effective =	4.44	m^2 K/W
Heat flow through 1m^2 of wall in winter (ΔT = 25 °C) =	5.6	W/m^2
=	812	kWh per month for 200 m^2 of wall

Wall 4: Steel Stud, EIFS

Material	Thick-ness (mm)	R (m^2K/W) Framing	Cavity
Air Film		0.03	0.03
Stucco	10	0.014	0.014
EPS Type II	50	1.316	1.316
steel stud	0	0.000	
Mineral Wool batt (Cavity)	140		3.256
Gypsum Sheathing	12	0.075	0.075
Air Film		0.120	0.120
Total		1.554	4.810
	%	25	75

RSI Effective	4.00	m^2 K/W
Heat flow through 1m^2 of wall in winter (ΔT = 25 °C) =	6.3	W/m^2
=	901	kWh per month for 200 m^2 of wall

B2 Sample Calculations for Summary Indices

These calculations were used to calculate the summary indices found in Section 6.2 and are based upon the Life Cycle Inventory (LCI) data found in Appendix C.

B2.1 Global Warming Potential (GWP)

global warming potential is an indicator that expresses global warming gases as an equivalent quantity (in kg) of CO_2.

The GWP is expressed as:

$$\text{GWP (kg)} = \Sigma_i w_i \cdot \text{GWPi}$$

where:

w_i = mass in kg of flow i
GWP_i = global warming potential of flow i

The index is expressed over a time horizon ranging from 20 years to 500 years. The 100-year time horizon recommended by the International Panel on Climate Change (IPCC) (cited in Lippiatt, 2000) will be used and are as follows for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O):

Gas	Global Warming Potential (GWP)
CO_2	1
CH_4	150
N_2O	63

Thus, 1 kg of CO_2, 1 kg of CH_4, and 1 kg N_2O would have a total GWP of

GWP = 1·1 + 1·150 + 1·63 = 214 kg GWP or CO_2 equivalent

B2.2 Acidification Potential

Gases that may lead to acidification can be expressed in an acidification potential:

acidification potential = $\Sigma_i w_i \cdot AP_i$ where

w_i = mass in grams of flow i
AP_i = equivalent grams of hydrogen with same acidifying potential as flow i

Flow (i)	(Hydrogen-Equivalents) API
Sulfur oxides	0.031
Nitrogen oxides	0.022
Ammonia	0.059
Hydrogen Fluoride	0.050
Hydrogen Chloride	0.027

(CML cited in Lippiatt, 2000)

B2.3 Eutrophication Potential

The eutrophication potential represents the loading of mineral nutrients to the soil or water. Eutrophication results when mineral loadings such as Phosphorus and Nitrogen encourage the growth of certain microorganisms that alter the natural balance of aquatic bodies or soil. For example, excess loadings of Phosphorus and Nitrogen can cause algal blooms in water, leading to a oxygen deprived ecosystem. This in turn results in the death of species such as fish (Lippiatt, 2000). The index is based upon phosphate equivalents and is calculated as follows:

eutrophication potential = $\Sigma_i w_i \cdot EPi$, where
w_i = weight of inventory flow i, (in grams),
EPi = equivalent grams of phosphate ions with same eutrophication potential as flow i, from the following:

Flow	Phosphate equivalents (E_p)
Phosphates	1.00
Nitrogen Oxides	0.13
Ammonia	0.42
Nitrogenous Matter	0.42
Nitrates	0.10
Phosphorous	3.06
Chemical Oxygen Demand	0.02

(CML cited in Lippiatt, 2000)

B3 Atmospheric Emissions by Fuel Type

These factors were used to determine the emissions generated from the seeding, baling and harvesting of strawbales. These factors were also used in determining the emissions generated by transport of materials. The emissions can be found in the raw LCI data located in Appendix D.

Fuel	Emission					
	CO_2 (g/MJ)	CO (g/MJ)	SO_2 (g/MJ)	NO_x (g/MJ)	VOC (g/MJ)	CH_4 (g/MJ)
Natural Gas	49.7000	0.0150	0.0002	0.0590	0.0010	0.0010
Coal/coke	86.0000	0.0880	1.1500	0.2400	0.0014	0.0005
Diesel	70.7000	0.4430	0.1020	0.8070	0.0870	0.0220
Gasoline	68.0000	3.8050	0.0140	0.3210	0.4340	0.0430

(Energy, Mines and Resources Canada, 1990)

Note: Particulate emissions by fuel type not available.

B4 Embodied Energy Calculation for Straw

Assumptions

bales per hectare (approx .14 m^3 each) = 125 bales
Average density = 120 kg/m^3
Weight of straw baled per hectare (# bales/ha x density) = 2100 kg
Energy content of diesel fuel = 36.68 MJ/L
Truck (Diesel) transport energy = 1.18 MJ/tonne.km
Mass of straw in 3m high wall, 0.46m thick, 1 metre long (120 kg/m^3 x 3m x 0.46m x 1m) = 165.6 kg

Energy consumption from farm machinery

		Seeding	Harvesting	Baling	
Fuel (diesel) used per ha (litres)	=	9	19	9	L/ha
Energy Consumption per ha (litres fuel used x 38.68 MJ/L)	=	361.8	723.5	361.8	MJ/ha
Energy per kg straw ((energy/ha) / (2100 kg straw/ha))	=	0.172	0.345	0.172	MJ/kg straw

Transportation energy for diesel trucks

Delivery distance by diesel transport = 40 km
Transport energy (1.18MJ/t.km x 40km) = 0.0472 MJ/kg straw

Summary

		Seeding	Harvesting	Baling	Transp.	Total	
Energy per kg straw ((energy/ha) / (2100 kg straw/ha))	=	0.172	0.345	0.172	0.047	0.736	MJ/kg straw
Embodied energy of straw for 3m high wall, 0.46m thick, per metre length (energy/kg x 120 kg/m^3 x 0.46m x 3m)	=	28.53	57.06	28.53	7.82	121.93	MJ/wall length

B5 Extra Wood Materials Required per Metre Length of Strawbale Wall

Softwood Density (S-P-F)	420 kg/m^3
Plywood Density	522 kg/m^3

Softwood		Volume (m^3)	Mass (kg)
38mm x 140mm x 1000mm x 2 pcs.		0.00532	2.23
38mm x 89mm x 1000mm x 2 pcs.		0.00676	2.84
	Total	0.01208	5.08
Plywood			
16mm x 460mm x 1000mm		0.00736	3.84

B6 Calculation for Amount of Welded Wire Mesh (Strawbale Wall)

Material Description:

14 gauge 50mm x 100mm (2-in x 4-in),
welded wire mesh (galvanised), used for plaster reinforcement,
placed vertically in strips with 100mm overlap each side,
interior and exterior wall surface.

Width of welded wire mesh roll = 1.5 m

Mass per m^2 = 0.76 kg/m^2

Overlap per strip is one cell (100mm) each side,
effective width (1.5m - 2 x 0.1m) = 1.3 m

Appendix C Summary Life Cycle Inventory (LCI) Data for Wall Assemblies

The tables that follow pertain to the four wall assemblies considered in this study. They include aggregated LCI data for strawbale, wood stud, concrete block and steel stud construction based upon the LCI data present for each of the constituent materials which can be found in Appendix D. Each table represents the LCI data available per unit wall of 1 m. length by 3 m. high.

The following notes apply to the tables:

Blank entries represent unreported values.
Totals may not agree due to rounding.
Decimal places do not indicate significant digits.
Extraction and manufacturing transport emissions are included in manufacturing column, unless otherwise stated.
Transport to construction site from manufacturer or warehouse included in manufacturing, or in construction emission estimate if present, or in delivery emissions if stated.
These are aggregated values, see material LCI data for sources of data (Appendix D).

Summary LCI Data -		Wall # 1 - Strawbale			
Category	Unit	Extraction	Manufacturing	Transport	Total
Energy					
Electricity	(kWh)	See Material tables for Specific Energy Splits			
Natural Gas	(MJ)				
Coal/Coke	(MJ)				
Diesel/HFO	(MJ)				
Gasoline	(MJ)				
Bio Fuel	(MJ)				
Feed Stock	(MJ)				
Other	(MJ)				
Total	(MJ)	98.0	828.4	28.9	955.4
Emissions to Air					
CO_2	kg	8.2	120.6	1.7	130.5
CO	g	34.0	224.5	9.5	268.0
SO_2	g	23.2	97.6	3.1	123.9
N_2O	g	66.0	306.4	17.7	390.1
PM	g	117.8	59.0	0	176.8
VOCs	g	7.3	30.9	2.6	40.9
CH_4	g	11.8	30.0	0.7	42.5
Phenols	g	0.006	0.06	0	0.07
Acid Gases (excl. HCl & HFl)	g	0	0	0	0
Non-CH_4 HC	g	0	0	0	0
Metals	g	0.006	0.02	0	0.03
HCl	g	0.1	0.5	0	0.6
HFl	g	0.02	0.08	0	0.1
Other	g	0	0	0	0
total	g	260.3	749.2	33.5	1043.0
Water Emissions					
flow	L/unit				
pH					
BOD	mg	0	2.8	0	2.8
SS	mg	26779.7	13626.7	0	40406.5
DS	mg	0	2021.3	0	2021.3
PAH	µg	0	0	0	0
COD	mg	0	32603.3	0	32603.3
Hydrocarbons	mg	0	0	0	0
Non-Fe Metals	mg	0	38.9	0	38.9
Cyanide	mg	0	46.7	0	46.7
Phenols	µg	2.3	10788.4	0	10790.8
Phosphates	mg	0	28.6	0	28.6
Ammonia & Ammonium		212.1	801.3	0	1013.5
Non-Halogenated Organics	µg	0	0	0	0
Halogenated Organics	µg	0	311.1	0	311.1
Chlorides	mg	144610.2	11573.9	0	156184.1
Aluminum & Aluminum	mg	61.4	4.6	0	66.1
Oil & Grease	mg	1415.4	1128.6	0	2544.0
Na+	mg	0	0	0	0
Sulphates	mg	119119.4	10820.6	0	129940.0
Sulphides	mg	38.3	7.8	0	46.0
Nitrates & Nitrites	mg	1285.6	32.5	0	1318.0
Dissolve OC	mg	1927.7	0	0	1927.7
Phosphorus	mg	1.2	0	0	1.2
Iron	mg	0	626.9	0	626.9
Other Metals	mg	20.9	101.2	0	122.0
Acids	mg	0	57.4	0	57.4
total (excl. BOD, COD)		295476.5	128397.1	0	423873.6
Solid Waste					
Bark/ Wood Waste	kg	0	1.1	0	1.1
Blast Furnace Slag	kg	0	1.4	0	1.4
Blast Furnace Dust	kg	0	1.4	0	1.4
Steel Waste	kg	0	0	0	0
Concrete waste	kg	0	1.4	0	1.4
Other Solid Waste	kg	0	4.2	0	4.2
Summary Indexes					
Air tox index (for ref. only)		89.4	461.2	0.002	550.6
Water tox index (for ref. only)		0	207.7	0	
GWP	kg CO_2	14.2	144.4	2.9	161.4
Acidification Potential (AP)	H+ eq.	1.6	9.8	0.5	11.8
Eutrophication Potential	P eq.	7.5	40.9	2.3	50.7

Summary LCI Data - **Wall #2 - Wood Stud / EIFS**

Category	Unit	Extraction	Manufacturing	Transport	Total
Energy					
Electricity	(kWh)	See Material tables for Specific Energy Splits			
Natural Gas	(MJ)				
Coal/Coke	(MJ)				
Diesel/HFO	(MJ)				
Gasoline	(MJ)				
Bio Fuel	(MJ)				
Feed Stock	(MJ)				
Other	(MJ)				
Total	(MJ)	65.0	656.3	44.3	765.6
Emissions to Air					
CO_2	kg	11.2	36.2	0.5	48.0
CO	g	42.3	19.6	1.8	63.7
SO_2	g	34.0	49.1	1.4	84.5
N_2O	g	73.8	112.4	3.6	189.8
PM	g	25.8	40.0	0.06	65.8
VOCs	g	7.5	13.3	1.0	21.8
CH_4	g	28.0	24.2	0.9	53.1
Phenols	g	0.03	1.0	< 0.001	1.0
Acid Gases (excl. HCl & HFl)	g	0	0.001	0	0.001
Non-CH_4 HC	g	2.4	8.2	0.1	10.7
Metals	g	0.01	0.02	< 0.001	0.03
HCl	g	0.2	0.5	< 0.001	0.7
HFl	g	0.02	0.08	< 0.001	0.09
Other	g	0.2	0	0	0.2
total	g	214.3	268.2	9.0	491.5
Water Emissions					
flow	L/unit				
pH					
BOD	mg	1160.0	34.0	4.0	1198.0
SS	mg	4942.5	2785.0	17.0	7744.6
DS	mg	46.2	11465.5	0.09	11511.8
PAH	µg	0.01	0.01	0.01	0.03
COD	mg	2.1	18939.6	0.03	18941.7
Hydrocarbons	mg	0.06	0.2	< 0.001	0.2
Non-Fe Metals	mg	0.02	0.08	0.004	0.1
Cyanide	mg	0	0.002	0	0.002
Phenols	µg	9.9	2.4	0	12.3
Phosphates	mg	< 0.001	16.6	< 0.001	16.6
Ammonia & Ammonium		28.7	230.3	0.5	259.6
Non-Halogenated Organics	µg	3700.0	7.2	0.002	3707.2
Halogenated Organics	µg	~0	~0	~0	< 0.001
Chlorides	mg	18615.0	52146.1	126.0	70887.1
Aluminum & Aluminum	mg	7.7	0.7	0.003	8.4
Oil & Grease	mg	192.7	235.7	2.0	430.4
Na+	mg	1336.0	576.7	600.0	2512.7
Sulphates	mg	14903.0	40400.0	0.006	55303.0
Sulphides	mg	4.8	0.003	~0	4.8
Nitrates & Nitrites	mg	160.8	4.1	0.001	164.9
Dissolve OC	mg	241.0	0.1	0	241.1
Phosphorus	mg	0.1	0	0	0.1
Iron	mg	< 0.001	173.6	~0	173.6
Other Metals	mg	4.9	60.8	0.2	65.9
Acids	mg	3.7	33.2	~0	36.9
total (excl. BOD, COD)		46511.6	146094.9	753.9	193360.4
Solid Waste					
Bark/ Wood Waste	kg	0	6.9	0	6.9
Blast Furnace Slag	kg	0.003	0.03	0	0.03
Blast Furnace Dust	kg	0	0.2	0	0.2
Steel Waste	kg	0	0	0	0
Concrete waste	kg	0	0.2	0	0.2
Other Solid Waste	kg	0.2	3.4	0.002	3.6
Summary Indexes					
Air tox index (for ref. only)		0.8	1.7	0.01	2.5
Water tox index (for ref. only)		0	0.03	0	
GWP	kg CO_2	20.1	46.8	3.0	69.9
Acidification Potential (AP)	H+ eq.	2.6	4.0	0.5	7.1
Eutrophication Potential	P eq.	9.6	13.3	0.3	23.2

Summary LCI Data -		Wall #3 - Block / EIFS			
Category	Unit	Extraction	Manufacturing	Transport	Total
Energy					
Electricity	(kWh)	See Material tables for Specific Energy Splits			
Natural Gas	(MJ)				
Coal/Coke	(MJ)				
Diesel/HFO	(MJ)				
Gasoline	(MJ)				
Bio Fuel	(MJ)				
Feed Stock	(MJ)				
Other	(MJ)				
Total	(MJ)	57.5	1323.6	29.6	1410.6
Emissions to Air					
CO_2	kg	20.4	109.9	2.1	132.3
CO	g	23.2	190.9	12.7	226.9
SO_2	g	83.7	235.6	4.2	323.5
N_2O	g	102.5	315.3	23.1	440.9
PM	g	53.8	141.0	0.059	194.9
VOCs	g	5.1	31.4	2.5	38.9
CH_4	g	58.7	101.8	0.6	161.2
Phenols	g	0.03	1.04	< 0.001	1.07
Acid Gases (excl. HCl & HFl)	g	0	0	0	0
Non-CH_4 HC	g	5	16	0	21
Metals	g	0.05	0.1	< 0.001	0.2
HCl	g	0.6	2.1	< 0.001	2.7
HFl	g	0.09	0.4	~0	0.4
Other	g	0	0	0	0
total	g	333.1	1036.0	43.1	1412.2
Water Emissions					
flow	L/unit				
pH					
BOD	mg	206.2	10.6	0.7	217.5
SS	mg	3631.2	44879.7	3.0	48513.9
DS	mg	8.5	2185.7	0.02	2194.2
PAH	µg	0.002	0.002	0.002	0.005
COD	mg	0.4	145760.9	0.006	145761.2
Hydrocarbons	mg	< 0.121	< 0.351	~0	0.463
Non-Fe Metals	mg	0.004	31.0	< 0.001	31.0
Cyanide	mg	0	36.8	0	36.8
Phenols	µg	19.5	11643.1	0	11662.6
Phosphates	mg	~0	128.2	~0	128.2
Ammonia & Ammonium		26.9	833.5	0.09	860.5
Non-Halogenated Organics	µg	657.8	14	< 0.001	672.2
Halogenated Organics	µg	~0	251.0	~0	251.0
Chlorides	mg	18172.0	131462.0	22.4	149656.4
Aluminum & Aluminum	mg	7.7	100.9	< 0.001	108.6
Oil & Grease	mg	179.7	1323.5	0.4	1503.5
Na+	mg	237.5	105.6	106.7	449.8
Sulphates	mg	14892.3	39417.4	0.001	54309.6
Sulphides	mg	4.8	9.0	~0	13.8
Nitrates & Nitrites	mg	160.7	353.2	< 0.001	513.9
Dissolve OC	mg	241.0	681.2	0	922.2
Phosphorus	mg	0.1	0.6	0	0.7
Iron	mg	< 0.001	1595.7	~0	1595.7
Other Metals	mg	3.0	453.3	0.04	456.4
Acids	mg	0.7	257.2	~0	257.9
total (excl. BOD, COD)		38637.2	469035.5	134.0	507806.7
Solid Waste					
Bark/ Wood Waste	kg	0	0	0	0
Blast Furnace Slag	kg	0	1.1	0	1.1
Blast Furnace Dust	kg	0	0.2	0	0.2
Steel Waste	kg	0	0	0	0
Concrete waste	kg	0	0.2	0	0.2
Other Solid Waste	kg	0.12	3.3	< 0.001	3.4
Summary Indexes					
Air tox index (for ref. only)		4.6	8.2	0	12.8
Water tox index (for ref. only)		0	1.2	0	1.2
GWP	kg CO_2	35.6	144.7	5.7	186.1
Acidification Potential (AP)	H+ eq.	4.9	14.3	1.0	20.1
Eutrophication Potential	P eq.	13.4	42.5	2.9	58.7

Summary LCI Data - **Wall #4 - Steel Stud / EIFS**

Category	Unit	Extraction	Manufacturing	Transport	Total
Energy					
Electricity	(kWh)	See Material tables for Specific Energy Splits			
Natural Gas	(MJ)				
Coal/Coke	(MJ)				
Diesel/HFO	(MJ)				
Gasoline	(MJ)				
Bio Fuel	(MJ)				
Feed Stock	(MJ)				
Other	(MJ)				
Total	(MJ)	48.3	758.3	5.3	811.9
Emissions to Air					
CO_2	kg	12.7	48.8	0.4	61.9
CO	g	9.3	337.5	2.0	348.9
SO_2	g	53.2	163.4	1.2	217.7
N_2O	g	52.6	112.1	3.8	168.4
PM	g	29.3	47.7	0.06	77.1
VOCs	g	3.6	47.2	0.4	51.2
CH_4	g	32.8	53.7	0.1	86.7
Phenols	g	0.001	0.5	< 0.001	0.5
Acid Gases (excl. HCl & HFl)	g	0	0.001	0	0.001
Non-CH_4 HC	g	2.4	8.2	0.1	10.7
Metals	g	0.02	0.04	< 0.001	0.06
HCl	g	0.4	1.0	< 0.001	1.4
HFl	g	0.05	0.2	< 0.001	0.2
Other	g	0.2	0	0	0.2
total	g	183.8	771.6	6.7	962.1
Water Emissions					
flow	L/unit				
pH					
BOD	mg	1160.0	24.6	4.0	1188.6
SS	mg	4942.5	23038.8	17.0	27998.4
DS	mg	46.2	867.5	0.09	913.8
PAH	µg	0.01	0.01	0.01	0.03
COD	mg	2.1	55556.0	0.03	55558.1
Hydrocarbons	mg	0.06	0.2	< 0.001	0.2
Non-Fe Metals	mg	0.02	83.1	0.004	83.1
Cyanide	mg	0	98.4	0	98.4
Phenols	µg	9.9	23525.2	0	23535.1
Phosphates	mg	< 0.001	48.8	< 0.001	48.8
Ammonia & Ammonium		28.7	1969.1	0.5	1998.3
Non-Halogenated Organics	µg	3700.0	7.2	0.002	3707.2
Halogenated Organics	µg	~0	672.6	~0	672.6
Chlorides	mg	18615.0	1646.3	126.0	20387.3
Aluminum & Aluminum	mg	7.7	0.7	0.003	8.4
Oil & Grease	mg	192.7	1948.4	2.0	2143.1
Na+	mg	1336.0	576.7	600.0	2512.7
Sulphates	mg	14903.0	703.9	0.006	15606.9
Sulphides	mg	4.8	16.4	~0	21.2
Nitrates & Nitrites	mg	160.8	4.1	0.001	164.9
Dissolve OC	mg	241.0	0.1	0	241.1
Phosphorus	mg	0.1	0	0	0.1
Iron	mg	< 0.001	1190.2	~0	1190.2
Other Metals	mg	4.9	173.6	0.2	178.7
Acids	mg	3.7	98.0	~0	101.7
total (excl. BOD, COD)		46511.6	3503.3	753.9	50768.8
Solid Waste					
Bark/ Wood Waste	kg	0	0	0	0
Blast Furnace Slag	kg	0.003	2.9	0	2.9
Blast Furnace Dust	kg	0	0.4	0	0.4
Steel Waste	kg	0	0	0	0
Concrete waste	kg	0	0.2	0	0.2
Other Solid Waste	kg	0.2	4.5	0.002	4.8
Summary Indexes					
Air tox index (for ref. only)		9.8	5.5	0	15.3
Water tox index (for ref. only)		0	2.4	0	
GWP	kg CO_2	20.9	63.8	2.7	87.5
Acidification Potential (AP)	H+ eq.	2.8	7.5	0.5	10.8
Eutrophication Potential	P eq.	6.9	14.7	0.3	21.9

Appendix D Life Cycle Inventory (LCI) Data for Building Materials

This appendix provides the LCA data for each of the constituent materials used to construct the four wall assemblies. Emissions are reported for the materials in the quantities that are used per unit of wall (1 m. long x 3 m. high).

The following notes apply to the tables:

Notes:
Blank entries represent unreported values.
Totals may not agree due to rounding
Decimal places do not indicate significant digits
Extraction and manufacturing transport emissions are included in manufacturing column, unless otherwise stated.
Transport to construction site from manufacturer or warehouse included in manufacturing, or in construction emission estimate if present, or in delivery emissions if stated.

LCI Data -		Softwood Lumber					Plywood				
Description		38 x 140 softwood (Spruce/Pine/Fir (SPF)) kiln-dried wall assembly, 600 mm o.c. spacing					12mm exterior grade softwood plywood for sheathing				
Functional Unit (s) Mass unit basis Alternative unit(s)		30.7 kg (1m length of 3m high wall) 0.031 mBFM .0019 tonnes nails 0.07315 m^3					27.9 kg (1m length of 3m high wall) 0.046 msf (thousand square feet)				
Category	Unit	Extraction	Manufacturing	Transport (Extraction & Manufacturing)	Construction	Total	Extraction	Manufacturing	Transport (Extraction & Manufacturing)	Construction	Total
Energy											
Electricity	(kWh)	0.6	2.5	0	1.8	4.9	0.5	1.8	0	0.7	2.9
Natural Gas	(MJ)	0	31.7	0	0	31.7	0.5	62.8	0	0	63.3
Coal/Coke	(MJ)	1.5	7.0	0	4.9	13.5	0.2	0.7	0	1.8	2.7
Diesel/HFO	(MJ)	24.3	3.5	8.7	0.2	36.7	19.4	1.7	30.9	0.09	52.1
Gasoline	(MJ)	2.0	3.0	0	0	5.1	1.6	0.4	0	0	2.0
Bio Fuel	(MJ)	0	38.6	0	0	38.6	0	54.9	0	0	54.9
Feed Stock	(MJ)	0	0	0	0	0	0	13.4	0	0	13.4
Other	(MJ)										
Total	(MJ)	27.9	83.8	8.7	5.2	125.6	21.7	133.8	30.9	1.9	188.4
Emissions to Air											
CO_2	kg	2.7	11.3	0.04	2.6	16.6	2.1	10.3	0.2	0.9	13.5
CO	g	18.8	3.6	0.01	1.9	24.3	18.1	3.6	0.04	0.3	22.0
SO_2	g	7.0	21.6	0.07	15.9	44.6	3.1	14.2	0.3	6.2	23.8
N_2O	g	23.0	22.3	0.08	11.2	56.6	18.7	45.9	0.3	3.4	68.2
PM	g	0.9	11.9	0	2.8	15.5	0.1	12.1	0	1.0	13.3
VOCs	g	3.5	2.3	0.1	0.6	6.5	3.8	9.4	0.5	0.1	13.8
CH_4	g	2.7	9.4	0.2	5.0	17.3	1.6	6.8	0.7	1.8	10.8
Phenols	g	0.03	0.001	0	0.001	0.03	0.003	0.5	0	0	0.5
Acid Gases (excl. HCl & HFl)	g	0	0	0	0	0	0	0	0	0	0
Non-CH_4 HC	g	0	0	0	0 .	0	0	0	0	0	0
Metals	g	0.003	0.01	0	0.009	0.02	0	0.001	0	0.003	0.004
HCl	g	0.06	0.2	0	0.2	0.5	0.006	0.03	0	0.07	0.10
HFl	g	0.01	0.04	0	0.03	0.08	< 0.001	0.004	0	0.01	0.02
Other	g	0	0	0	0	0	0	0	0	0	0
total	g	55.9	71.3	0.5	37.6	165.4	45.4	92.4	1.8	13.0	152.6
Category	Unit	Extraction	Manufacturing	Transport (Extraction & Manufacturing)	Construction	Total	Extraction	Manufacturing	Transport (Extraction & Manufacturing)	Construction	Total
Water Emissions											
flow	L/unit										
pH											
BOD	mg		0.7			0.7		11.0			11.0
SS	mg		2035.3			2035.3		409.2			409.2
DS	mg		255.1			255.1		11173.3			11173.3
PAH	µg		0			0		0			0
COD	mg		17064			17064		1875.0			1875.0
Hydrocarbons	mg										
Non-Fe Metals	mg		0.06			0.06		0			0
Cyanide	mg		0.001			0.001		0			0
Phenols	µg		0.001			0.001		0			0
Phosphates	mg		15.0			15.0		1.6			1.6
Ammonia & Ammonium			0.08			0.08		0.2			0.2
Non-Halogenated Organics	µg		0			0		0			0
Halogenated Organics	µg		0			0		0			0
Chlorides	mg		20.2			20.2		50545.4			50545.4
Aluminum & Aluminum	mg		0			0		0			0
Oil & Grease	mg		6.0			6.0		195.9			195.9
Na+	mg										
Sulphates	mg		11.2			11.2		39721			39721
Sulphides	mg		0			0		0			0
Nitrates & Nitrites	mg		0			0		0			0
Dissolve OC	mg		0			0		0			0
Phosphorus	mg		0			0		0			0
Iron	mg		157.5			157.5		16.1			16.1
Other Metals	mg		52.9			52.9		6.5			6.5
Acids	mg		30.1			30.1		3.0			3.0
total (excl. BOD, COD)			36744			36744		105848			105848
							0	0			
Solid Waste							0	0			
Bark/ Wood Waste	kg		5.4		5.7	11.0	0	1.5		1.7	3.2
Blast Furnace Slag	kg		0.03		0	0.03	0	0		0	0
Blast Furnace Dust	kg		0.007		0	0.007	0	0		0	0
Steel Waste	kg										
Concrete waste	kg										
Other Solid Waste	kg		0.6		0.2	0.7	0	0.08		0	
Summary Indexes											
Air tox index (for ref. only)		0.7	0.7	0.002	0.5	2.0	-0.02	0.5	0.009	0.2	0.7
Water tox Index (for ref. only)						0	0	0	0	0	0
GWP	kg CO_2	4.5	14.1	0.08	4.0	22.7	3.5	14.3	0.3	1.4	19.4
Acidification Potential (AP)		0.7	1.2	0.004	0.7	2.6	0.5	1.5	0.01	0.3	2.2
Eutrophication Potential		3.0	3.3	0.01	.1.5	7.7	2.4	6.0	0.04	0.4	8.9
		(Athena, 2000a)					(Athena, 2000a)				

LCI Data -		Oriented Strand Board (OSB)					Cement Plaster					
Description		12mm OSB sheathing					Portland cement plaster (1:3 cement:sand) wall area 3 m^2 thickness 100 mm					
Functional Unit (s) Mass unit basis Alternative unit(s)		(1m length of 3m high wall) 0.046 msf (thousand square feet)					594.9 kg (per 1m length of 3m high wall)					
Category	Unit	Extraction	Manufacturing	Transport (Extraction & Manufacturing)	Construction	Total	Cement & Aggregate Extraction	Agg. Manufacture	Transport	Cement prod	Delivery	Total
Energy												
Electricity	(kWh)	0.9	6.9	0	0.7	8.5						
Natural Gas	(MJ)	0	43.1	0	0	43.1						
Coal/Coke	(MJ)	2.3	18.7	0	1.8	22.8						
Diesel/HFO	(MJ)	37.2	7.4	11.6	0.09	56.3						
Gasoline	(MJ)	3.1	0.4	0	0	3.5						
Bio Fuel	(MJ)	0	128.1	0	0	128.1						
Feed Stock	(MJ)	0	25.8	0	0	25.8						
Other	(MJ)											
Total	(MJ)	42.7	223.4	11.6	1.9	279.6	18.6	14.6	25.8	644.2	19.0	722.1
Emissions to Air												
CO_2	kg	4.1	27.6	0.06	0.9	32.7	1.3	0	1.8	116.5	1.3	121.0
CO	g	28.6	5.5	0.01	0.3	34.5	8.2	0	9.0	39.7	7.4	64.3
SO_2	g	7.5	56.0	0.10	6.2	69.8	1.9	0	4.2	15.1	2.8	24.0
N_2O	g	35.2	57.8	0.1	3.4	96.4	15.0	0	18.3	240.8	13.9	288.0
PM	g	1.3	30.0	0	1.0	32.4	121.9	22.5	0	49.3	0	193.7
VOCs	g	5.4	10.1	0.2	0.1	15.9	0.6	0	2.1	0.8	2.3	5.7
CH_4	g	4.1	23.1	0.2	1.8	29.4	0.4	0	7.3	0.4	0.5	8.6
Phenols	g	0.003	1.3	0	0	1.3						
Acid Gases (excl. HCl & HFl)	g	0	0	0	0	0						
Non-CH_4 HC	g	0	0	0	0	0						
Metals	g	0.004	0.03	0	0.003	0.04						
HCl	g	0.08	0.7	0	0.07	0.8						
HFl	g	0.01	0.1	0	0.01	0.1						
Other	g	0	0	0	0	0						
total	g	82.3	184.7	0.7	13.0	280.6	148.0	22.5	40.9	346.1	26.8	584.3
Category	Unit	Extraction	Manufacturing	Transport (Extraction & Manufacturing)	Construction	Total	Cement & Aggregate Extraction	Agg. Manufacture	Transport	Cement prod	Transport	Total
Water Emissions												
flow	L/unit						583.2					583.2
pH							2.4					2.4
BOD	mg		1.9			1.9						
SS	mg		5643.5			5643.5	33475			2828		36303
DS	mg		708.2			708.2						
PAH	µg		0			0						
COD	mg		47388			47388						
Hydrocarbons	mg											
Non-Fe Metals	mg		0			0						
Cyanide	mg		0			0	0					0
Phenols	µg		0			0	2.9			0		2.9
Phosphates	mg		41.7			41.7						
Ammonia & Ammonium			0.2			0.2	265.2					265.2
Non-Halogenated Organics	µg		0			0						
Halogenated Organics	µg		0			0						
Chlorides	mg		56.1			56.1	180763			5723.6		186486
Aluminum & Aluminum	mg		0			0	76.8			5.8		82.6
Oil & Grease	mg		15.1			15.1	1769.2			236.2		2005.4
Na+	mg											
Sulphates	mg		31.2			31.2	148899			6665.4		155565
Sulphides	mg		0			0	47.8			0		47.8
Nitrates & Nitrites	mg		0			0	1606.9			40.6		1647.5
Dissolve OC	mg		0			0	2409.7			0		2409.7
Phosphorus	mg		0			0	1.4			0		1.4
Iron	mg		436.5			436.5						
Other Metals	mg		146.9			146.9	26.1			0		26.1
Acids	mg		83.5			83.5						
total (excl. BOD, COD)			102025			102025	369346			15500		384846
Solid Waste								b1				
Bark/ Wood Waste	kg	0	7.7		1.7							
Blast Furnace Slag	kg	0	0		0							
Blast Furnace Dust	kg	0	0		0					1.6		1.6
Steel Waste	kg											
Concrete waste	kg									1.8		1.8
Other Solid Waste	kg	0	1.5		0					3.9		3.9
Summary Indexes												
Air tox index (for ref. only)		0.3	1.9	0.004	0.2	2.3	0.6			5.0		5.7
Water tox Index (for ref. only)		0	0	0	0	0	0			0.3		0.3
GWP	kg CO_2	6.9	34.7	0.1	1.4	43.1	2.3	0	4.1	131.8	2.3	140.4
Acidification Potential (AP)		1.0	3.0	0.005	0.3	4.3	0.4	0	0.5	5.8	0.4	7.1
Eutrophication Potential		4.6	8.5	0.01	0.4	13.5	2.2	0	2.4	31.3	1.8	37.7
		(Athena, 2000a)					(Venta, 1998)					

LCI Data -		Steel Studs					Welded Wire Mesh			
Description		Steel studs, 39 x 152, 20 Ga, 600 mm o.c.,					Mesh for plaster reinforcement in strawbale assembly			
Functional Unit (s) Mass unit basis Alternative unit(s)		emissions per 13.4 kg (per 10m length of 3m high wall) 0.1					5.2 KG 0.0052 tonne *(per 1m length of 3m high wall)*			
Category	Unit	Extraction	Manufacturing	Constructi	Delivery	Total	Extraction	Manufacturing	Delivery	Total
Energy										
Electricity	(kWh)	2.7	8.1	1.3		12.1	1.3	4.3		5.6
Natural Gas	(MJ)	9.3	22.3	0		31.6	4.4	54.7		59.1
Coal/Coke	(MJ)	7.3	284.7	3.5		295.5	3.5	135.7		139.1
Diesel/HFO	(MJ)	13.7	4.4	0.2	0.6	18.2	6.8	4.8	0.2	11.7
Gasoline	(MJ)	0.04	0.04	0		0.08	0.02	0.02		0.04
Bio Fuel	(MJ)	0	0	0		0	0	0		0
Feed Stock	(MJ)	0	0.001	0		0.001	0	0		0
Other	(MJ)	0	0	0			0	0		0
Total	(MJ)	33.0	319.6	4.9	0.6	357.5	14.7	195.2	0.2	209.9
Emissions to Air										
CO_2	kg	6.2	34.3	1.6	0.04	42.2	3.0	18.0	0.02	21.0
CO	g	3.9	325.1	0.08	0.3	329.0	2.0	153.7	0.1	155.7
SO_2	g	29.2	150.1	11.5	0.06	190.8	13.8	71.3	0.03	85.1
N_2O	g	20.4	67.9	6.2	0.5	94.5	10.0	34.7	0.2	44.7
PM	g	4.5	31.7	2.0	0	38.2	2.1	15.9	0	18.1
VOCs	g	3.3	45.7	0.3	0.05	49.3	1.6	21.2	0.02	22.8
CH_4	g	9.2	45.7	3.4	0.01	58.2	4.4	25.3	0.005	29.7
Phenols	g	0.001	0.001	0.001		0.003	< 0.001	< 0.001		< 0.001
Acid Gases (excl. HCl & HFl)	g	0	0	0		0	0	0		0
Non-CH_4 HC	g	0	0	0		0	0	0		0
Metals	g	0.01	0.04	0.006		0.06	0.006	0.02		0.02
HCl	g	0.3	0.8	0.1		1.2	0.1	0.4		0.5
HFl	g	0.05	0.1	0.02		0.2	0.02	0.07		0.09
Other	g	0	0	0		0	0	0		0
total	g	70.8	667.2	23.4		761.4	34.1	322.7	0.4	356.8
Category	Unit	Extraction	Man including Transport	Constructi		Total	Extraction	Manufacturing		Total
Water Emissions										
flow	L/unit									
pH										
BOD	mg		2.3			2.3		1.2		1.2
SS	mg		22698			22698		10971		10971
DS	mg		830.4			830.4		441.3		441.3
PAH	µg		0			0		0		0
COD	mg		55556			55556		29522		29522
Hydrocarbons	mg		0			0		0		0
Non-Fe Metals	mg		83.1			83.1		38.9		38.9
Cyanide	mg		98.4			98.4		46.7		46.7
Phenols	µg		23523			23523		10788		10788
Phosphates	mg		48.8			48.8		25.9		25.9
Ammonia & Ammonium			1739.1			1739.1		801.3		801.3
Non-Halogenated Organics	µg		0			0		0		0
Halogenated Organics	µg		672.6			672.6		311.1		311.1
Chlorides	mg		65.6			65.6		35.0		35.0
Aluminum & Aluminum	mg		0			0		0		0
Oil & Grease	mg		1914.6			1914.6		911.7		911.7
Na+	mg		0			0		0		
Sulphates	mg		36.6			36.6		19.4		19.4
Sulphides	mg		16.4			16.4		7.8		7.8
Nitrates & Nitrites	mg		0.001			0.001		0		0
Dissolve OC	mg		0			0		0		0
Phosphorus	mg		0			0		0		0
Iron	mg		1190.2			1190.2		598.6		598.6
Other Metals	mg		172.2			172.2		91.5		91.5
Acids	mg		98.0			98.0		52.1		52.1
total (excl. BOD, COD)			0			0		95349		95349
Solid Waste										
Bark/ Wood Waste	kg							0		0
Blast Furnace Slag	kg		2.9	0		2.9		1.4		1.4
Blast Furnace Dust	kg		0.2	0		0.2		0.1		0.1
Steel Waste	kg		0	0.3		0.3		0		
Concrete waste	kg		0			0		0		
Other Solid Waste	kg		1.8	1.9		3.7		1.0		1.0
Summary Indexes										
Air tox index (for ref. only)		9.7	5.0	3.8		18.6	88.8	457.0		545.7
Water tox Index (for ref. only)		0	2.4	0		2.4	0	207.5		207.5
GWP	kg CO_2	8.9	45.4	2.7	0.08	56.9	4.2	24.0	0.03	28.2
Acidification Potential (AP)		1.4	6.2	0.5	0.01	8.0	0.7	3.0	0.005	3.6
Eutrophication Potential		2.7	10.7	0.8	0.07	14.2		5.5	0.03	5.5
		(Athena, 2000a)					(Athena, 2000a)			

LCI Data -		Concrete blocks				Drywall			Straw				
Description		150 cm ungrouted conrete masonry blocks and mortar				12mm Gypsum Drywall			Baled Wheat Straw, Ontario, small - medium size farm				
		per	3		m^2								
Functional Unit (s) **Mass unit basis** **Alternative unit(s)**		510 (per 1m length of 3m high wall)			kg	28.8 kg (per 1m length of 3m high wall)			165.6 kg (per 1m length of 3m high wall)				
Category	Unit	extraction	man	Delivery	Total	Extraction & Manufacturing	Delivery	Total	Seeding	Harvesting	Baling	Delivery	Total
Energy													
Electricity	(kWh)	3.2	18.3		21.5	Energy Split not Available							
Natural Gas	(MJ)	0	283.3		283.3	54.6		54.6					
Coal/Coke	(MJ)	8.6	200.9		209.5	52.8		52.8					
Diesel/HFO	(MJ)	29.0	88.1	24.1	117.2	16.9	1.4	18.2	28.5	57.1	28.5	7.8	121.9
Gasoline	(MJ)	0	0		0	2.7		2.7					
Bio Fuel	(MJ)	0	0		0								
Feed Stock	(MJ)	0	14.3		14.3								
Other	(MJ)												
Total	(MJ)	37.6	604.9	24.1	645.7	127.0	1.4	128.3	28.5	57.1	28.5	7.8	121.9
Emissions to Air													
CO_2	kg	5.9	83.9	1.7	89.8	1.2	0.10	1.3	2.0	4.0	2.0	0.6	8.6
CO	g	13.2	57.8	10.7	71.0	7.5	0.6	8.1	12.6	25.3	12.6	3.5	54.0
SO_2	g	26.9	174.2	2.5	201.2	1.7	0.1	1.9	2.9	5.8	2.9	0.8	12.4
N_2O	g	36.6	250.2	19.4	286.8	13.6	1.1	14.7	23.0	46.0	23.0	6.3	98.4
PM	g	28.3	122.1	0	150.4								0
VOCs	g	3.6	12.8	2.1	16.4	1.5	0.1	1.6	2.5	5.0	2.5	0.7	10.6
CH_4	g	9.8	81.6	0.5	91.4	0.4	0.03	0.4	0.6	1.3	0.6	0.2	2.7
Phenols	g	0.03	0.03		0.06								
Acid Gases (excl. HCl & HFl)	g	0	0										
Non-CH_4 HC	g	0	0										
Metals	g	0.03	0.09		0.1								
HCl	g	0.3	1.8		2.1								
HFl	g	0.06	0.3		0.4								
Other	g	0	0		0								
total	g	118.8	701.0	35.2	819.8	24.7	2.0	26.6	41.7	83.4	41.7	11.4	178.1
Category	Unit	extraction	man		Total	Total	Delivery	Total	Seeding	Harvesting	Baling	Transport	Total
Water Emissions													
flow	L/unit					No emission data available.			Not directly attributable to current straw production				
pH													
BOD	mg		5.2										
SS	mg		36114										
DS	mg		1869.0										
PAH	µg		0										
COD	mg		125031										
Hydrocarbons	mg												
Non-Fe Metals	mg		0										
Cyanide	mg		0.03										
Phenols	µg		2861.1										
Phosphates	mg		109.9										
Ammonia & Ammonium			143.7										
Non-Halogenated Organics	µg		0										
Halogenated Organics	µg		0										
Chlorides	mg		130671										
Aluminum & Aluminum	mg		100.1										
Oil & Grease	mg		583.4										
Na+	mg												
Sulphates	mg		38736										
Sulphides	mg		2.9										
Nitrates & Nitrites	mg		349.1										
Dissolve OC	mg		681.0										
Phosphorus	mg		0.6										
Iron	mg		1151.6										
Other Metals	mg		387.6										
Acids	mg		220.5										
total (excl. BOD, COD)			467138										
Solid Waste						No emission data available.							
Bark/ Wood Waste	kg												
Blast Furnace Slag	kg												
Blast Furnace Dust	kg												
Steel Waste	kg												
Concrete waste	kg												
Other Solid Waste	kg		1.8		1.8								
		(Athena, 1000)				(CMHC, 1991; Demkin, 1996)							
Summary Indexes													
Air tox index (for ref. only)		0.9	5.8		6.7								
Water tox Index (for ref. only)		0	0.3		0.3								
GWP	kg CO_2	9.6	111.9	3.0	121.6	2.1	0.2	2.3	3.6	7.1	3.6	1.0	15.2
Acidification Potential (AP)		1.7	11.0	0.5	12.6	0.4	0.03	0.4	0	1.2	0.6	0.2	2.6
Eutrophication Potential		4.8	35.2	2.5	37.3				3.0	6.0	3.0	0.8	12.8
		(Athena, 2000a)				(CMHC, 1991)			(Ankenman, personal communication, July 21, 2000)				

LCI Data -		**Expanded Polystyrene Insulation (EPS)**				**Mineral Wool**			
Description		Polystyrene insulation material, pentane expanded				Slag and rock mineral fibre insulation from BEES			
Functional Unit (s)		thickness:	50 mm			0.67			
Mass unit basis			2.4 kg			4.05 kg			
Alternative unit(s)			(per 1m length of 3m high wall)			(per 1m length of 3m high wall)			
Category	Unit	Fuel Production and Use	Manufacturing	Transport	Total	Extraction	Manufacturing	Transport	Total
Energy									
Electricity	(kWh)								
Natural Gas	(MJ)		56.4		56.4				
Coal/Coke	(MJ)		5.9		5.9				
Diesel/HFO	(MJ)		25.9	0.8	26.7				
Gasoline	(MJ)			0.1	0.1				
Bio Fuel	(MJ)				0				
Feed Stock	(MJ)		114.7		114.7				
Other	(MJ)		-3.1		-3.1				
Total	(MJ)		199.8	1.0	200.8	9.4	47.5	0.4	57.4
Emissions to Air									
CO_2	kg	5.9	0.01	0.06	0.006	0.3	1.7	0.03	2.0
CO	g	3.4	0.08	0.3	0.004	0.3	0.9	0.1	1.4
SO_2	g	22.6	0.2	0.6	0.02	0.8	9.9	0.03	10.7
N_2O	g	27.4	0.5	0.5	0.03	1.4	6.0	0.3	7.7
PM	g	4.2	0.08	0.03	0.004	6.2	11.0	0.04	17.2
VOCs	g	0	0	0	0				0
CH_4	g	22.3	0.8	0	0.02	0.6	6.8	0.02	7.5
Phenols	g	0	0.5	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Acid Gases (excl. HCl & HFl)	g	0	0.001	0	~0				0
Non-CH_4 HC	g	2.4	8.2	0.1	0.01				0
Metals	g	0.010	0.002	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
HCl	g	0.08	0.002	0	< 0.001	0.01	0.2	< 0.001	0.3
HFl	g	0.006	0.001	0	~0	0.001	0.03	< 0.001	0.03
Other	g	0.2	0	0	< 0.001				
total	g	82.5	10.3	1.6	0.09	9.4	34.9	0.5	44.7
Category	Unit	Fuel Production and Use	Manufacturing	Transport	Total	Extraction	Manufacturing	Transport	Total
Water Emissions									
flow	L/unit								
pH									
BOD	mg	0.010	0.3		< 0.001	1160.0	22.0	4.0	1186.0
SS	mg	0.07	1.7		0.002	1595.0	56.0	17.0	1668.0
DS	mg	0.2	0.1		< 0.001	46.0	37.0	0.09	83.1
PAH	µg					0.01	0.01	0.01	0.03
COD	mg	0.01	0.01		0.02	2.1	0.2	0.03	2.3
Hydrocarbons	mg	0.06	0.2		0.2	0.005	0.005	< 0.001	0.01
Non-Fe Metals	mg	0	0.01		0.01	0.02	< 0.001	0.004	0.03
Cyanide	mg	0	0.001		0.001				
Phenols	µg	9.6	2.4		12.0				
Phosphates	mg	0	0.01		0.01	< 0.001	0	< 0.001	< 0.001
Ammonia & Ammonium		0.002	0.03		0.03	2.2	230.0	0.5	232.7
Non-Halogenated Organics	µg	0	7.2		7.2	3700.0	0	0.002	3700.0
Halogenated Organics	µg	0	0		0	~0	~0	~0	< 0.001
Chlorides	mg	0	8.2		8.2	538.7	1000.0	126.0	1664.7
Aluminum & Aluminum	mg	0	0.1		0.1	0.02	0.006	0.003	0.03
Oil & Grease	mg	0	0.1		0.1	15.8	10.0	2.0	27.8
Na+	mg	0	1.7		1.7	1336.0	575.0	600.0	2511.0
Sulphates	mg	0	0.6		0.6	13.1	0.2	0.006	13.3
Sulphides	mg	0	0.002		0.002	~0	< 0.001	~0	< 0.001
Nitrates & Nitrites	mg	0	0.02		0.02	0.09	0	0.001	0.09
Dissolve OC	mg	0	0.1		0.1	0	0	0	0
Phosphorus	mg					0	0	0	0
Iron	mg	0	0.001		0.001	< 0.001	0.002	~0	0.002
Other Metals	mg	0.001	0.7		0.7	2.3	0.7	0.2	3.2
Acids	mg	0.002	0.09		0.09	3.7	0	~0	3.7
total (excl. BOD, COD)		0.02	0.03		31.1	9577.0	1953.3	753.9	12284.2
Solid Waste									
Bark/ Wood Waste	kg	0	0		0				
Blast Furnace Slag	kg	0.003	0.001						
Blast Furnace Dust	kg	0	0		0.09				
Steel Waste	kg	0	0		0				
Concrete waste	kg	0	0		0				
Other Solid Waste	kg	0.05	0.009		0.06	0.2	2.3	0.002	
Summary Indexes									
Air tox index (for ref. only)									
Water tox Index (for ref. only)									
GWP	kg CO_2	11.0		0.09	0.01	0.4	3.1	0.05	3.6
Acidification Potential (AP)		1.3		0.03	0.001	0	0.4	0.007	0.5
Eutrophication Potential		3.6		0.06	0.004	0.2	0.9	0.04	1.1
		(Boustead 1999a)				(Ecobalance, 1999)			

Appendix E Checklists for Materials & Assemblies

The tables that follow in this appendix and the next two, provide the checklists themselves, and comments on the checklists used in the analysis of the four wall assemblies for materials (Appendix F) and the four wall assemblies (Appendix F) respectively.

The entire set of checklists for both the materials and wall assemblies are shown in this appendix. The checklists were adapted from Graedel and Allenby (1996; 1998) to fit the principles outlined in Section 3.3 after Vanderburg (2000) and tailored to fit the requirements of building materials and assemblies.

Figure A-1 shows how the results are displayed.

While the material matrix (Level 1) generally applies to materials only, the assembly matrix (Level 2) is also used for the materials to capture the context in which the material is used. For the wall assemblies, only the assembly matrix is used.

The rationale that pertains to the numerical values chosen for each matrix element is provided where appropriate.

The purpose of the sustainability matrix is to highlight potential concerns or "hot spots" associated with a given material or design. As such, the tables that follow in Appendix F and Appendix G were generated based upon the following criteria:

Comments from the checklists that are not shown in the tables are as follows:

- questions and resulting answers that were not applicable (N/A), and
- questions whose answer is obvious and needs no comment.

Comments are shown for:

- questions whose answer is true (✓), but require comments or clarifications,
- questions whose answer is false (✗),
- questions that require further investigation or where the answer is unknown (**?**), and
- questions which were not answered.

In this way, only the potential concerns are shown for each material and wall assembly.

E1 Checklists for Materials

Question #	**Pre-Production: ecological concern**
1	The extraction/reuse/recycling of the material causes little or no ecological concerns (4).
2	The location where preproduction occurs is not ecologically sensistive.
3	If virgin plant/animal materials are used, are they from certified sustainable sources?
4	Biota/biodiversity, if affected by raw material extraction or production, is restored to sustainable and local (natural) conditions.
5	The raw material does not require the use of pesticides, herbicides and chemical fertilizers.?
6	The material does not incorporate genetically modified or non-local invasive/problematic species.
7	The preproduction or material extraction does not significantly reduce or disrupt ecosystem services sources or sinks.
8	Preproduction or raw material extraction does not significantly alter the climate of the local environment.
9	The preproduction does not involve the use of toxic materials that could potentially be released.
10	Infrastructure created/maintained for the preproduction, minimises the impact on biota.
11	Preproduction does not generate other material streams that have potential impacts on the biota in this, or any life-cycle stage.
12	General comments for score:

Question #	**Pre-Production: energy**
1	Energy use is negligible for the provision of raw materials for production (i.e. no virgin materials whose extraction is energy intensive)
2	Energy used is from renewable sources.
3	Energy used is appropriate for function.
4	The distance of incoming materials and components is minimised.
5	Energy use is minimised by using less energy intensive raw materials and/or efficient processes (e.g. no-till, etc. or wastes, recycled materials).
6	Energy required to recycle/process waste materials is minimal.
7	No suitable materials/components/processes exist that are less energy intensive/environmentally preferable.
8	The material pre-production does not produce waste materials that are energy intensive to recycle/refurbish/reuse.
9	Material extraction does not require energy intensive cleanup/remediation to restore the site to ecological productivity.
10	Energy usage for extraction:

Question #	**Pre-Production: solid**
1	The extraction or production of material from recycled streams does not produce significant amounts of solid residues.
2	The extraction of raw material or production of material from recycled streams does not generate toxic solid residues.
3	The solid residues are minimised.
4	The solid residues are closed loop.
5	Metals from virgin ores are not used, creating substantial waste rock residues that could be avoided by the use of recycled material. (0 if false)
6	The transportation to the manufacturer does not generate significant solid residues (i.e. from packaging, material losses, solid residues from transp. equipment).
7	No packaging is used or supplier takes back all packaging material or incoming packaging is totally reused/recycled e.g. pallets, raw material containers/drums
8	Incoming packaging volume and weight, at and among all levels (primary, secondary and tertiary), is minimised.
9	Materials diversity is minimised in incoming packaging < 3 materials.

Question #	**Pre-Production: liquid**
1	The extraction of raw material or production of material from recycled streams does not produce significant amounts of liquid residues (including transp.).
2	The extraction of raw material or production of material from recycled streams does not generate toxic liquid residues (including transp.).
3	The liquid residues are minimised.
4	The liquid residues are closed loop (reusable and reused for other process)
5	No suitable materials/components exist that are environmentally preferable.
6	Metals from virgin ores that cause substantial acid mine drainage are not used where suitable material is available from recycling streams. (e.g. Cu, Fe, Nickel, Pb, Zn cause acid mine drainage).
7	Packaging does not contain toxic or hazardous substances that might leak from it if improper disposal occurs.
8	The use of incoming components that require cleaning that involves a large amount of water or that generates liquid residues needing special disposal methods is avoided. (e.g. oils on metals)
9	Refillable/reusable containers are used for incoming liquid materials where appropriate.

Question #	**Pre-Production: air**
1	The extraction of raw material or production of material from recycled streams does not produce significant amounts of residues released to the air.
2	The extraction of raw material or production of material from recycled streams: ☐ - does not generate toxic emissions,
3	The extraction of raw material or production of material from recycled streams - does not generate smog-producing gases .
4	The extraction of raw material or production of material from recycled streams - does not generate greenhouse gases (e.g. not virgin Al, Cu, Fe, Pb, Ni, Zn, paper and paper products, and concrete)
5	The residues released to the air have been minimised (e.g. process redesign, etc.)
6	The airborne/gaseous residues are closed loop (reusable and reused for other process)
7	No suitable materials/components exist that are environmentally preferable.

Question #	**Manufacturing: ecological concern**
1	The product does not contain toxic substances not essential to product function (The use of toxic material is avoided or minimised).
2	Toxic substances, if needed, are supported by a suitable collection/reclamation system (non-dissipative). (closed loop)
3	The product manufacture minimises the use of dissipative processes/materials.
4	The manufacturing process avoids the use of materials that are in restricted supply.
5	The use of radioactive material avoided.
6	The use of non-renewable material is avoided.
7	The chemical treatment of materials has been minimised.
8	Ozone depleting substances are not used in the manufacturing process, whether contained in the product or not.
9	The ratio of incoming material : usable product is high.
10	The activity of the manufacturing plant does not significantly stress the local ecosystem.

Question #	**Manufacturing: energy**
1	Energy use for product manufacture is small
2	The form of energy used is appropriate to the manufacturing process.
3	Energy is from renewable sources (all above: 4)
4	The manufacturing process use co-generation, heat exchangers and or other techniques to utilise otherwise wasted energy.
5	Energy use is minimised by using less energy intensive materials and/or efficient processes.
6	The manufacturing facility is powered down when not in use.

Question #	**Manufacturing: solid emissions**
1	The production of the material or sub-component does not generate significant amounts of solid residues.
2	The production of the material or sub-component does not generate significant amounts of toxic residues.
3	Suitable materials/components that are environmentally preferable do not exist.
4	Residues generated are minimised and reuse/recycling programs are in use (closed loop).
5	Open loop: - The resale of all solid residues as inputs to other processes/products has been investigated and implemented
6	Open loop: - Solid manufacturing residues that do not have resale value are minimised and recycled.
7	No packaging is used or supplier takes back all packaging material or incoming packaging is totally reused/recycled e.g. pallets, raw material containers/drums
8	Incoming packaging volume and weight, is minimised.
9	The transportation to the manufacturer does not generate significant solid residues (i.e. from packaging, material losses, solid residues from transp. equipment)
10	Materials diversity is minimised in incoming packaging < 3 materials.

Question #	**Manufacturing: liquid emissions**
1	The production of the material or sub-component does not generate significant amounts of liquid residues.
2	The production of the material or sub-component does not generate significant amounts of liquid toxic residues.
3	Suitable materials/components that are environmentally preferable do not exist.
4	Residues generated are minimised and reuse/recycling programs are in use (closed loop).
5	Open loop: - The resale of all liquid residues as inputs to other processes/products has been investigated and implemented.
6	Open loop: - Liquid manufacturing residues that do not have resale value are minimised and recycled.
7	No packaging is used or supplier takes back all packaging material or incoming packaging is totally reused/recycled e.g. pallets, raw material containers/drums
8	The transportation to the manufacturer does not generate significant liquid residues (i.e. material losses in liquid handling containers)
9	If solvents and oils are used in the manufacture of this product, their use minimised and preferable alternatives have been investigated and implemented.
10	The manufacturing processes have been designed for the maximum recycled liquid process chemicals rather than virgin materials?
11	If liquid discharges contain biological nutrients, have they been minimised or are they being used as input to another process?

Question #	**Manufacturing: air emissions**
1	The production of the material or sub-component does not generate significant amounts of gaseous residues.□ GWP in CO2 eq./Acid Rain in kgSO2 eq./Smog kgC2H6 eq. /Eutr. kg NO3- eq.
2	The production of the material or sub-component does not generate or use toxic gaseous material.
3	Emissions to the air are minimised.
4	No smog producing materials are used in the manufacturing process.
5	No Ozone depleting gases (CFCs) or global warming gases (HCFCs, CH4, CO2) are directly used or released during the manufacture (include energy only if emissions generated on-site).
6	The resale of all gaseous residues as inputs to other processes/products has been investigated and implemented.
7	Internal recycling/reuse of gaseous material occurs.
8	Suitable materials/components for this product that are environmentally preferable do not exist.
9	No emissions to the air affect liveability of locality (Odour, particulates)

Question #	**Transportation / Packaging: ecological concern**
1	The packaging used for the materials as used in the building assembly are: minimised (without adversely affecting product)
2	The packaging used for the materials as used in the building assembly are non-toxic
3	The packaging used for the materials as used in the building assembly are reusable and reused
4	The packaging used for the materials as used in the building assembly are recyclable and recycled

Question #	**Transportation / Packaging: energy**
1	Waste streams from packaging that are energy intensive to recycle are minimised
2	Packaging and transportation is not energy intensive
3	Packaging and transportation energy is minimised (specify how)
4	Emissions due to energy usage are minimised
5	Energy is from renewable sources
6	Energy used for Transport / Packaging

Question #	**Transportation / Packaging: solid**
1	No packaging is used for the delivery of the materials for the building system.
2	Packaging is taken back by the manufacturer and totally reused/recycled.
3	Packaging from materials is completely reused or recycled.
4	Materials that require packaging are minimised (i.e. use bulk or local materials).

Question #	**Transportation / Packaging: liquid**
1	No liquid wastes are generated from the packaging, transportation or unpacking of the material to the construction site (no toxic, no potential leaking).
2	Packaging for liquids are reused or designed for minimal product loss.
3	The use of materials that generate significant or toxic liquid residues from the packaging, transportation, unpacking, in the context of the building assembly have been minimised.
4	No heavy metal based inks, etc. that would leach out upon eventual disposal.

Question #	**Transportation / Packaging: air**
1	Few emissions to the atmosphere result from the packaging, transportation or unpacking of the material to the construction site.
2	Packages are reused or designed for minimal product loss to the air.
3	The use of materials that generate significant or toxic emissions to the air from the packaging, transportation, unpacking, in the context of the building assembly have been minimised.
4	Packaging does not contain substances that are dissipative to the air upon eventual disposal.
5	Containers are reused to minimise product loss,.

Question #	**Use / maintenance**
	This is covered in "assembly" section since it applies to the context of the material

Question #	**End - Use**
	End use treated in context of assembly

E2 Checklists for Assembly

Question #	**Material Production: Extraction -> Production,: materials choice**
1	4: No virgin or non-renewable material is used in the materials for the building assembly and consumables used are minimised and/or of the lowest possible environmental burden.
2	3: Mostly reused, recycled or renewable material is used and the use of virgin material is minimised (through design).
3	2,1: Some renewable and/or recycled material, but largely non-renewable/virgin material.
4	0: No information is available regarding the content(s), or scarce or virgin materials are used where suitable alternatives exist, and their use is not minimised.
5	Does the building system use the most environmentally preferable materials?
6	Is the building system designed to minimise the use of materials in restricted supply?
7	The building system does not involve the use of toxic substances during material production.

Question #	**Material Production: Extraction -> Production,: energy**
1	4: Negligible amount of energy is required to produce all of the materials for the building assembly and waste streams are not energy intensive to recycle.
2	3: *Moderate amount of energy are required to produce the materials for the assembly*, but their use is minimised and energy is derived from renewable sources, and/or resulting emissions/ecological burden is low.
3	2: The system is designed to minimise the use of energy intensive materials (virgin or otherwise) (i.e. by minimising amount of mat'l or using waste streams.
4	0,1: The materials for the building assembly use energy intensive materials and suitable alternatives exist. (e.g. mat'ls from virgin ores such as Cu, Al, Steel, virgin petroleum, concrete are used and their use is not minimised).
5	Total energy for material production.

Question #	**Material Production: Extraction -> Production,: solid**
1	4: Few solid residues are generated during the manufacture (raw material extraction or recycling, production) of the materials used in the building assembly.
2	3: Building system minimise the use of materials whose production: generates toxic residues, or generates significant amounts of solid waste (e.g. metals from virgin ores (waste rock))
3	Building system does not use metals from virgin ores that create significant waste rock residues that could be avoided by the use of recycled material.
4	For a score of "0": significant amounts or toxic solid residues result from the production of the materials for the building assembly or Building system uses large quantities of metals from virgin ores that create significant waste rock residues that could be minimisd by using recycled material.

Question #	**Material Production: Extraction -> Production,: liquid**
1	4: few liquid residues result from the manufacture of the materials used in the context of the building assembly.
2	3,2. The use of materials that generate significant or toxic liquid residues during extraction/processing/manufacture, in the context of the building assembly have been minimised.
3	0,1,2. Significant or toxic liquid residues result from the manufacture of the constituent materials for the required building assembly and suitable materials that do not are available from waste streams (recycling/reuse). (i.e. metals from virgin ores that require energy intensive extraction)

Question #	**Material Production: Extraction -> Production,: air**
1	Few airborne residues are produced during resource extraction and/or production of materials by recycling (4)
2	Airborne residues are minimised. (Residues cannot be further minimised through product redesign or process redesign)
3	Airborne residues are closed loop.
4	No suitable materials/components exist that are environmentally preferable.
5	The materials used do not cause substantial emissions of toxic, smog-producing or greenhouse gases into the environment, and suitable alternatives that do not are available (Al, Cu, Fe, Pb, Ni, Zn, paper products, and concrete) (0)
6	The product is designed to minimise the use of materials whose extraction or purification involves the generation of gaseous (toxic or large quantities of) residues (Al, Cu, Fe, Pb, Ni, Zn)

Question #	**Assembly Construction: materials choice**
1	The construction of the wall assembly poses few health/ecological threats during construction.
2	Emissions as a result of construction have minimal ecological impact and do not pose a threat to worker health.

Question #	**Assembly Construction: energy**
1	Net worker transportation is minimised (e.g. local labour, ride sharing)
2	Energy used for construction is:□ □ - minimised,
3	Energy used for construction is□ □ - appropriate,
4	Energy used for construction is□ □ - from renewable resources.

Question #	**Assembly Construction: solid emissions**
1	The construction of the building assembly generates minimal solid waste (toxic or other).
2	Construction solid waste is minimised through building system design and construction practices. (specify which)
3	Waste products/materials are safely reused or recycled on site (fill, etc.) (>90%)
4	Solid residues generated are reused/recycled by others.

Question #	**Assembly Construction: liquid emissions**
1	The construction of the building assembly generates minimal liquid waste (toxic or other).
2	Construction liquid waste is minimised through building system design and construction practices.
3	Liquid waste products/materials are safely reused or recycled on site. (>90%)
4	Liquid residues generated are reused/recycled by others.

Question #	**Assembly Construction: air emissions**
1	Emissions to the air have been minimised and BAT is used.
2	The construction of the building assembly does not release significant concentrations of toxic, hazardous or nuisance substances.
3	Emissions to the air pose no potential long-term threat to worker.

Question #	**Use / maintenance: ecological concern**
1	Maintenance activities do not expose materials that contain hazardous materials?
2	Maintenance or refurbishment activities do not expose harmful substances that are otherwise benign in original context (particulates, emissions from paints, etc.)
3	The building system prevents suitable conditions for the growth of bacteriological contaminants.

Question #	**Use / maintenance: energy**
1	The building system contributes to the energy conservation - specify..
2	The building system requires minimal inputs of energy for routine maintenance
3	The repair and/or replacement of the system within the expected lifespan of the building is not energy intensive.

Question #	**Use / maintenance: solid emissions**
1	Solid emissions resulting from normal product use such as wear, oxidation, decomposition (dissipative) are: ☐small,
2	Solid emissions resulting from normal product use such as wear, oxidation, decomposition (dissipative) are☐ ☐non-toxic,
3	Solid emissions resulting from normal product use such as wear, oxidation, decomposition (dissipative) are☐ ☐minimised,
4	Solid emissions resulting from normal product use such as wear, oxidation, decomposition (dissipative) are☐ ☐recycled/reused.
5	Solid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are:☐small,
6	Solid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐non-toxic,
7	Solid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐minimised,
8	Solid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐recycled/reused.
9	Solid emissions resulting from repair/ refurbishment/ replacement are: ☐ ☐small,
10	Solid emissions resulting from repair/ refurbishment/ replacement are☐ ☐non-toxic,
11	Solid emissions resulting from repair/ refurbishment/ replacement are☐ ☐minimised,
12	Solid emissions resulting from repair/ refurbishment/ replacement are☐ ☐recycled/reused.

Question #	**Use / maintenance: liquid emissions**
1	Liquid emissions resulting from normal product use (e.g. condensate, leaks, i.e. dissipative) are: ☐ ☐non-toxic,
2	Liquid emissions resulting from normal product use (e.g. condensate, leaks, i.e. dissipative) are☐ ☐minimal,
3	Liquid emissions resulting from normal product use (e.g. condensate, leaks, i.e. dissipative) are☐ ☐minimised,
4	Liquid emissions resulting from normal product use (e.g. condensate, leaks, i.e. dissipative) are☐ ☐recycled/reused.
5	Liquid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are:☐ ☐non-toxic,
6	Liquid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐minimal
7	Liquid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐minimised
8	Liquid emissions resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐recycled/reused
9	Liquid emissions resulting from repair/ refurbishment/ replacement are: ☐ ☐non-toxic,
10	Liquid emissions resulting from repair/ refurbishment/ replacement are☐ ☐minimal,
11	Liquid emissions resulting from repair/ refurbishment/ replacement are☐ ☐minimised,
12	Liquid emissions resulting from repair/ refurbishment/ replacement are☐ ☐recycled/reused.

Question #	**Use / maintenance: air emissions**
1	Emissions to the air resulting from normal use (e.g. wear, oxidation, off-gassing, decomposition) are: ☐ ☐non-toxic,
2	Emissions to the air resulting from normal use (e.g. wear, oxidation, off-gassing, decomposition) are☐ ☐minimal,
3	Emissions to the air resulting from normal use (e.g. wear, oxidation, off-gassing, decomposition) are☐ ☐minimised,
4	Emissions to the air resulting from normal use (e.g. wear, oxidation, off-gassing, decomposition) are☐ ☐recycled/reused.
5	Emissions to the air resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are: non-toxic,
6	Emissions to the air resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐minimal,
7	Emissions to the air resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐minimised,
8	Emissions to the air resulting from preserving utility such as cleaning, touch ups (patching, sanding, painting) are☐ ☐recycled/reused.
9	Emissions to the air resulting from repair/ refurbishment/ replacement are:☐ ☐non-toxic,
10	Emissions to the air resulting from repair/ refurbishment/ replacement are☐ ☐minimal,
11	Emissions to the air resulting from repair/ refurbishment/ replacement are☐ ☐minimised,
12	Emissions to the air resulting from repair/ refurbishment/ replacement are☐ ☐recycled/reused.
13	No ozone depleting substances or greenhouse gases are released directly or indirectly during product use (excepting energy use)
14	Scoring:

Question #	**End - Use: ecological concern**
1	The assembly maximises or preserves future material/component reusability.
2	The building assembly minimises the bonding of dissimilar materials that makes separation difficult.
3	The disassembly, or transfer of materials does not pose ecological or human health burdens.
4	The system minimises the use of toxic materials.
5	Total rating of 0 if toxic, or containing, mercury, lead, cadmium, zinc parts that are not clearly identifiable, removable or separable.)
6	Major system components are free of polybrominated flame retardants or heavy metal-based additives
7	The system minimises the use of persistent pesticide/herbicide/dioxin containing products.
8	Constituent materials can easily be identified for potential reusability.
9	Consumable materials have been designed in light of their end-use.

Question #	**End - Use: energy**
1	The disassembly of the system into constituent materials minimise energy intensive steps.
2	The reuse of components preserves their embedded energy.
3	Transportation of materials for reuse/recycling is not energy-intensive due to weight or location of recycling facilities.
4	If no other use: the material can be used as a safe fuel source.

Question #	**End - Use: solid emissions**
1	Reusable/recyclable components are easily separable from consumable items (types of fasteners, no chemical bonding that is difficult to remove)
2	The material is biodegradable (&non-toxic)
3	Score of 0 if: Building system consists of primarily unrecyclable/ unreusable materials. (i.e. most materials are landfilled)

Question #	**End - Use: liquid emissions**
1	Building system creates little or no liquid residues for disassembly and end-use. Reconditioning/recycling of material does not generate/require large quantities or toxic liquids.
2	Else: 0. Significant or toxic liquid residues result from the disassembly, reuse, recycling or disposal of the building system.

Question #	**End - Use: air emissions**
1	Building system creates little or no emissions to air as a result of disassembly and end-use. Reconditioning/recycling of material does not generate/require large quantities or toxic air emissions.
2	Building assembly is designed to minimise large or toxic air emissions upon disassembly, reuse, recycling or disposal.
3	If building system is used as a fuel, it does not contain toxic compounds and has been designed/formulated for use as a fuel.
4	Else: 0. Significant or toxic air emissions result from the disassembly, reuse, recycling or disposal of the building system.

Checklists derived from Graedel and Allenby (1996), and after Vanderburg (2000).

Appendix F Checklist Results for Materials

F1.1 Checklist results for Cement Plaster - Material

Question #	Pre-Production: Ecological Concern	
1	×	
2	?	Typically open mines, susceptible to groundwater contamination (all component materials originate from quarries). The extent of ecologically productive land removed is relatively low.
4	?	Old quarries are typically flooded to create aquatic ecosystems. Not restored to original conditions
7	×	Quarrying/mining removes most ecosystem sinks, but relative ecological significance is low.□ Raw materials : sand/gravel/limestone in abundance
8	?	
10	?	
12	×	Aggregate extraction and limestone quarrying have a low extent (area) impacted, are generally restored to productive uses, and have a low initial ecological significance. (Wayne B. Trusty & Associates, & Environmental Policy Research, 1994)

Question #	Pre-Production: energy	
1	×	Aggregate and limestone extraction not very energy intensive per qty used in wall.
2	×	Petroleum.
4	?	
5	×	
7	?	Less energy intensive plasters e.g. gypsum, lime, earthen.
9	×	Significant energy would be required to restore open pit mine to original capacity. Alternate ecosystems viable (e.g. aquatic)
10	×	See LCI Data

	Pre-Production: solid, liquid, air	
		See LCI Data

Question #	Manufacturing: ecological concern	
1	?	*Product may contain industrial waste as a result of fuel source.*
3	?	
6	?	

Question #	Manufacturing: energy
	See LCI Data

Question #	Manufacturing: solid emissions
	See LCI Data

Question #	Manufacturing: liquid emissions	
1	×	Significant amounts discharged, but mostly treated on-site in settling ponds.
4	✓	Wash water reclaimed from settling ponds (Wilson, 1993).
5	✓	Uncured concrete returned to plant often used for manufacturing of retaining blocks or barricades (Wilson, 1993).

Question #	Manufacturing: air emissions	
		See LCI Data

Question #	Transportation / Packaging: ecological concern	
1	×	Packaging use is large for 45kg bags of cement, lime, etc. No aggregate packaging waste.
2	?	Heavy metal based inks may be used on packaging (unregulated).
3	×	
4	×	Recyclable but generally not recycled due to residual waste material.

Question #	Transportation / Packaging: energy	
1	✓	Waste streams (paper, plastic), not energy intensive to recycle, may be used as fuel source.
2	?	Packaging is generally paper based, some plastic liners may be used. Transportation distance not greater than 80km but depends upon location of manufacturing facility to builder's yard and builder's yard to site.
3	×	
4	×	Typically diesel transport truck delivery.
5	×	
6	?	

Question #	Transportation / Packaging: solid	
1	×	Extensive packaging used. Approx 1 bag per .1m^3 plaster, or 1 bag for every 2 m^2 38mm finish.
2	×	
3	×	
4	×	

Question #	Transportation / Packaging: liquid	
1	×	Liquid wastes generated from polymer admixes (if used), sealants, cement, lime from residuals left in packages.
2	×	20L pails often reused within trades.
3	?	Ready-mix concrete may be available if concrete plasters used, though requires different application techniques (i.e. grout pump, stucco pump, etc.)
4	×	Packaging material may contain heavy metal-based inks.

Question #	Transportation / Packaging: air	
1	?	
2	×	Bag packages not reused, residual may become airborne.
3	×	
5	×	

F1.2 Checklist Results for Cement Plaster- Assembly

Question #	Assembly Construction: materials choice	
	?	High pH of concrete can cause concrete burns if proper protection not used.

Question #	Assembly Construction: energy
	Material/assembly's stage/context not specifically considered, see assembly info.

Question #	Assembly Construction: solid emissions	
1	?	Depends upon skill of applicator and method of application (spraying, trowelling).
2	✓	Construction practices: solid waste reduced by accurate take-offs of material needed, timing of batches.
3	✓	Concrete, plasters (cured) safely used on-site as fill, unless toxic additives used.
4	✓	If not batched on site: some concrete plants produce concrete products from returned concrete batches.

Question #	Assembly Construction: liquid emissions	
1	×	
2	×	Batch applications of cement-based render generate significant liquid waste that is disposed on site.
3	×	Wastewater from cleaning of equipment is highly alkaline and is toxic to vegetation, aquatic species.
4	×	

Question #	Assembly Construction: air emissions	
1	?	Cement Plaster: Assume protective equipment is worn for on-site mixing.
2	×	Cement Plaster: Particulate matter from mixing requires protective equipment.
3	×	Cement Plaster: Particulate matter from mixing poses risk of respiratory disease (silicosis, etc.)

Question #	Use / maintenance: materials choice	
1	?	
3	?	Potential vapour retarder on exterior surface (polymer modified only) may create vapour trap, causing water build up inside assembly.

Question #	Use / maintenance: energy
	Material/assembly's stage/context not considered.

Question #	Use / maintenance: solid emissions	
2	?	
4	×	Dissipative.
5	×	Paints, sealants may be toxic, especially exterior paints containing fungicides, mildewcides.
6	?	Material replaced is limited to area of damage but reapplication of finish usually extends beyond area of repair in order to match/blend in.
7	✓	Natural pigments in stucco, stains frequently used.
8	×	
9	×	Paints, sealants may be toxic, especially exterior paints containing fungicides, mildewcides.
11	×	Replacement of small areas often requires repainting of entire surface to match.
12	×	

Question #	**Use / maintenance: liquid emissions**	
1	✓	Very Small amounts of dust from sealed plaster surfaces.
5	?	Depends on sealant, frequent application is necessary (5years)
6	×	Cleaning may generate significant amounts of wastewater
7	✓	Natural pigments in stucco, stains frequently used: reduce coating requirements.
8	×	
10	×	
11	×	Uneven plaster surfaces increases sealant use, porous surface requires large quantities of product (sealant) to be effective.
12	×	Emissions are as overspray, drips, and cleaning preparation.

Question #	**Use / maintenance: air emissions**	
1	?	Cement admixtures, if used, may contribute to off-gassing (Wilson, 1993).
2	?	
3	?	
5	?	Depends upon finish applied.
10	?	Dust from cutting may cause respiratory problems, can be minimised by wet-sawing.
11	?	

Question #	**End - Use: materials choice**
	Insignificant ecological impacts, relatively inert.

Question #	**End - Use: energy**	
1	×	Plaster/stucco difficult to separate from reinforcing mesh.
2	×	No reuse feasible.
3	×	Low value, high weight material that is energy intensive to transport and reprocess. Usable for on-site fill.
4	×	

Question #	**End - Use: solid, liquid, air emissions**
	See Wall # 1 and text for description.

F2.1 Checklist Results for Strawbale - Material

Question #	**Pre-Production: ecological concern**	
1	✓	Non-perpetual harvesting of straw is relatively renewable.
2	✓	Farmlands
3	×	No certification exists for straw/ secondary agricultural products but organic certification is possible.
5	×	If grain production is primary crop, then pesticides/herbicides/fertilizers used for straw are secondary. If straw is primary crop, (as for bedding/industrial use) pesticide/herbicide toxicity may increase since not for food value.
6	×	Primary crops are mostly genetically modified, affecting biodiversity indirectly.
7	×	Modern farming (non-sustainable) results in soil depletion, loss of carbon content and nutrients that encourage synthetic replacements. These reduce ecological productivity and ability to assimilate future wastes.
10	✓	Existing road network utilised.

Question #	**Pre-Production: energy**	
1	×	Energy use is attributed to seeding, exclude fertilizer and pesticide energy content.
2	×	Energy for growing is, else: petroleum for machinery and chemical fertilizers
4	✓	Bales are locally available in most regions of Ontario
5	?	Energy use could be minimised using no-till, organic farming, but largest consumption is still farm machinery for seeding.
6	?	If straw is considered waste material, then yes - minimal amount of energy required for baling.
7	×	Farm machinery not fuel efficient.
10	×	See LCI Data

Question #	**Pre-Production: solid**
	No significant solid waste

Question #	**Pre-Production: liquid**
	No significant liquid emissions

Question #	**Pre-Production: air**
	See LCI Data for emissions from fuel consumption.

Question #	Manufacturing: ecological concern	
1	?	Pesticide residues may be present.
7	?	Possible to eliminate pesticide residues using organic farming techniques.
9	✓	Very little waste.
10	×	Neglecting tillage, fertilisers and harvesting: Baling: ? Transportation: ?

Question #	Manufacturing: energy
	See LCI Data

Question #	Manufacturing: solid emissions
	See LCI Data

Question #	Manufacturing: liquid emissions
	See LCI Data

Question #	Manufacturing: air emissions
	See LCI Data

Question #	Transportation / Packaging: ecological concern
	No significant impacts.

Question #	Transportation / Packaging: energy	
2	✓	If local delivery available.
3	✓	No packaging except for reusable tarpaulins. Transportation minimised by distance (direct cost to buyer).
4	×	Energy usage is small, but emissions of farm machinery/delivery may be high. Less stringent emission standards/compliance may be low.
5	×	
6	?	If straw is considered waste material, then yes - minimal amount of energy required for baling.

Question #	Transportation / Packaging: solid	
3	✓	If packaging used, it is generally reusable tarps.

Question #	Transportation / Packaging: liquid
	No known burdens for this material's stage/context

Question #	Transportation / Packaging: air	
1	?	Local Material, transportation distances small in suburban or rural areas. Emissions to air dependent upon emissions of farmer's vehicle which may be high. Insignificant emissions to air from product.
2	×	Some product loss may occur during transport, but relatively benign (straw).

Question #	Use / maintenance: See Assembly
Question #	End - Use: See Assembly

F2.2 Checklist Results for Strawbale - Assembly

Question #	Assembly Construction: See comments for Wall #1

Question #	Use / maintenance: ecological concern	
1	?	Potential source of moulds and fungi if moisture related damage.
3	✓	If detailed properly.

Question #	Use / maintenance: energy	
1	✓	High insulative value, RSI 4.6 w/mmC. Plastered wall construction provides air tight assembly.
2	?	Pigmented plasters and silicon based sealants/repellents reduce maintenance (finish) requirements.
3	?	Long term maintenance figures not available.

Question #	Use / maintenance: solid emissions	
1	✓	Should not biodegrade if detailed properly. Otherwise no maintenance required.
5	✓	Maintenance activities require removal of finish coats, with associated burdens. Straw itself is non toxic, though may cause nuisance dust.
9	?	Depends upon extent of damage, little data available on replacement.
10	?	
11	?	
12	✓	Straw is compostable, natural product. If damaged, Stucco plasters must be replaced. Plasters not recycled/recyclable.

Question #	Use / maintenance: liquid emissions	
1	✓	No significant emissions
5	✓	No emissions *for replacement of straw.*
9	✓	No Emissions.

Question #	Use / maintenance: air emissions	
1	×	Decomposition poses health risks due to moulds and fungi, should bales get wet (fail).
9	×	If repair of straw itself is necessary, water is likely culprit and emissions are toxic, though minimal protection is required to safeguard against this.
10	?	*Depends on amount of repair/cause of damage.*
12	×	

Question #	Deconstruction / End Use: See Wall #1

F3.1 Checklist Results for Galvanized Steel (Studs and Wire Mesh) - Material

Question #	Pre-Production: Materials Choice	
1	×	Significant ecological damage from pit, strip mining. waste rock produces acid mine drainage, but most steel can be made from recycled sources, reducing amount of disruption.
2	?	
4	?	
7	×	Loss of existing ecosystem due to iron and coal mining. Replacement vegetation, ecosystem is not native due to change in soil characteristics.
10	?	
12	×	Similar impacts as in quarrying, aggregate extraction. Most steel products contain recycled material, reducing demand for iron ore.

Question #	Pre-Production: energy	
1	×	
2	×	Petroleum, Coke/coal.
3	?	*Electric-arc furnace transfers emissions from steel mill to power plant. Net system efficiency unknown.*
5	✓	Recycled steel is used.
8	?	
9	?	
10	×	See LCI Data

Question #	Pre-Production: Solid, Liquid, Emissions to Air: See LCI Data

Question #	Manufacturing: See LCI Data	
Question #	**Transportation Included in LCI Data**	
	Packaging included in Assembly consideration	

F3.2 Checklist Results for Galvanized Steel (Studs and Wire Mesh) - Assembly

Question #	Assembly Construction: ecological concern, energy
	See Walls # 1,3,4

Question #	Assembly Construction: energy
	Material/assembly's stage/context not considered.

Question #	Assembly Construction: solid emissions	
2	✓	For studs/furring: available in custom sizes to minimise/eliminate cutting and waste.
3	×	
4	✓	Steel waste is recyclable and is recycled.

Question #	Assembly Construction: liquid emissions	
1	✓	Minimal liquid emissions.

Question #	Assembly Construction: air emissions	
1	✓	Few significant air emissions.

Question #	Use / maintenance: ecological concern	
1	✓	No expected maintenance activities.

Question #	Use / maintenance: energy	
1	×	Thermal conductor, causes thermal bridging in wall assemblies (studs, lintels). Insignificant effect for ties.
3	?	If replacement needed due to corrosion e.g., then covering materials will also need replacement.

Question #	Use / maintenance: solid emissions	
1	?	Impacts are due to coatings, and dependent upon isolation from interior/exterior environment.
2	?	Zinc from galvanized products is toxic to plants, humans. Steel is relatively non-toxic.
3	?	Oxidation inherent: dissipative due to oxidation, but minimised by being protected within the wall assembly.
4	×	Not possible.
5	✓	No maintenance required on interior/protected steel.
9	?	
10	?	Depends upon extent of repair. Extent of impact from galvanized steel at end use uncertain, but not likely a serious concern.
11	×	Whole members must be replaced.
12	✓	Recycled.

Question #	Use / maintenance: liquid emissions
	Material/assembly's stage/context not considered.

Question #	Use / maintenance: air emissions
	Material/assembly's stage/context not considered.

Question #	Deconstruction / End Use: See Wall #4 Checklists and text.

F4.1 Checklist Results for Plywood Sheathing - Material

Question #	Pre-Production: Ecological Concern	
1	×	All impacts same as for dimensional wood, burdens shown here are related to glues/binders.
2	×	Petroleum derived chemicals used as binders e.g. phenol formaldehyde. Depends on extraction location.
3	×	Mostly from non-certified sources
4	×	Most logging results in the conversion of lands to monoculture stands, biodiversity affected by clearing
5	×	pest/herb/fert. are all used in both "clearing" after logging and regeneration to ensure "desirable" species
6	✓	Except as in monoculture crops.
7	×	Reduces source of non-renewable energy (petroleum)
8	✓	Climate may be affected, see wood.
9	×	Refining and glue production produces volatile compounds derived from benzene. For low-VOC compounds: manufacture of MDI glues, Urea Formaldehyde and Phenol Formaldehyde glues pose risk to surrounding ecosystem.
10	?	Roads cause significant ecological damage during and after logging as a result of erosion
11	×	Preproduction (oil refining) produces many other compounds that are hazardous.
12	×	Intensity and duration of impacts are large due to timber extraction from boreal forests. Larger dimensioned trees required for softwood plywood manufacture, increasing ecological impacts.

Question #	Pre-Production: energy, solid, emissions to air
	See LCI Data

Question #	Manufacturing: See LCI Data

Question #	Transportation / Packaging: ecological concern
	Assumed insignificant ecological concern.

Question #	Transportation / Packaging: energy
	See LCI data for transport energy, assumed minimal energy in packaging.

Question #	Transportation / Packaging: solid	
1	×	
2	×	
4	✓	Minimal packaging required since delivered and packaged in bundles.

Question #	Transportation / Packaging: liquid
	Minimal liquid emissions

Question #	**Transportation / Packaging: air**
1	See LCI Data for transport emissions.

Question #	**Use / maintenance: See Walls #2,4**

Question #	**End - Use: See Walls #2,4**

F4.2 Checklist Results for Plywood Sheathing - Assembly

Question #	**Assembly Construction: See Walls #2,4**

Question #	**Use / maintenance: ecological concern**
	No known burdens for this material's stage/context

Question #	**Use / maintenance: energy**
	See Walls #2,4

Question #	**Use / maintenance: solid emissions**	
1	✓	No significant solid emissions.
6	✓	No maintenance generally required unless failure occurs.
9	?	Plywood is toxic due to glues/binders used.
10	?	Depends upon extent of repair.
11	×	Depends upon location and size of repair needed. Material must be replaced at stud spacing but may be minimised by replacing only height of affected area. If damaged, replacement requires removal of outer layers of assembly to gain access.
12	×	Not recyclable, sent to landfill.

Question #	**Use / maintenance: liquid emissions**
	No significant liquid emissions.

Question #	**Use / maintenance: air emissions**
	No significant air emissions.

Question #	**Deconstruction / End Use: See Walls #2,4**
	Material/assembly's stage/context not considered.

F5.1 Checklist results for Mineral Fibre Insulation - Material

Question #	**Pre-Production: Ecological Concern**	
1	×	Ecosystem is significantly disrupted from open pit mining (Demkin, 1996.). Effects include noise, vibration, dust, groundwater drawdown, topographical changes, native vegetation removed (Sengupta, 1993). Ecosystem disruption from slag transport is minimal.
2	?	Depends on where basalt (raw material) is found.
4	✓	Quarrying/mining typically restored to artificial lakes, though may be landfilled with garbage.
7	×	Loss of terrestrial ecosystem on mine site.
10	?	
12	×	Impacts are relatively low from quarrying activities. Most of raw material is from industrial (steel mill) slag (70-100% slag content).

Question #	**Pre-Production: energy**	
1	✓	Energy for extraction of rock from open pit mines (~20% avg. of product) is energy intensive but not relative to actual product use (low weight). Slag is already waste product of steel industries (Demkin, 1996).
2	×	
4	✓	Location of manufacturing plant often located near slag source.
5	✓	Slag (80%) used instead of rock.
6	?	Info not available
9	×	Significant energy would be required to restore open pit mine to original capacity. Alternate ecosystems viable (e.g. aquatic)
10	×	See LCI Data

Question #	**Pre-Production: solid**	
1	✓	Most of rock from mining is used, waste rock is returned on site. Depends on quality of mine. Steel slag is already waste material, preparation done at manufacturing stage.
2	?	Data not available on solid emissions from steel slag transfer to manufacturing.

Question #	Pre-Production: liquid	
1	✓	Settling ponds used.
3	✓	Minimised by reducing quantity of rock needed by substituting steel slag.
4	✓	Settling ponds used.

Question #	Pre-Production: air	
1	?	See LCI Data, dust from mining could be significant.
2	×	Emissions to air are result of energy intensive mining operations.
3	×	Related to machinery used for extraction, see above.
4	×	Related to machinery used for extraction, see above.
5	×	Product already minimises emissions by reducing rock content by substituting steel slag (50-75% steel slag) (Wilson, 1995)
6	×	

Question #	Manufacturing: ecological concern	
1	?	
7	?	If no Phenol Formaldehyde binders used, alternative: oils.

Question #	Manufacturing: energy	
1	?	See LCI Data
2	?	High heat is required, source not known.
3	×	
4	?	Possibly, if sited near other manufacturers.
5	?	
6	?	

Question #	Manufacturing: solid emissions	
1	✓	Few wastes produced. (Demkin, 1996)
2	✓	Wastes: Phenol-Formaldehyde binders burned off in manufacturing stage and captured. Binders not always used.
9	✓	Plants located near slag sources.

Question #	Manufacturing: liquid, air emissions	
		See LCI Data

Question #	Transportation / Packaging: ecological concern	
1	?	
2	✓	Polyethylene wrap
3	×	Reusable as tarps but size limits application. Could be designed for use as waste container.
4	×	Recyclable but not recycled.

Question #	Transportation / Packaging: energy	
1	✓	Product compacted
2	✓	Not energy intensive per functional unit.
3	✓	Product compacted to save packaging & transport energy.
4	×	Governed by principle mode of transport: Truck, Rail.
5	×	Petroleum
6	×	See LCI Data

Question #	Transportation / Packaging: solid	
1	×	Packaging greater than for equivalent fibreglass application since denser product. Less packaging than non-compressible insulation.
2	×	
3	×	
4	×	

Question #	Transportation / Packaging: liquid	
4	?	Inks on packaging may contain heavy metals.

Question #	Transportation / Packaging: air	
1	?	See LCI Data, no data available on packaging energy

F5.2 Checklist results for Mineral Fibre Insulation - Assembly

Question #	Assembly Construction: See relevant wall assemblies (#2,3&4)	

Question #	Assembly Construction: air emissions	
1	✓	Mineral Fibre: Large fibre size, low binder content relative to other batt insulation.
2	?	Mineral Fibre: Suspected carcinogen, but respirable amounts are low due to large fibre size. Minimised use of binders.
3	?	Mineral Fibre: Potential concern of respiratory diseases developing after long-term use.

	End - Use: See relevant wall assemblies (#2,3 &4)

F6.1 Checklist Results for Expanded Polystyrene (EPS) - Material

Question #	Pre-Production: Ecological Concern	
1	?	Petro-chemical derived,
2	?	
4	?	
7	×	non-renewable resource
8	?	
9	×	
10	?	
11	?	Many by-products of petroleum industry generated.
12	×	Ecological impacts of resource extraction per unit of product are unknown, assumed impact.

Question #	Pre-Production: energy	
1	×	
2	×	
4	✓	large transport distances for crude oil to refinery
5	?	
6	✓	Most oil by-products are used as inputs to other processes.
7	×	Raw materials could be sourced from waste stream.
9	×	
10	?	Combined with manufacturing energy, split not available.

Question #	Pre-Production: solid, liquid, emissions to air
	See LCI Data

Question #	Manufacturing: ecological concern	
1	×	Styrene used is a "suspected carcinogen, mutagen, chronic toxin and environmental toxin" according to USEPA (Wilson, 1995).
2	✓	Polystyrene recycling in pre-consumer and post-consumer applications.
3	✓	Blowing agent losses minimised through recovery (95%) (Wilson, 1995)
6	×	Petroleum product based on benzene. Blowing agent is also petroleum product (pentane)

Question #	Manufacturing: energy
	See LCI Data

Question #	Manufacturing: solid emissions	
1	✓	Solid residues from manufacturing are minimal, polystyrene is a thermoset and can be reincorporated into product manufacture (Demkin, 1996), See LCI Data for further data.

Question #	Manufacturing: liquid emissions
	See LCI Data

Question #	Manufacturing: air emissions	
3	?	
4	×	Smog producing pentane used as blowing agent.
7	✓	95% of pentane is recovered close-loop (Wilson, 1995).
8	?	Alternatives to styrene use not investigated.
9	×	Emissions from styrene production are noxious and nuisance.

Question #	Transportation / Packaging: ecological concern	
1	✓	Can be purchased in bulk, otherwise polyethylene.
3	×	Larger package sizes could be reused.
4	×	Recyclable but not recycled in all areas.

Question #	Transportation / Packaging: energy	
	No Data Available	

Question #	Transportation / Packaging: solid	
1	×	Low density material requires significant packaging relative to compressible insulation materials.
2	×	
3	×	
4	×	

Question #	Transportation / Packaging: liquid	
4	?	Inks on packaging may contain heavy metals.

Question #	Transportation / Packaging: air	
1	?	

F6.2 Checklist Results for Expanded Polystyrene (EPS) - Assembly

Question #	Assembly Construction: materials choice	
	No Significant concerns.	

Question #	Assembly Construction: energy	
	No Significant concerns.	

Question #	Assembly Construction: solid emissions	
1	?	
2	✓	Minimised by laying out walls in increments of panel size. Small scraps not usable in system.
3	?	Polystyrene has potential use on site as soil amendment if ground up.
4	✓	Scrap material is recyclable.

Question #	Assembly Construction: liquid emissions	
	Minimal liquid emissions	

Question #	Assembly Construction: air emissions	
1	×	EPS: Pentane used as blowing agent may accumulate in enclosed spaces. Other substitute blowing agents are used in Europe (CO2)
2	?	
3	?	EPS: Unknown.

Question #	Use / maintenance: ecological concern
	No known burdens for this material's stage/context

Question #	Use / maintenance: energy
	See Wall Assemblies # 2,3,4

Question #	Use / maintenance: solid, liquid emissions
	No significant solid or liquid emissions

Question #	Use / maintenance: air emissions	
1	×	Polystyrene emits VOCs during product lifespan.
2	?	Amount and nature of VOCs not well studied (Demkin, 1996)
3	×	
4	×	

Question #	End - Use: See Walls # 2,3,4

F7.1 Checklist Results for Gypsum Wallboard - Material

Question #	Pre-Production: ecological concern	
1	×	Predominantly open-pit mining for gypsum extraction results in loss of ecosystem. Gypsum is 40% of material excavated, rest is overburden (Yost, 2000)
2	?	Depends upon source of gypsum.
4	✓	Open pit mining of gypsum is restorable to productive, aquatic environments, although acidification possible depending on sulphur content of overburden.
7	✓	Gypsum in abundance. (Demkin, 1996)
8	?	
10	?	Depends upon size of deposit, and distance to plant. Open pit mining infrastructure impacts governed by distance to processing plant, since pit serves as infrastructure within. Pit infrastructure impacts linked to overall ecological loss from size of mine
12	×	Impacts from raw material extraction are low. Many gypsum wallboard products contain gypsum from FGD (Flue Gas Desulpherization) sources. (Yost, 2000)

Question #	Pre-Production: energy	
1	×	
2	×	Energy is from fossil fuels (machinery) and chemical sources (blasting) (Demkin, 1996).
4	✓	*Depends upon plant location.*
5	×	Possible to manufacture gypsum board from 100% Flue Gas Desulphurisation (FGD) gypsum.
6	?	Waste material (overburden) is landfilled, if landfilled to other location, transportation energy may be significant.
7	×	100% FGD Gypsum board possible, paper facing is 100% recycled paper.
8	?	Waste materials (overburden) currently unusable as input to other processes.
9	✓	Flooding not energy intensive if mine converted to aquatic environment. Restoration to previous use requires energy intensive earth moving.
10	×	See LCI Data

Question #	Pre-Production, Manufacturing
	Minimal Data Available, see cement production for approximation.

Question #	Transportation / Packaging: ecological concern
	Insignificant ecological impacts.

Question #	Transportation / Packaging: energy
	See Transport Data

Question #	Transportation / Packaging: solid	
1	✓	Delivered just-in-time or protected inside on-site. Banding (metal or plastic) is minimal.

Question #	Transportation / Packaging: liquid
	No known burdens for this material's stage/context

Question #	Transportation / Packaging: air
	See air emissions due to transport in LCI Data

F7.2 Checklist Results for Gypsum Wallboard - Assembly

Question #	**Assembly Construction: materials choice**
	See Walls # 2,3,4

Question #	**Assembly Construction: energy**
	No data Available.

Question #	**Assembly Construction: solid emissions**	
1	?	
2	✓	Many sizes available to minimise waste. Design should be in increments that reduces waste material.
3	×	Use of Gypsum boards as fill causes acidification of soils and potential sulphate release.
4	✓	Construction gypsum waste recycling available in most urban areas.

Question #	**Assembly Construction: liquid emissions**	
1	?	Wastewater generated from mixing equipment for joint compounds.
2	✓	Joints are generally minimised.
3	×	Disposed on-site.
4	×	

Question #	**Assembly Construction: air emissions**	
1	×	Gypsum Wallboard: Emissions as a result of product installation have increased with the use of rotary tool cutters.
2	×	
3	?	

Question #	**Use / maintenance**
	See Walls #2,3,4

Question #	**Deconstruction / End - Use**
	See Walls #2,3,4

F8.1 Checklist Results for Concrete Blocks - Material

Question #	**Pre-Production: ecological concern**	
		See cement plaster considerations

Question #	**Pre-Production: energy**	
1	×	
2	×	
4	?	
5	×	Could use fly ash instead of cement.
6	?	
7	×	Could use fly ash instead of cement.
8	?	
10	×	See LCI Data

Question #	**Pre-Production: solid, liquid, air**	
		See LCI Data

Question #	**Manufacturing: ecological concern**	
		See cement plaster considerations

Question #	**Manufacturing: energy**	
1	×	See LCI Data
3	×	Fossil fuels and wastes for cement production. Block production uses electricity and natural gas. Some cement production facilities use agricultural waste as fuel for calcining (Wilson, 1993)
4	?	
5	×	Could substitute fly ash up to 25%.
6	?	

Question #	**Manufacturing: solid, liquid, air emissions**	
		See LCI Data

Question #	**Transportation / Packaging: ecological concern**
	Insignificant Ecological Impacts

Question #	**Transportation / Packaging: energy**	
2	×	Minimal packaging, transportation energy intensive due to weight of materials.
3	✓	Packaging used: reusable skids.
4	×	Diesel transport (truck).
5	×	
6	?	

Question #	**Transportation / Packaging: solid**	
1	×	Skids, Banding.
2	✓	Skids reused.

Question #	**Transportation / Packaging: liquid**
	No known burdens for this material's stage/context

Question #	**Transportation / Packaging: air**
	See Transport emissions in LCI Data

Question #	**Use / maintenance**
	Minimal Impacts during this stage.

Question #	**End - Use: See Wall #3**

F8.2 Checklist Results for Concrete Blocks - Assembly

Question #	**Assembly Construction: material concern**
	Unknown impacts, assumed small.

Question #	**Assembly Construction: energy**
	Construction data not available, estimates only.

Question #	**Assembly Construction: solid emissions**	
1	×	Concrete block waste is minimal. Mortar waste not contained in wall may be significant in quantity.
2	?	Depends upon number of complete blocks per wall and architectural features. Extensive cutting may produce significant waste material.
3	?	Safely used as fill on site, but difficult to collect and contain (located close to wall, may detract from finish soil quality).
4	×	

Question #	**Assembly Construction: liquid emissions**	
1	×	Significant amounts of wastewater generated from cleaning of equipment, generally not minimised nor controlled or monitored.
2	×	Water usage & waste water emissions reduction not encouraged since water usage not metered. *Process water is generally conserved for convenience in barrels.*
3	×	Contamination of soil near mixing area likely near mixing area due washing operations.
4	×	

Question #	**Assembly Construction: air emissions**	
1	×	Masonry: Largely worker health related emissions. Particulate emissions from cutting of blocks is significant.
2	×	Masonry: Particulate emissions high in masonry construction due to mixing and residual mortar on equipment, planks on scaffolding. Mixing exposure preventable, difficult to wear protective equipment otherwise.
3	×	Masonry: Long-term exposure may cause respiratory diseases such as silicosis of lung due to cement and lime dusts.
	t	

Question #	**Use / maintenance**
	Insignificant impacts during this stage, durable material.

Question #	**Deconstruction / End - Use: See Wall #3**

F9.1 Checklist Results for Dimensional Softwood Lumber - Materials

Question #	Pre-Production: Ecological Concern	
1	×	see below
2	?	
3	×	Mostly from non certified sources.
4	×	Most logging results in the conversion of lands to monoculture stands, biodiversity affected by clearing.
5	×	Pest/herb/fert are all used in both "clearing" after logging and regeneration to ensure "desirable" species.
6	✓	Except as in monoculture crops.
7	×	Significant loss of CO2 sequestering ability in non-mature forests, and other ecosystem services such as erosion control, water filtering. Ability to store Carbon in soil increases with tree stand age and increases exponentially.
8	×	Tempering ability of forest lost, increased surrounding air/soil temperatures
9	×	After Clearing, liberal application of herbicides used to control "undesired" tree species.
10	×	Roads cause significant ecological damage during and after logging as a result of erosion. Logging roads damage soil, where 40% of carbon is stored. (Franklin and Maser, 1984).
12	×	Intensity and duration of impacts are large due to timber extraction from boreal forests.

Question #	Pre-Production: energy	
1	×	
2	×	
3	?	
4	?	Dependent on distance from logging to mill
5	×	Energy use may be minimised by clearcutting
6	?	Waste material is used as energy source for kiln drying. Waste Materials are used to manufacture other wood products.
7	×	Selective forestry using less energy intensive equipment, lumber local to mill, FSC certified may encourage less energy intensive practices (less roads, etc)
8	✓	compostable, usable as fuel
9	×	replanting, restoration, energy intensive if using mechanised equipment and pesticides/herbicides
10	×	27.9 MJ/m

Question #	Pre-Production: solid	
1	✓	no significant solid wastes and those that are produced are able to breakdown naturally
2	✓	no significant toxic solid residues result from logging
4	✓	composted/biodegraded in-situ
6	✓	no packaging, material losses minor

Question #	Pre-Production: liquid	
1	✓	except if dust suppression used
2	?	possible liquid residues from pesticide herbicides used if replacement tree stand is farmed

Question #	Pre-Production: air	
1	✓	

Question #	Manufacturing: ecological concern	
6	✓	material is renewable
7	✓	except for pressure treated wood containing arsenic compounds.

Question #	Manufacturing: energy	
1	?	83.8 MJ/m
2	✓	35% Natural Gas□ 40% Bio from wood waste
3	✓	0.4
4	✓	unusable wood waste is used for kiln drying
5	?	
6	?	

Question #	Manufacturing: solid emissions	
1	✓	solid residues are mainly ash from combustion of wood waste
10	✓	tarps only & strapping

Question #	**Manufacturing: liquid emissions**	
1	?	limits for COD etc?
		See LCI Data

Question #	**Manufacturing: air emissions**	
1	?	See LCI Data

Question #	**Transportation / Packaging: ecological concern**	
2	✓	relatively non-toxic polyethylene/polypropylene tarps □ banding has low toxicity
3	✓	tarps are mostly reused on site for other construction related purposes
4	×	packaging is potentially recyclable but not collected□ some bands are recycled in metal recycling bins

Question #	**Transportation / Packaging: energy**	
		See LCI Data

Question #	**Transportation / Packaging: solid**	
1	×	
2	×	
3	✓	Mostly reused as tarps if woven polypropylene used, recyclable.
4	✓	Minimal packaging required since delivered and packaged in bundles.

Question #	**Transportation / Packaging: liquid**	
4	?	Inks on packaging may contain heavy metals.

Question #	**Transportation / Packaging: air**	
1	×	

F9.2 Checklist Results for Dimensional Softwood Lumber - Assembly

Question #	**Assembly Construction: solid emissions**	
1	×	*large quantities of wood waste : 5.6 kg per unit with minimal attempts at reduction*□ waste however, is relatively non-toxic and may be reprocessed into wood products, used for mulch or as fuel.
2	×	Planning and proper sorting may reduce amount of solid waste generated, though not generally practiced.
3	✓	*May be chipped/shredded on site for use as mulch, not suitable as fill.*
4	✓	Wood recycling/reprocessing is available in some urban areas.

Question #	**Assembly Construction: liquid emissions**	
1	✓	Minimal liquid emissions.

Question #	**Assembly Construction: air emissions**	
1	?	Wood: Low emissions to air from construction, but burning of waste material is significant if practiced.
3	?	Wood: Exposure to sawdust may cause respiratory ailments.

Question #	**Use / maintenance: ecological concern**
	No known burdens for this material's stage/context

Question #	**Use / maintenance: energy**
	Unknown impacts for this material/assembly's stage/context

Question #	**Use / maintenance: solid emissions**	
5	✓	Exposed wood members require reapplication of finishes. Assume wood members interior of wall assembly and do not need re-application of sealants/preservatives.
9	✓	Dependent upon nature of damage/need for replacement.
10	?	
11	?	*Dependent upon nature of damage/need for replacement.*
12	✓	Potentially composted.

Question #	**Use / maintenance: liquid emissions**	
1	✓	Non-toxic material.
2	×	.

Question #	**Use / maintenance: air emissions**
	No Significant air emissions

Question #	***Deconstruction / End - Use: See Wall #2***

Appendix G Checklist Results for Wall Assemblies

G1 Checklist Comments for Wall # 1 - Strawbale

Question #	Material Production: Extraction -> Production,: Materials Choice	
3	×	Cement from virgin sources, straw renewable. Virgin material is not minimised. Wall system is predominantly (by volume) renewable straw but only 20% by mass.
6	✓	No materials in restricted supply.

	Material Production: Extraction -> Production,: energy	
4	×	Heavy use of energy intensive cement accounts for more than 60% of embodied energy and is not minimised. Welded wire mesh contributes 22% of embodied energy. As a result, GWP is high. The use of these high embodied energy materials is not minimised.
5	×	955.4MJ/m, GWP: 161 kg CO2/m

	Material Production: Extraction -> Production,: solid	
1	✓	Minimal solid wastes generated and most are non-toxic or recoverable.

	Material Production: Extraction -> Production,: liquid	
3	×	Eutrophication potential is high. Emissions of phenols resulting in high ecotoxicity (largely from cement production) are not minimised. Other liquid residues from cement production are significant and not minimised.

	Material Production: Extraction -> Production,: air	
2	?	
3	✓	Cement plant airborne residues are captured and reprocessed into other products.
4	?	Possible substitute for cement plaster i.e. gypsum, earth, lime.
5	×	Global warming potential (161.4 kg CO@) is high, acidification potential average (11.8 g H equiv.) Overall airborne emissions are above average compared to other wall assemblies studied, largely due to dement content and wire mesh.
6	?	Use of concrete could be minimised.

	Assembly Construction: ecological concern	
1	✓	No significant burdens from straw, except risk of fire (common but preventable). High pH of cement can cause concrete burns if proper protection not used.

	Assembly Construction: energy	
1	?	Typically built in "workshop" or "house-raising" style, where participants (many) come from afar. On site camping is frequently supplied to minimise day to day transport.
2	?	Some trimming with gas-powered power tools may be done: emissions high. Extremely labour intensive, data not available on energy for construction, but mixing of plaster uses significant amounts of energy.
3	✓	Human Labour
4	✓	Human Labour
	Assembly Construction: solid emissions	
1	✓	No data on actual quantity of waste. Waste material (straw) is compostable and waste plaster may be used on site as fill. Loose straw used as stuffing/filler around bales. Excess added to first stucco mixes as levelling compound.
2	✓	Designs are laid out for common bale increments, no bale waste.
3	✓	Primary waste material (cement plaster) can be safely used on site for fill, straw compostable.

	Assembly Construction: liquid emissions	
1	?	Few liquids emitting during bale raising, but emissions from rendering may be significant due to quantity used.
2	×	Batch applications of cement-based render generate significant liquid waste that is disposed on site.
3	×	Wastewater from cleaning of equipment is highly alkaline and is toxic to vegetation, aquatic species.
4	×	

	Assembly Construction: air emissions	
1	?	Straw: few emissions to be minimised. Cement plaster: assume protective equipment is worn for on-site mixing.
2	?	Straw: Some allergic reactions to moulds, spores and straw. Cement Plaster: Particulate matter from mixing requires protective equipment.
3	×	Cement Plaster: Particulate matter from mixing poses risk of respiratory disease (silicosis, etc.)

	Use / maintenance: ecological concern	
1	✓	No significant ecological concerns due to materials/assembly properties during Use/Maintenance phase.
3	?	

	Use / maintenance: energy	
1	✓	High R-value
2	✓	Durable finishes.
3	?	Unknown durability.

	Use / maintenance: solid emissions
	No significant Impacts

	Use / maintenance: liquid emissions
	No significant Impacts

	Use / maintenance: air emissions	
1	?	Cement admixtures, if used, may contribute to off-gassing (Wilson, 1993).
5	✓	High durability finish if cement or gypsum plasters used, low-maintenance if pigmented.
9	?	Data not available.
10	?	
11	?	
12	?	
14	✓	Generally low emissions from this type of system if pigmented finish coat used (assumed). Otherwise, use of paints/sealants common to all wall systems and not dependent upon material/wall system properties.

	End - Use: ecological concern	
1	×	No reusable components.
2	×	Straw bonded to cement, difficult to separate.

	End - Use: energy	
1	✓	Requires heavy machinery due to large amount of cement based plaster.
2	×	No reuse feasible.
3	?	Reuse of cement only likely on-site due to transportation energy.
4	×	

	End - Use: solid emissions	
2	✓	Straw
3	✓	Cement

	End - Use: liquid emissions
	No significant Impacts

	End - Use: air emissions	
1	×	
2	×	
3	×	
4	?	Possible large releases of particulate matter.

G2 Checklist Comments for Wall # 2 - Wood Stud / EIFS

Question #	**Material Production: Extraction -> Production: Materials Choice**	
2	✓	Insulation manufactured from wastes (slag), wood is renewable, plaster is minimised (10mm), drywall has high waste content if made from FGD gypsum.
5	×	Ecological impacts significant from timber extraction if not from well-managed forests.
6	✓	No materials in restricted supply.
7	×	Heavy use of pesticides and herbicides during production of timber, many toxic by-products from polystyrene production, binders in plywood pose human toxicity concerns during manufacture.

Question #	**Material Production: Extraction -> Production,: energy**	
2	✓	Use of cement plaster is minimised, energy is largely due to feedstock in polystyrene and may potentially be reduced through recycled material. Energy intensive insulation contributes to energy savings but is derived from petroleum.
4	?	
5	×	765.6 MJ/m, GWP: 68 kg CO2/m

Question #	**Material Production: Extraction -> Production,: solid**	
2	×	Few solid and/or toxic wastes that are not reprocessed into new materials.

Question #	**Material Production: Extraction -> Production,: liquid**	
2	×	Dissolved solids, organic compounds large (largely from plywood) significant. Other emissions relatively small. Impacts unknown. Eutrophication potential is low.

Question #	**Material Production: Extraction -> Production,: air**	
1	✓	Global warming potential (67.7 kg CO@) is low as is acidification potential (6.7 g H equiv.) Low overall air emissions. Potentially significant emissions of Phenols from plywood and EPS manufacture.
4	?	

Question #	**Assembly Construction: ecological concern**	
1	✓	Protection must be used for installation of mineral wool insulation. No significant ecological concerns.

Question #	**Assembly Construction: energy**	
1	?	Depends upon location, assume some ride sharing.
2	✓	Pre-cut/sized lengths of lumber available, can also be minimised through design. Energy for plastering is largest consumer of energy from mixing equipment.
3	?	
4	?	Human labour is renewable (with rest and foodl), electricity used for cutting and compressors may be from non-renewable sources.

Question #	**Assembly Construction: solid emissions**	
1	×	Large quantities of wood waste : 5.6 kg per unit with minimal attempts at reduction. Wood waste is relatively non-toxic and may be reprocessed into wood products, used for mulch or as fuel. Drywall waste potentially significant but drywall may be recycled.
2	?	Planning and proper sorting may reduce amount of solid waste generated (wood, drywall, polystyrene), though not generally practiced. Plywood used as sheathing creates large amounts of waste if non-standard spacing, sizes used. Batts sized for common stud spacing increments & available in many sizes, thicknesses.
3	✓	Concrete, plasters (cured) safely used on-site as fill, unless toxic additives used. Polystyrene has potential use on site as soil amendment if ground up. Wood may be chipped/shredded on site for use as mulch, not suitable as fill. Plywood difficult to reuse on site due to spacing of studs. Extra insulation may be used in interior walls or added to other building elements (i.e. roofs). Use of Gypsum boards as fill causes acidification of soils and potential sulphate release.
4	✓	Some concrete plants produce concrete products from returned concrete batches (if not mixed on site). Polystyrene scrap material is recyclable. Wood recycling/reprocessing is available in some urban areas. Plywood not recyclable due to binders used. Insulation scrap may be recycled and used as blown in/loose fill material by others. Construction gypsum waste recycling available in most urban areas.

Question #	**Assembly Construction: liquid emissions**	
1	?	Liquid releases predominantly from plastering activities.
2	✓	Cement render liquid waste is minimised by minimising thickness of application/total quantity.
3	✗	Wastewater from cleaning of equipment is highly alkaline and is toxic to vegetation, aquatic species, but use is minimised.
4	✗	

Question #	**Assembly Construction: air emissions**	
1	?	Cement Plaster: Assume protective equipment is worn for on-site mixing. EPS: Pentane used as blowing agent may accumulate in enclosed spaces. Other substitute blowing agents are used in Europe (CO2). Wood: Low emissions to air from construction, but burning of waste material is significant if practiced. Mineral Fibre: Large fibre size, low binder content relative to other batt insulation. Gypsum Wallboard: Emissions as a result of product installation have increased with the use of rotary tool cutters.
2	?	Cement Plaster: Particulate matter from mixing requires protective equipment. Plywood: Depends upon number of cuts needed, can be minimised through design. Mineral Fibre: Suspected carcinogen, but respirable amounts are low due to large fibre size. Minimised use of binders.
3	✗	Cement Plaster: Particulate matter from mixing poses risk of respiratory disease (silicosis, etc.). EPS: Unknown. Plywood: Respirable sawdust may contain phenol or urea formaldehyde binders which are known carcinogens and allergens. Wood: Exposure to sawdust may cause respiratory ailments. Mineral Fibre: Potential concern of respiratory diseases developing after long-term use.

Question #	**Use / maintenance: ecological concern**	
1	✓	No significant ecological concerns due to materials/assembly properties during Use/Maintenance phase.

Question #	**Use / maintenance: energy**	
1	✓	High R-value

Question #	**Use / maintenance: solid emissions**
	No significant Impacts

Question #	**Use / maintenance: liquid emissions**
	No significant Impacts

Question #	**Use / maintenance: air emissions**	
1	✗	Some emissions from drywall system (VOCs) may pose problems for some individuals.
14	✗	Dust from repair and maintenance is primary irritant in addition to impacts related to construction. Emissions once cured are insignificant. Emissions from paints (not reported) are largest source of indoor air contaminants.

Question #	**End - Use: ecological concern**	
1	✓	Depends upon services, design of wall (not selection of materials).
2	✗	EPS not recoverable due to bonding with cement plaster.
6	✗	EPS has polybrominated flame retardant.
9	?	

Question #	**End - Use: energy**	
1	✓	Can be dissassembled with minimal usage of heavy machinery.
3	?	
4	?	

Question #	**End - Use: solid emissions**	
3	?	

Question #	**End - Use: liquid emissions**
	No significant Impacts

Question #	**End - Use: air emissions**	
4	?	

G3 Checklist Comments for Wall # 3 - Concrete Block / EIFS

Question #	Material Production: Extraction -> Production,: Materials Choice	
3	✓	Significant impacts from concrete production, see individual material descriptions.
5	?	
7	?	Most significant toxic concern is from petroleum-derived polystyrene, (toxic by-products from polystyrene production).

Question #	Material Production: Extraction -> Production,: energy	
4	×	Energy intensive concrete (47%), polystyrene (29%) largest contributors to the high embodied energy of this wall system. Worst performer of all wall systems.
5	×	1414 MJ/m, GWP: 184 kg CO2 /m

Question #	Material Production: Extraction -> Production,: solid	
2	✓	Waste generated during manufacture is relatively inert and often used as inputs to other processes. (concrete, etc.)
4	×	

Question #	Material Production: Extraction -> Production,: liquid	
3	×	High eutrophication potential, and significant and toxic liquid emissions largely from *cement production.*

Question #	Material Production: Extraction -> Production,: air	
1	×	Significant airborne emissions. GWP is high (184 kg CO2) as is acidification (19.6 g H+). High Phenol emissions.
5	×	

Question #	Assembly Construction: ecological concern	
1	✓	Large amounts of dust from masonry construction, high pH of mortar may cause alkali burns.

Question #	Assembly Construction: energy	
1	?	Depends upon location, assume some ride sharing.
2	×	High usage of heavy machinery (forklifts, etc.) that often idle for long periods of time. Winter heating of work area and mixing water is often inefficient and wasteful.
3	?	Blocks laid by hand, heavy equipment used for onsite transportation.
4	?	laying of blocks: human labour (renewable), gasoline engines used for mixing and transportation of materials generate significant emissions.

Question #	*Assembly Construction: solid emissions*	
1	×	Concrete block waste is minimal. Mortar waste not contained in wall may be significant in quantity.
2	?	Depends upon number of complete blocks per wall and architectural features. Extensive cutting of block may produce significant waste material. See other wall types for descriptions of other materials.
3	✓	Safely used as fill on site, but difficult to collect and contain (located close to wall, may detract from finish soil quality).
4	×	

Question #	Assembly Construction: liquid emissions	
1	×	Liquid releases predominantly from plastering and bricklaying activities.
2	×	Cement render liquid waste is minimised by minimising thickness of application/total quantity. Liquid waste from mortar mixing is significant: encouraged since water usage not metered. Process water is generally conserved for convenience in barrels.
3	×	Contamination of soil near mixing area likely near mixing area due washing operations.
4	×	

Question #	Assembly Construction: air emissions	
1	×	Cement Plaster: Assume protective equipment is worn for on-site mixing. EPS: Pentane used as blowing agent may accumulate in enclosed spaces. Other substitute blowing agents are used in Europe (CO2). Masonry: Largely worker health related emissions. Particulate emissions from cutting of blocks is significant. Mineral Fibre: Large fibre size, low binder content relative to other batt insulation. Steel: Few significant air emissions. Gypsum Wallboard: Emissions as a result of product installation have increased with the use of rotary tool cutters.
2	×	Cement Plaster: Particulate matter from mixing requires protective equipment. Masonry: Particulate emissions high in masonry construction due to mixing and residual mortar on equipment, planks on scaffolding. Mixing exposure preventable, difficult to wear protective equipment otherwise. Mineral Fibre: Suspected carcinogen, but respirable amounts are low due to large fibre size. Minimised use of binders.
3	×	Cement Plaster: Particulate matter from mixing poses risk of respiratory disease (silicosis, etc.). EPS: Unknown. Masonry: Long-term construction exposure may cause respiratory diseases such as silicosis of lung due to cement and lime dusts. Mineral Fibre: Potential concern of respiratory diseases developing after long-term use.

Question #	Use / maintenance: ecological concern	
1	✓	No significant ecological concerns due to materials/assembly properties during Use/Maintenance phase.

Question #	Use / maintenance: energy	
1	✓	High R-value.

Question #	Use / maintenance: solid emissions
	Minimal impacts from this stage.

Question #	Use / maintenance: liquid emissions
	Minimal impacts from this stage.

Question #	Use / maintenance: air emissions	
1	?	Some emissions from drywall system (VOCs) may pose problems for some individuals.
14	?	Concrete block has negligible emissions, but may be a source of radon (CMHC 1995). Dust from repair and maintenance is primary irritant in addition to impacts related to construction. Emissions once cured are insignificant. Emissions once cured are insignificant.

Question #	End - Use: ecological concern	
1	✓	Block is reusable in theory. Other materials aren't.
2	×	EPS not recoverable due to bonding with cement plaster.
6	×	EPS has polybrominated flame retardant.
9	?	

Question #	End - Use: energy	
ALL	?	

Question #	End - Use: solid emissions	
ALL	?	

Question #	End - Use: liquid emissions
	Minimal impacts from this stage.

Question #	End - Use: air emissions	
4	?	

G4 Checklist Comments for Wall # 4 - Steel Stud / EIFS

Question #	Material Production: Extraction -> Production: Materials Choice	
2	×	Polystyrene is from non-renewable sources and has low recycled content, but it minimises the use of cement plaster (as opposed to strawbale). Other wall components contain high percentages of recycled material (steel, gypsum board, mineral wool). Good use of recycled/waste materials overall.
5	?	
6	✓	No materials in restricted supply are used.
7	?	Emissions from galvanizing are potentially toxic to humans and ecosystems.

Question #	Material Production: Extraction -> Production: energy	
2	✓	Emissions/impacts from energy are similar to wood framed wall, waste streams are less energy intensive to recycle than from virgin sources.
3	✓	Steel is recycled, minimising virgin ore extraction. Mineral wool is recycled content. Polystyrene from virgin sources but could be recycled. Cement use in plaster is minimised.
5	×	815 MJ/m, GWP: 85 kg CO2 /m

Question #	Material Production: Extraction -> Production,: solid	
2	×	Steel is used, but primarily recycled and use is minimised by pre-cutting and efficient spacing. Other waste materials/flows are not significant.

Question #	Material Production: Extraction -> Production,: liquid	
2	×	Use of material in wall assembly has been minimised, but unreported metal emissions from steel production may be significant. Significant releases of phenols & cyanide. Eutrophication potential is low.

Question #	Material Production: Extraction -> Production,: air	
1	×	GWP below average (85.4 kg CO2), Acidification slightly below average (10.4 g H+). Significant emissions of HC and Phenols.
2	?	
3	✓	Blast furnace slag sent for manufacturing into insulation. FGD sent for gypsum board.
4	?	
5	?	
6	?	

Question #	Assembly Construction: ecological concern	
1	✓	Protection must be used for installation of mineral wool insulation, oils on studs may be a concern to hypersensistive individuals (CMHC, 1995)

Question #	Assembly Construction: energy	
1	?	Depends upon location, assume some ride sharing.
2	✓	Energy similar to wood framed wall, largely from power tools for cutting which can be minimised through design.
3	?	
4	?	Human labour is renewable (with rest and food!), electrical energy used for screw guns depends upon source of electricity.

Question #	Assembly Construction: solid emissions	
1	×	Drywall waste potentially significant but drywall may be recycled.
2	?	Planning and proper sorting may reduce amount of solid waste generated (steel, drywall, polystyrene). Plywood used as sheathing creates large amounts of waste if non-standard spacing, sizes used. Batts sized for common stud spacing increments & available in many sizes, thicknesses. Steel studs pre-cut.
3	?	Concrete, plasters (cured) safely used on-site as fill, unless toxic additives used. Polystyrene has potential use on site as soil amendment if ground up. Wood may be chipped/shredded on site for use as mulch, not suitable as fill. Plywood difficult to reuse on site due to spacing of studs. Extra insulation may be used in interior walls or added to other building elements (i.e. roofs). Use of Gypsum boards as fill causes acidification of soils and potential sulphate release.
4	✓	Some concrete plants produce concrete products from returned concrete batches (if not mixed on site). Polystyrene scrap material is recyclable. Steel is recycled. Plywood not recyclable due to binders used. Insulation scrap may be recycled and used as blown in/loose fill material by others. Construction gypsum waste recycling available in most urban areas.

Question #	Assembly Construction: liquid emissions	
1	?	Liquid releases predominantly from plastering activities.
2	✓	Cement render liquid waste is minimised by minimising thickness of application/total quantity.
3	×	Wastewater from cleaning of equipment is highly alkaline and is toxic to vegetation, aquatic species, but use is minimised.
4	×	

Question #	Assembly Construction: air emissions	
1	?	See wood stud wall.
2	?	Cement Plaster: Particulate matter from mixing requires protective equipment. Plywood: Depends upon number of cuts needed, can be minimised through design. Mineral Fibre: Suspected carcinogen, but respirable amounts are low due to large fibre size. Minimised use of binders.
3	×	Cement Plaster: Particulate matter from mixing poses risk of respiratory disease (silicosis, etc.). EPS: Unknown. Mineral Fibre: Potential concern of respiratory diseases developing after long-term use.

Question #	Use / maintenance: ecological concern	
1	✓	No significant ecological concerns due to materials/assembly properties during Use/Maintenance phase.

Question #	Use / maintenance: energy	
1	✓	High R-value

Question #	Use / maintenance: solid emissions	
	?	

Question #	Use / maintenance: liquid emissions	
	✓	No significant liquid impacts during this stage.

Question #	Use / maintenance: air emissions	
	?	Some emissions from drywall system (VOCs) may pose problems for some individuals.

Question #	End - Use: ecological concern	
1	×	Reuse of steel studs not likely, Highly recyclable and separable though.
2	×	EPS not recoverable due to bonding with cement plaster.
6	×	EPS has polybrominated flame retardant.
9	?	

Question #	End - Use: energy	
1	?	

Question #	End - Use: solid emissions
	Material/assembly's stage/context not considered.

Question #	End - Use: liquid emissions	
	?	

Question #	End - Use: air emissions	
4	?	