Estimating the Environmental Consequences of Building Envelope Failures

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ABSTRACT

There is reasonably widespread knowledge of the recent trend of large scale building envelope failures in North America. These failures are common in the Pacific coastal regions, but are also occurring in Atlantic coastal and interior regions of Canada and the United States. There have been numerous studies completed on the causal factors of these failures with some understanding of the financial consequences, but there has been little written about the environmental effects associated with these failures.

One important environmental effect associated with building envelope failures is the consequence of increased material use. Materials that fail to achieve a reasonable service life represent increased environmental effects associated with the production of new replacement materials. The environmental effects associated with the production, use, and disposal of materials are known as the embodied environmental effects of materials. Large-scale building envelope failures represent significant impacts to the environment due to these embodied material effects.

This paper will present a methodology to determine the environmental material effects associated with building envelope failures. The methodology will be demonstrated through two case studies in Ottawa, Ontario Canada. The case studies will involve one high-rise building and one low-rise building complex, and are based on real projects in recent years.

Embodied environmental material impacts were estimated using ATHENA's Environmental Impact Estimator software. The ATHENA software is an internationally recognized tool for obtaining comprehensive and reliable environmental life cycle burdens of buildings. It covers building material and system life cycle stages from the "cradle" (natural resource extraction or recycling facility) through to its "end-of-life" (grave). For this paper, results reporting of material effects will include aggregate ecologically weighted resource requirements, embodied energy, global warming potential, an index of air and water pollution effects, and solid wastes as indicators of environmental burden.

INTRODUCTION

In recent years there have been numerous widespread failures of building envelopes in many regions in North America. These include the residential EIFS failures in the southern US, the condominium envelope failures in the Northwest coastal regions North America, and similar failures in many other parts of the continent. The reasons for these failures have been extensively researched and reported, and are fairly well understood. The purpose of this paper is not to further explore the reasons for failure, but rather to explore one of the consequences of this type of failure. Specifically, this paper presents a methodology, with examples, to understand the environmental consequences associated with increase material use resulting from these types of failures.

Methodology: Embodied Environmental Effects

An environemental life cycle assessment tool was used to determine the embodied environmental effects of the various buidling envleope systems. A full life cycle assessment is a formal process of examining the environmental effects of a

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material or product through its entire life cycle, from raw resource or material acquisition through manufacture and use to waste disposal. Instead of a single attribute analysis of a material's environmental impact, such as its recycled content, LCA takes a "holistic" approach to the possible impacts of a material throughout its life cycle.

A life cycle inventory (LCI) is fundamental to an LCA. As the name implies, the LCI involves collecting and documenting data on the relevant environmental flows or burdens associated with the various life cycle stages, including transportation within and between stages and the upstream effects of energy use (i.e., the energy and emissions associated with producing and moving energy). While LCI/LCA has been around in various forms since the early 1960s, it was only in the mid-to-late 90s' that the protocol for completing such studies was standardized by the International Organization for Standardization (ISO14040-42). Currently, the Athena Institute's *Environmental Impact Estimator* (EIE) software[1] (v3.0) encompasses LCI profiles for steel, wood and concrete structural products and assemblies, as well as a full range of envelope materials (e.g., cladding, insulation, glazing, roofing, etc.). It also covers a building's life cycle stages from the "cradle" (natural resource extraction or recycling facility) through to its "end-of-life" (grave). Specifically the model encompasses the following building life cycle stages:

- *Product manufacturing.* includes resource extraction (from nature or the technosphere), resource transportation and manufacturing of materials, products or building components;
- *On-site construction.* includes product/component transportation from the point of manufacture to the building site and on-site construction activities;
- *Maintenance and replacement.* includes life cycle maintenance and replacement activities associated with the structure and envelope components based on building type, location and a user defined life for the building;
- *Building "end-of-life".* simulates demolition energy and final disposition of the materials incorporated in a building at the end of the building's life.

The software also includes a calculator to convert operating energy to primary energy and generate emissions to allow users to compare embodied and operating energy environmental effects over the building's life. It was determined to ingore operating energy implications: It was felt that any effects on operating enregy, such as those due to changes in the envelope or changes in budling energy use durigi retrofit work, would be minimal in most cases.

In terms of results, the software provides a detailed environmental life cycle inventory of the embodied effects associated with the building as well as a set of six summary measures. These summary measures include primary (embodied) energy and raw material use; greenhouse gas potential (both fuel and process related); measures of air and water pollution; and, solid waste emissions. For this paper, results reporting of material effects has been purposely limited to embodied energy and global warming potential as indicators of environmental burden.

Embodied primary energy is reported in Giga-joules (Gj) and includes all non-renewable energy, direct and indirect, used to transform or transport raw materials into products and buildings. Also included in this measure is the inherent energy contained in raw or feedstock materials that are also used as common energy sources. (For example, natural gas used as a raw material in the production of various plastic (polymer) resins.) In addition, the model captures the indirect energy use associated with processing, transporting, converting and delivering fuel and energy. Global Warming Potential (GWP) is a reference measure for greenhouse gas emissions and is reported on a mass basis. Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "CO2 equivalence effect" which is simply a multiple of the greenhouse potential (heat trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time. As yet, no consensus has been reached among policy makers about the most appropriate time horizon for greenhouse gas calculations. The International Panel on Climate Change100-year time horizon figures have been used here as a basis for the equivalence index:

$$CO_2\text{Equivalent } t = CO_2 t + (CH_4 t \times 23) + (N_2O t \times 296)$$

(t = tonnes)

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modelling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcination of limestone). Because Athena™ uses data developed by a detailed life cycle modelling approach, all relevant process emissions of greenhouse gases are included in the resultant global warming potential index.

The software and its embedded databases are North American in scope, representing average or typical manufacturing technologies and appropriate modes and distances for transportation. The model simulates 12 geographic regions represented by Vancouver, Calgary, Winnipeg, Toronto, Ottawa, Montreal, Quebec City, Halifax, Minneapolis, Atlanta, Pittsburgh and a US Average. This study drew on the Ottawa regional database. The results also exclude any maintenance or "end-of-life" effects due to limiting the assessment to the building's first twenty-years.

1. Information available at www.athenaSMI.ca

Buildings Reviewed

Two buildings were reviewed as part of this project: a real commercial high rise building, and a low-rise residential row unit complex, each of which suffered a major building envelope failure. Each of these sites is based on real projects that were undertaken in 2005/2006 in the Ottawa area. Due to client confidentiality, the specific names and addresses of these projects are not presented. More information on each project is included below:

High Rise Commercial Building. This building was originally constructed circa 1998. It is a high-rise building in a Canadian cold climate zone was diagnosed with systematic water penetration through the Exterior Insulation and Finish System ("EIFS") building envelope. This building utilized a factory-manufactured, modular panelized cladding system for the exterior walls that included EIFS building envelope components. The original panel design had some components intended to perform as a "drained" system which, when coupled with a factory controlled manufacturing environment, is normally considered a lower risk, higher performance, good practice approach. Nevertheless, there was water penetration into the interior, with resulting water damage and related environmental problems to panel structural components and interior finishes.

This building has undergone a large-scale exterior recladding in the affected areas in 2006. The repair involved the removal of all exterior wall building envelope components, a re-design of the building envelope system that included the use of a new drained EIFS approach, and the installation of the new wall system on the building. The new assembly was similar in design and appearance of the original assembly, but incorporated some important modifications, including better detailing and the use off a drainage layer material. The original wall assembly consisted of:

- Vinyl wall covering
- Polyethylene sheeting
- 12.7 mm (1/2") gypsum board
- 92 mm (3.5") steel studs
- Glass fibre reinforced gypsum sheathing
- EIFS system (3" expanded polystyrene, latex based lamina)

Low Rise Residential Row Units (Stacked Townhouses). This complex consisted of 105 stacked townhouse units that were originally constructed circa 1995. This complex was located in Ottawa, Ontario, Canada. The complex was clad in a combination of PVC siding, clay brick, and split faced concrete block. Three storey wood frame d balconies were present at the fronts and backs of the units.

Water penetration was noted by the owner soon after construction, and an ineffective program of remediation was implemented. Around 2002, the owner concluded that the windows were the reason for the water leakage, and began the process to have the windows replaced. During this process, it was discovered that the problem was poor detailing, no only at the windows but also at balconies, through wall flashings, doors, and changes in cladding. These problems lead to major degradation of many exterior wall areas. The rehabilitation work included replacement of all windows, wood framed balconies, exterior PVC cladding, and selected areas of brick split faced concrete block cladding. The finished product was similar in nature to the original, but incorporated better detailing, a functional drainage layer, PVC framed windows (instead of wood), and PVC cladding (to replace aluminum cladding). The original wall construction consisted of:

- Latex based paint
- Polyethylene sheeting
- 12.7 mm (1/2") gypsum board
- 152 mm (5.5") wood studs with glass fibre insulation
- 12.7 mm OSB sheathing
- 15 lb asphalt impregnated felt building paper
- Either aluminum, brick, or split faced concrete block cladding

Material Environmental Effects Due to Premature Failures

Most constructed systems, including systems used within buildings, are intended to provide a defined service life. This defined service life varies across the different element: A light bulb might be expected to survive 2 years, while a roof might be expected to last 20 years. Building elements that fail to achieve a reasonable service life, regardless of the cause, typically result in increased material use from the resulting repairs or replacement work performed.

For this paper, we are concerned only with a systems inability to reach a service life, and not with the reasons for a premature failure. A failure of a sheathing material may have little to do with the sheathing itself, but rather with the detailing of a window, for example. Regardless, it was the sheathing that did not reach its service life, and the sheathing that required repair or replacement and the resulting material effects. Accordingly, this paper does not in any way imply that any building material is or was appropriate or inappropriate for its intended use.

From a material durability perspective, there are two fundamental types of building material or systems, those which are expected to survive the life of the building, and those which are expected to be periodically replaced. These systems must be considered differently in estimating the environmental effects of premature building envelope failures.

Elements that were expected to survive the life of the building, but were replaced as a result of premature building envelope failures, result in the use off new materials that would not have been utilized had there not been a premature building envelope failure. For example, a wood stud wall assembly should last the life of the building, and replacement of that wood stud assembly with a different assembly results in the extraction, production, transportation, operation, and demolition effects of the new assembly. On the assumption that both the high and low rise building would survive 60 years,, the following elements or systems were assumed to be capable of providing a similar service life:

- Interior gypsum board
- Polyethylene sheeting
- Steel and wood stud wall assemblies
- Batt insulation within stud wall assemblies
- Exterior sheathings and drainage planes
- Brick cladding
- Split faced concrere block cladding

Estimating the effects of elements that would be cyclically replaced is not as simple, and requires a number of assumptions, such as an estimation of the total life of the building and the life and nature of future cyclic replaced elements. Fundamentally, the effect of a premature failure of a cyclical building element is the use of a similar replacement element prior to when it should have been used (had it achieved a typical service life). However, the early replacement of a cyclically replaced element may not result in a dramatic increase in material use over the life of the building because of the possibility of wasted service life near the end of the building life. This is best described with an example: If a building is expected to service 50 years, and a roofing system is expected to last 20 years, then the last roofing system will be removed at building demolition, despite the roofing system having 10 years of life remaining (wasted service life). Accordingly, if any single roofing system in the life of the building achieves only a 10 year life (instead of the expected 20 year life), then the complex would still only require three complete roofing systems, so there would be no increase in the number of roofing systems used, and little overall environmental effect from that single premature roofing failure. However, there are several other complicating issues in the estimation of the embodied effects off premature replacement of cyclic items,:

- Many building elements evolve over time: A roof system in 2007 is not likely to be replaced with an identical system in 2050. Materials and technologies, as they evolve, result in changes to elements in buildings, and even to the popularity of entire systems. For example, a built-up roofing assembly would typically utilize coal tar pitch in the 1960's, and roofing asphalt in the 1980's. Another example is that aluminum siding installed in the 1970's or 1980's is typically replaced with PVC siding today (due to changes in material costs and technologies).
- Evolution of environmental effects: The environmental effects of materials evolve over time as new energy technologies and processing techniques become available, and as the nature of the energy grid changes. The premature failure of a cyclical element will have the result of changing the time in which future similar elements are replaced, even if the total number of elements in the life of the building does not change. These shifts in time will result in a change in environmental effects.
- Evolving character of buildings: As buildings age, their character typically changes. A new building is typically maintained well for a period of time, but this level of maintenance often drops over time. Often, near the end of life of a building, maintenance will drop far below what is typical, with the understanding that a major retrofit or demolition is imminent.

The above issues are difficult to resolve, as they depend on the nature of the building, the owner, and further trends that are difficult to estimate. For this paper, assumptions were made that (i) each building will be maintained to a reasonable degree through its life cycle, (ii) each building would incorporate identical cyclic elements (as they are replaced), and (iii) the embodied effects of the new assembly would be identical to those of the final assembly on the building.

A list of the cyclically replaced items, and their typical estimated service lives is presented below:

- Vinyl wall covering, 6 year service life
- Latex based paint finish, 8 year service life
- PVC cladding, 20 year service life
- EIFS cladding, 20 year service life
- Wood windows, 20 year service life
- Wood balconies, stairs, and decks, 20 year service life

Using the 60 year building life assumption noted above, and with the understanding that the rehabilitation work was performed in year 8 of the high rise building and year 11 of the low rise building, it would be reasonable to assume that the premature failures resulted in one additional cyclic replacement for all elements except the vinyl wall covering (it only had one year of remaining life a the time the work was performed).

EMBODIED ENVIRONMENTAL EFFECTS

The embodied environmental effects of the relevant items replaced during the work was estimated using the Athena EIE software:

To put these numbers into perspective, table 3 and figures 1 and 2 provide comparisons between the embodied environmental effects for the low and high rise building envelope failures to the embodied effects of the entire buildings, including structural, envelope and interior wall finishes. Table 3 also includes a comparison to the annual operational environmental effects of an efficient (Energystar) 2200 ft^2 house in Ottawa.

DISCUSSION

The results presented above are for demonstration purposes only. Material environmental effects will vary by location and by the degree of rehabilitative work required. A cursory sensitivity analysis was performed on the two projects

Table 1. High Rise Complex Embodied Environmental Effects

Element	Steel Stud Wall Assembly (Including Interior Gypsum Board, Polyethylene, Studs, Insulation, and Exterior Sheathing)	EIFS Assembly	Total
Primary Energy (MJ)	1,226,555	379,162	1,605,717
Solid Waste (kg)	20,022	263	20,285
Air Pollution Index	15,986	2,996	18,982
Water Pollution Index	230	1	231
Global Warming Potential (Equiv. CO_2 kg)	63,007	15,129	78,136
Weighted Resource Use (kg)	173,152	12,943	186,095

Table 2. Low Rise Complex Embodied Environmental Effects

Element	Wood Stud Wall Assembly [1]	Cladding (Pvc, Brick, Block)	Wood Decks, Stairs, and Railings	Windows	Total
Primary Energy (GJ)	140049	1002425	146204	731140	2019818
Solid Waste (kg)	2408	3717	5657	3260	15042
Air Pollution Index	1653	12867	1238	12289	28047
Water Pollution Index	0	1	32	3	36
Global Warming Potential (Equiv. CO_2 kg)	4772	43111	7435	50029	105347
Weighted Resource Use (kg)	31649	92040	71600	36279	231568

[1]Including interior gypsum board, polyethylene, studs, insulation, and exterior sheathing.

Table 3. Results Comparisons

	Low Rise Building Embodied Effects		High Rise Building Embodied Effects		Operating Energy
	Envelope Failure	Whole Building	Envelope Failure	Whole Building	Energystar home
Primary Energy (MJ)	2,019,818	8,200,000	1,605,717	29,000,000	106503
Solid Waste (kg)	15,042	275,000	20,285	900,000	223
Air Pollution Index	28,047	205,000	18,982	668,000	2625
Water Pollution Index	36	314	231	1,400	0
Global Warming Potential (Equiv. CO_2 T)	105	500	78	2400	5478
Weighted Resource Use (kg)	231,568	3,100,000	186,095	19,000,000	1973

noted above, simply by switching the locations of the building to other locations, and it was found that most effects varied by as much as 25% between the best and worst case locations. Accordingly, it is important to perform the analysis shown for each specific project in order to gain a realistic understating of the environmental effects.

However, regardless of the sensitivity of the results, this paper has demonstrated how the embodied effects associated with premature building envelope failures can be determined, and the potential magnitude of these types of failures compared to other relevant environmental effects.

For the two example projects, it was found that the embodied effects of the building envelope failures for each example represented less than 25% (and as low as 1%) of the total embodied effects of their respective buildings. However, the effects are not meaningless, as they can also be shown to represents between 10 and 100 years of operational effects for a single family home (dependent on the summary measure).

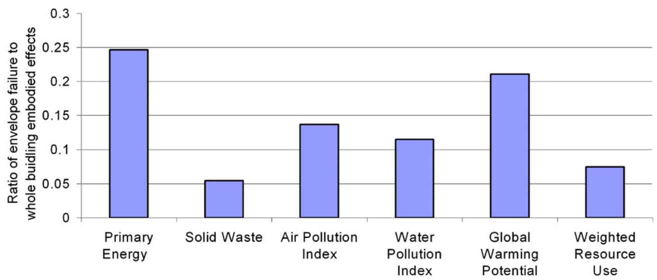

Figure 1 *Embodied environmental effects results comparisons: single family home.*

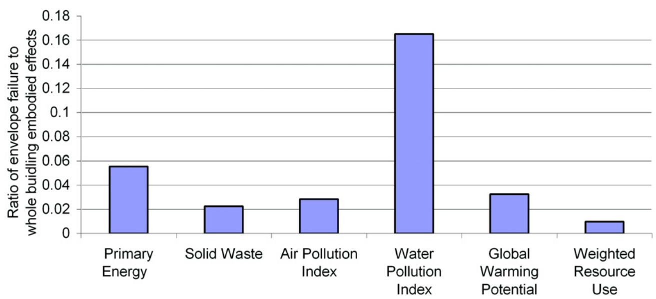

Figure 2 *Embodied environmental effects results comparisons: high rise.*

Note that the variability in results is due to the nature of the comparison. The operational effects are largely energy related, with relatively small waste, water, and resource use impacts (energy production tends to have relatively small effects on these measures of environmental degradation). Accordingly, the comparison of impacts between material and energy use should not rely on these impact measures as a means of determining relevance. It is suggested that the other indicators, namely embodied energy, global warming potential, and air pollution, are meaningful indicators for both material and energy, so that comparisons of these indicators between embodied and operational effects would be valid. Note that when we limit the comparisons to these indicators, the embodied effects of each example represented between 10 and 20 years of operational effects for a single family home (dependent on the summary measure).

Embodied energy and global warming potential (CO_2) are popular measures of estimating environmental effects: Accordingly, it is worthwhile presenting these summary measures separately from the rest:

- For these projects, the embodied energy represented approximately 20 years of operational effects for a single family home and between 3 times the total embodied effects of a 2200 ft^2 single family home.
- For each of the example projects, it was found that 80 to 100 Tonnes of CO_2 was emitted to the atmosphere as a result of the increase material use associated with the building envelope failures.

SUMMARY

This paper has demonstrated how the embodied effects associated with premature building envelope failures can be estimated, and the magnitude of these types of failures compared to other relevant environmental effects.

This paper demonstrated the methods to estimate the embodied environmental effects using two real examples of building envelope failures in Ottawa Ontario Canada. The first was a high rise building which required complete exterior wall replacement eight years after construction, and the second was a low rise complex which underwent a variety of exterior wall and balcony work eleven years after original construction. The environmental effects associated with increased material use were calculated using the Athena Environmental Impact Estimator Software, and were compared to the embodied and operational effects of an energy efficient single family home in Ottawa. The environmental impacts were estimated using six (embodied) impact measures: Primary Energy, Solid Waste, Air Pollution Index, Water Pollution Index, Global Warming Potential, and Weighted Resource Use. It was found that the relevant embodied effects of each example of a building envelope failure represented between 10 and 20 years of operational effects for a single family home (dependent on the summary measure) and between 1 to 3 times the total embodied effects of a 2200 ft^2 single family home.

Embodied energy is a popular measure of embodied environmental effects, and it is worthwhile presenting this summary measure separately from the rest: For these projects, the embodied energy represented approximately 20 years of operational effects for a single family home and between 3 times the total embodied effects of a 2200 ft^2 single family home.

Another popular measure of quantifying environmental effects is the amount of CO_2 emitted to the atmosphere. For each of the example projects, it was found that 80 to 100 Tonnes of CO_2 was emitted to the atmosphere as a result of the increase material use associated with the building envelope failures.

Typically, the effects of failures are presented as primarily economic, yet clearly, these material effects are significant and should not be ignored. This is particularly relevant in this age when environmental effects are known to be resulting in climate change.

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