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The Environmental Side of Sustainability:

Using Life Cycle Assessment to Assess True Performance

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INTRODUCTION

The focus of this paper is on the environmental aspects of sustainability in relation to infrastructure. However, the word 'infrastructure' is one of those relatively vague terms that can refer to a wide range of facilities and systems required to support the functioning of society. Most often, we think in terms of public facilities provided by various levels of government or by regulated utilities, especially transportation, communications, water supply and sewage treatment facilities. But infrastructure also encompasses schools and a variety of light industrial (e.g., garages, workshops, and warehouses), institutional, and office buildings (e.g., courthouses and municipal offices).

From an environmental perspective, the complexity of facilities ranges widely, from relatively straightforward structures such as a highway bridge or utility pole to highly complex facilities such as a water treatment plant. Irrespective of where a facility is on the spectrum, however, all have in common a life cycle that involves design, construction, operations and maintenance, and eventually, for most, de-commissioning and disposal. Throughout this life cycle, our approach to materials is a key determinant of ultimate environmental effects, and that starts with design. In some ways, the life cycle implications of design decisions are even more important in the case of infrastructure, compared to other aspects of the built environment, precisely because such facilities are generally dominant in terms of their social and economic significance, the required capital investments, and the scale of operations both geographically and over time.

When faced with material decisions, there are no simple measures or rules of thumb that make the selection process easy and we are constantly forced into a balancing act, trading off a good effect here with a not-so-desirable outcome there. Even in the case of a simple utility pole, the decision to use steel, wood, or concrete has cost, construction, maintenance and end-of-life implications that in turn have implications for energy use, global warming, toxic releases to water, biodiversity and a variety of other measures.

This paper, and the accompanying presentation, focuses on life cycle assessment (LCA) as an increasingly important method for making decisions throughout the entire decision process from conceptual design through specification and procurement. The sections that follow provide a brief overview of LCA, highlight some of the tools that are available, address some concerns and cautions with regard to materials selection, and present a case study where LCA has been used to compare alternative materials for road construction.

LIFE CYCLE ASSESSMENT

Put simply, LCA is a methodology for assessing the environmental performance of a product over its full life cycle, often referred to as cradle-to-grave or cradle-to cradle analysis. Environmental performance is generally measured in terms of a wide range of potential effects, such as the following:

- fossil fuel depletion;
- other non-renewable resource use;
- global warming potential;
- stratospheric ozone depletion;
- ground-level ozone creation (smog);
- nutrification/eutrophication of water bodies;
- acidification and acid deposition (dry and wet); and
- toxic releases to air, water, and land.

All of these measures are indicators of the environmental loadings that can result from the manufacture, use and disposal of a product. The indicators do not directly address the ultimate human or ecosystem health effects, a much more difficult and uncertain task, but they do provide good measures of environmental performance on the premise that reducing any of these effects is a step in the right direction.

In the application of LCA, we use the term <u>initial embodied effects</u> for the effects associated with the manufacture, transport and installation of all materials used in the construction process. The subsequent materials-related effects of maintenance and replacement activities throughout the use phase of a structure or product are referred to as <u>recurring embodied effects</u>. We could add a third category, <u>final or end-of-life embodied effects,</u> to cover the demolition and disposal effects. However, although these effects can be important and should be included, they are highly speculative given that most infrastructure constructed today is unlikely to be demolished for several decades, if then. Finally, there are <u>operating effects</u>, such as water and energy use that are especially significant in the case of buildings, but also in the case of other infrastructure such as roads and underground utilities.

The LCA of a product or system should take account of the production and use of other products required for cleaning or maintenance during the use phase of the life cycle. For example, we should take account of restorative/maintenance measures for concrete roadways or bridges, such as crack and joint resealing. We must similarly take account of the replacement of individual products such as roofing or cladding through the life cycle of a building.

When it comes to buildings, the tendency is to focus on embodied energy and to then compare it to operating energy. The inevitable conclusion is that operating energy is so much greater over the life of a building that we should not devote much time and effort on concerns about embodied energy, and therefore should not undertake LCA. From this perspective LCA is treated as synonymous with embodied energy. However, as the above list of environmental impact measures makes clear, embodied effects go well beyond energy to include a wide spectrum of emissions to air, water and land. Solid wastes are generated during the resource extraction, manufacturing and on-site construction stages of the life cycle; significant air emissions are generated during all of the intermediate transportation steps; and toxic releases to water and air are almost entirely a function of product manufacturing as opposed to building operations. Moreover, it takes energy to make and move energy in useful forms, and those production processes, in turn, result in various kinds of emissions called pre-combustion effects.

The final point to note about LCA is that it is not the same as life cycle costing (LCC). The two methodologies are complementary, but LCC focuses on the dollar costs of constructing, maintaining and operating a facility over its life cycle, while LCA focuses on environmental performance measured in the units appropriate to each emission type or impact category. For example, global warming gases are characterized in terms of their heat trapping effects compared to the effects of CO_2, and global warming potential is then measured in equivalent tonnes of CO_2.

A TOOL CLASSIFICATION SYSTEM

There are a variety of tools available to help with the design and project delivery process, but there is often confusion about which tool is best used for which task and at which stage in the process. The Athena Sustainable Materials Institute therefore developed a simple tool classification system to help sort the toolkit. The system suggests three main levels of tools, labeled simply as Level 1, 2, and 3, dealing with the spectrum from individual product decisions through to whole building assessment and rating systems.

Level 1 tools can be used to assess and compare individual products or reasonably straightforward assemblies such as such as pipelines, bridges or roads. These tools are used to make comparisons in terms of environmental and/or economic criteria, especially at the specification stage of project delivery.

With regard to LCA, the Level 1 tools can be further grouped into those intended for use by LCA practitioners — **Level 1A tools** — and those intended for people who want the answers with the detailed LCA work done in the background — **Level 1B**. SimaPro (www.pre.nl/simapro), GaBi (www.gabi-software.com) and Umberto (www.umberto.de) are examples of Level 1A tools for LCA practitioners. *BEES* is a Level 1B tool developed by the U.S. National Institute of Standards and Technology (www.bfrl.nist.gov/oae/software/bees.html) so that design teams can make product-to-product comparisons based on LCA and LCC data, without having to actually undertake LCA or LCC studies.

One could argue that labeling systems like the *Environmental Choice* program (www.environmentalchoice.com) operated by Terra Choice (www.terrachoice.ca) and various forest certification systems are also Level 1 tools. The caution is that many labeling programs focus on single attributes, or performance measures (energy use or recycled content, for example), and may therefore be misleading when they convey a ‘green’ label. The product in question may indeed be excellent in terms of the criteria selected for the evaluation, but that does not necessarily mean it would score well in a full LCA that takes more attributes into account.

Level 2 tools focus on whole facilities, or on complete assemblies or elements, with each tool typically providing decision support with regard to specific areas of concern such as operating energy, lighting, life cycle costing, and life cycle environmental effects. These tools tend to be data-oriented and objective, and apply from the early conceptual through detailed design stages. Examples include energy simulation tools such as EE4 (www.buildingsgroup.nrcan.gc.ca/ee4), life cycle costing tools, and the Athena *Environmental Impact Estimator (www.athenasmi.ca/tools/software)* for doing LCA at the whole building level.

Level 3 tools are whole building assessment frameworks or systems that encompass a broader range of environmental, economic and social concerns or issues considered relevant to sustainability. They use a mix of objective and subjective inputs, leaning on Level 2 tools for much of the objective data — energy simulation results, for example. All use subjective scoring or weighting systems to distill the information and provide overall measures, and all can be used to inform or guide the design process. Green Globes® (www.greenglobes.com) and LEED® (www.cagbc.org) are examples.

Eventually, we will see the development of a Level 4 category of tools for decision support at a broader campus, neighbourhood or community level. Such tools are already in development to help us to better understand the interrelationships among buildings and between buildings and the supporting infrastructure.

It is important to be aware, and take advantage of, the complementarities among tools, even those in the same classification level. Too often we see comparisons based on the implicit assumption that all LCA tools are competitive, without regard for their intended function or where they fit in the decision process. The reality is that seemingly similar tools in the same level can complement each other. Pliers and vice grips may appear to do essentially the same job, but each has it own special function and a well-stocked toolkit will hold both.

MATERIALS FROM A SUSTAINABILITY PERSPECTIVE

We would all welcome rules of thumb or labels to tell us which materials or products are truly green, taking all factors into account over the whole life cycle. The unfortunate fact is that we can't get those answers without formal life cycle assessment or some equally thorough approach. In the absence of that kind of information, we should regard seemingly easy answers with caution. This section highlights some key factors to bear in mind when making product comparisons or selections.

Maintaining Functional Equivalence

We should be especially careful to ensure that product comparisons are truly apples-to-apples comparisons. In LCA-based comparisons, we use the term 'functional equivalence' when referring to the problem of ensuring that two or more products provide the same level of service. Ensuring functional equivalence is more straightforward for some comparisons than others. In the case of a utility pole, for example, we could define functional equivalence in terms of basic dimensions and load bearing capacity. Intended service life could also be added as an element in the definition, or it could be accounted for by maintenance and replacement considerations in the LCA itself, assumed a defined study period.

Given a proper functional equivalence definition, material options can be fairly compared using LCA. However, functional may not be so easily defined in more complex assemblies because the choice of one product may lead to, or even require, the choice of other products. For example, the choice of wood, steel or concrete structural systems for a building will likely influence, or even dictate, the choice of insulation materials, and an above-grade assembly using high mass materials may require more concrete in footings than a lighter assembly.

These are examples of situations where product comparisons should take account of other material-use implications of the alternatives. In other words, material comparisons should be made in a systems context rather than on a simple product-to-product basis. Even though two products may appear to be equivalent in terms of specific criteria like load bearing capacity, they may not be at all equivalent in the sense of true functional equivalence.

In a similar vein, we should be careful to take account of all the components that may be required during construction to make use of a product. Rebar goes hand in hand with concrete and an asphalt concrete road requires the use of more aggregate than a Portland cement concrete road.

Not all products pose a functional equivalence problem to the same degree. In general, product-to-product comparisons are more likely to be misleading when dealing with complex assemblies, such as a building structure and envelope or a large bridge, where the systems context is key. Product-to-product comparisons are more realistic for simpler assemblies, such as the utility pole example, or for building components such as window systems. Although part of the envelope, windows are typically delivered to a construction site as pre-assembled components that can be compared to each other in terms of thermal performance or other criteria, without too much regard for broader systems implications.

In short, we can think in terms of a continuum from very systems oriented products at the one end of the scale to more stand-alone products at the other end. The task is to exercise caution and judgment to make sure any given comparison is legitimate and fair.

Conventional Wisdom vs. Objective Analysis

There is a body of conventional wisdom about the environmental effects of materials that does not always stand up to objective analysis — recycling should always be preferred, agricultural products are more friendly than long-rotation renewable, local purchasing is best, durability is a direct function of material properties, and so on. In some cases, recycling for example, there is a confusion of ends and means, with the means becoming objectives in their own right to the possible detriment of environmental performance. It is too often presumed that using recycled materials will automatically result in reduced environmental burdens. However, this may not always be the case, and recycling may be more or less beneficial depending on the situation. There is no doubt that recycling can save landfill space, but the process of recycling a given product may take more energy and adversely affect air or water quality more profoundly than would production from virgin resources. The focus on recycling ignores this possibility and implicitly gives more weight to solid waste and resource depletion issues than to global warming or other measures.

The point is not that one issue or indicator is more important than the other, but that commonly held beliefs or assumptions appear to take precedence over data and facts in the decision process. In fact, recycling is probably the best example of a confusion of ends and means. Recycling has always been only a means to the objective of reduced flows from and to nature, but over time it has taken on the mantle of an objective in its own right.

In the case of local purchasing, the presumption is that local purchasing will reduce environmental footprints because of the reduced transportation requirements. That may indeed be the case if we know that the local manufacturer of a product has an efficient plant in terms of energy, water and resource use, and is at least an acceptable performer in terms of toxic or other releases to the air, water and land. We also have to ask whether a local supplier is drawing inputs from very long distances or from poor environmental performers. And, finally, we have to recognize that different transportation modes have different environmental implications per tonne-kilometer of transportation service; local purchasing should be defined in terms of short distances for suppliers entirely dependent on truck transportation, longer when rail is used, and longer still for water transportation.

THE RELATIVE ENVIRONMENTAL MERITS OF MATERIALS

Irrespective of the facility, the design task is to use materials in the best combination from an environmental perspective, while meeting all of the service life, aesthetic, cost and other design criteria. As previously noted, deciding among materials usually involves trade-offs that reflect the full range of manufacturing, use and disposal effects. To understand some of the trade-offs, it is useful to look briefly at two of the principal materials used in infrastructure — steel and concrete.

Steel offers high post-industrial and post-consumer recycled content, resistance to pests, and high recyclability. Its manufacture, however, requires high energy input and can result in significant levels of water pollution, although the industry has made tremendous strides over the past 10 to 15 years in reducing emissions to water. The ultimate significance of the high energy use depends in part on the energy forms used directly or to generate electricity, especially for the 'mini-mills' that use electric arc furnace technology.

Concrete is the most widely used of all construction materials. At the same time, it is a material that seems to be subject to an unusual level of myth and misunderstanding among members of the green design community, and therefore deserves a somewhat more detailed discussion.

Concrete is typically made from locally available and abundant raw resources, with aggregates accounting for a large proportion of the total mass of concrete. The extraction and processing of the basic raw materials is relatively benign, with environmental concerns focused on the high levels of carbon dioxide released during the manufacturing of Portland cement. These CO_2 releases are unquestionably high. However, Portland cement is just a component of concrete, accounting for only about 7 to 15% of the mass of concrete, depending on the strength. Concrete is the building material, and cement is just one ingredient in the recipe, a critical distinction that relates to the issue of functional equivalence and is too often ignored. Concrete is certainly not as CO_2 intensive, and therefore detrimental, as often presumed.

The use of fly ash, or other supplementary cementitious materials (SCMs), as a substitute for Portland cement in the concrete mix is one way to make concrete a more environmentally friendly material. But again there are misconceptions about the nature and use of SCMs, especially fly ash. Fly ash comes from power plants that burn coal, and not all fly ash is created equal. It depends, for example, on the type of coal burned, the efficiency of the furnace burning the coal, and the emission control technologies in place. Since the making of concrete is essentially a chemical process, the exact make-up of fly ash can be a critical factor in the mix, and can have a direct bearing on the amount of substitution of fly ash for Portland cement that is practical in a given situation. Substitution at levels above 25 to 35% requires very careful batch testing of the concrete. Substitution levels in the order of 60% or more can be achieved through the replacement of Portland cement by blast furnace slag, a waste from steel production that is itself a cementitious material if appropriately treated at the steel plant. But again, this is not necessarily a straightforward process, with potential concerns such as set-up and curing times depending on the ambient temperatures.

The point here is that all materials have their positive and negative sides from an environmental perspective, and that even seemingly obvious ways to overcome the negatives are not always as clear cut as they appear to be at first glance. The subject of 'green materials' is complex no matter which material is under consideration, including bamboo, agricultural products, or other high profile 'green' alternatives. The more complex the assembly, the more important it is to ensure that each material is used to its best advantage, and to optimize around the full life cycle in terms of the entire assembly. This requires a focus on environmental implications at the earliest possible stage in design and material selection.

CONCRETE VS. ASPHALT ROADWAYS: AN LCA CASE STUDY

The Athena Institute recently completed a study comparing the embodied primary energy (i.e., with pre-combustion effects taken into account) and global warming potential (GWP) associated with the construction and maintenance of various kinds of Canadian roads. The study provides a good example of the application of LCA techniques to the materials side of infrastructure design decisions.

The study compared asphalt (flexible) and Portland cement based (rigid) concrete across the following road types and regions:

- Canadian (average) arterial roadways;
- Canadian (average) high volume highways;
- a Quebec urban freeway; and
- a section of the Highway 401 freeway in Ontario.

The primary study unit was a two-lane kilometer (including inner and outer shoulders) of functionally equivalent road, with functional equivalence defined in terms of accepted road design criteria. The study unit was changed to a three-lane kilometer (including inner and outer shoulders) for the analysis of the Highway 401 tangent section in Ontario. In all cases, the assumed study period was 50 years, a period which takes into account original road construction and major rehabilitation activities for both asphalt and Portland cement concrete road types.

Study Scope and Boundaries

For all road type cases, the system analysis boundaries were set at the subgrade and the finished road and shoulder surfaces. The study therefore took account of material use and construction for the granular sub-base, base, shoulder and finished road and shoulder surfaces. It excluded right-of-way clearing, subgrade construction, lane divider painting, barrier construction, right-of-way restoration and other activities common to both concrete and asphalt roadways. It also excluded energy use for lighting in urban areas, which has been found to be a significant factor in some European studies, and other operational considerations that may differ by road type such as energy use by trucks. These types of effects should be considered and taken into account in any decisions predicated on life cycle environmental effects, but they were beyond the scope of this study.

The flexible and rigid Canadian average arterial and high volume roadway designs were developed in a separate report prepared for the Cement Association of Canada (CAC) by Applied Research Associates (*Pavement Engineering Technical Services Equivalent Pavement Designs, Flexible and Rigid Alternatives*, December, 2003). The report considered two soil foundation types for each road type and material design. Provincial Ministry of Transportation staff developed both the Quebec freeway and the Ontario Highway 401 flexible and rigid roadway material quantity take-offs.

Since the study dealt with embodied primary energy and greenhouse gas emissions for initial road construction and major rehabilitation activities, it primarily reflected the effects of producing and transporting materials and components (e.g., concrete, asphalt, dowel and tie bars, granular materials, recycled materials, etc.).

Method

Regionally specific estimates were developed for the primary energy and greenhouse emissions associated with the production and transportation of a unit (i.e., m3 or tonne) of each of the materials identified as potentially significant during pavement design. The primary energy estimates included the upstream or pre-combustion energy necessary to extract, produce, and transport primary fuels to their point of use. In the case of electricity generation, the study also accounted for generation efficiency by fuel type as well as transmission line losses to estimate the net primary energy and greenhouse gas emissions associated with delivering a unit of electricity.

Separate energy and greenhouse gas emissions estimates were developed per m3 of asphalt concrete, assuming 0 and 20% recycled asphalt pavement (RAP) in the final asphalt concrete hot mix.

As well, the asphalt concrete energy estimates included the inherent or feedstock energy[1] attributable to new asphalt (as opposed to RAP). The feedstock energy component of

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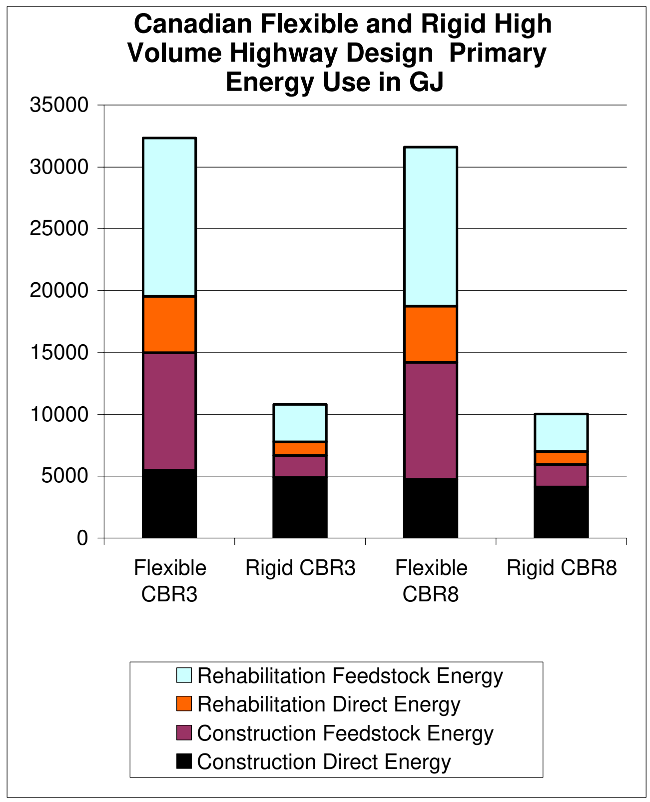
[1] Feedstock energy is the gross combustion heat for any material input to a product system that may be considered as an energy source, but is not being used as an energy source. Bitumen clearly falls into this category. The Alberta tar sands are an excellent example of bitumen being extracted and refined for energy production purposes.

total embodied primary energy was depicted separately in all of the results so that its significance could be readily seen.

All greenhouse gas emissions estimates (CO_2, CH_4 and N_2O) were converted to a measure of direct global warming potential (GWP) using the well-accepted CO_2 equivalence method as developed by the International Panel on Climate Change (*3rd Assessment Report, Technical Summary, Working Group 1*, 2000). The energy and GWP estimates per unit of material were then combined with the pavement structure design and rehabilitation quantity take-off scenarios to develop comparative embodied primary energy and GWP estimates per roadway functional unit (a two- or three-lane kilometer) for each of the asphalt and Portland cement based concrete alternatives.

Results

The figure opposite shows the embodied primary energy results for flexible (AC) and rigid (PC) designs for a two-lane kilometer of the Canadian high volume highway for two soil foundation support classes (California Bearing Ratios — CBR3 and CBR8). Although the absolute numbers changed from one road class and region to another, the pattern of results was similar for the other four roadway designs.

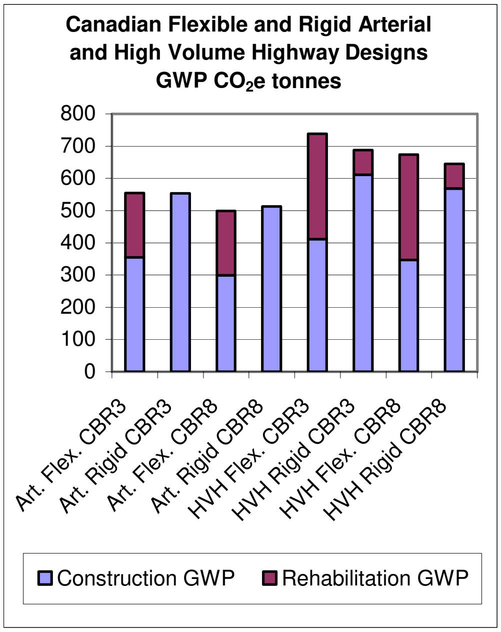


For all six pavement structure design comparisons, the asphalt concrete alternatives clearly required significantly more energy than their Portland concrete counterparts from a life cycle perspective. Across the two-lane kilometer designs, it was noted that the energy advantage of Portland concrete roadways grew as soil bearing capacity declined or as the class of roadway increased.

The feedstock energy component was the largest contributor to total energy for all of the asphalt pavement structures. Even when feedstock energy was excluded, Portland cement based concrete still enjoyed a significant energy advantage relative to its asphalt counterpart.

The inclusion of 20% RAP in the binder course mix for the Canadian arterial and high volume highway designs reduced the total primary energy estimates by 3.5 to 5% for the rigid Portland cement-based highways, and from 5 to 7.5% for the flexible asphalt highways. While these reductions in energy use for asphalt concrete narrowed the gap between asphalt and Portland concrete, the remaining differences were still significant, especially at the total primary energy level.

In terms of GWP effects, the overall results vary by less than 10% for each of the design comparisons as shown in the figure below. Typically, the corresponding rigid concrete design incurs a higher GWP effect at the time of construction, but the flexible asphalt concrete design requires a greater frequency of rehabilitation and by the end of the first 50-year operating period, there is little difference in the GWP for the two designs.



To access the full report or related fact sheets, please visit CAC's website (www.cement.ca) or contact the CAC national office at 613.236.9471.

IN CONCLUSION

In an age of increasing environmental consciousness, we rightly place considerable emphasis on the selection of green materials or products as an important aspect of sustainability. As mentioned earlier, we would all like simple measures or rules of thumb that would make the material or product selection process easy, but they are hard to come by, if they exist at all. The reality is that we are constantly forced into a balancing act, trading off a good effect here with a not-so-desirable outcome there.   Those designing new infrastructure of all kinds, or charged with the ongoing maintenance and rehabilitation of aging systems, face a difficult challenge in this regard.   Prescriptive rules of thumb may not be sufficient, and could actually lead in the wrong direction depending on the specific environmental concerns. Even the search for reliable information can be time consuming and costly. Fortunately, there are tools that can help, with more being developed; tools that bring the power of LCA to bear as we shift from prescriptive to true environmental performance measures in decision-making.   LCA is not a panacea, and it has to be applied in a way that ensures fair and meaningful comparisons, but it is an absolutely essential companion to life cycle costing and life cycle performance approaches.