A Methodology for Total Life-Cycle Costing of Buildings Designed for Disassembly

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Abstract

A Methodology for Total Life-Cycle Costing of Buildings Designed for Disassembly

Nadir Ashraf Khawaja

Although the concepts and principles of Life cycle costing are very well established and practiced by the construction industry, what is lacking is the incorporation of the environmental impacts of the design options into the selection criteria and thus the application of the concept of Total Life cycle costing of the project. The concept of Total Life cycle costing developed earlier suggest, that different relevant environmental impacts associated with each design option be converted to the financial format and added to the calculated values of Life cycle cost of the design option.

However the situation is complicated by the introduction of the concepts of design for disassembly into the design options, and the resulting requirement to distribute the environmental impacts over different life cycles of the component design assemblies throughout their useful life. The purpose of this research is to propose a methodology to tackle the problem.

Keywords: Sustainable development, Design for disassembly, Life cycle costing, Life cycle assessment.

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Chapter 1

1.0 Introduction

Sustainability in the construction sector has emerged as a universal commitment of the communities in the face of the deteriorating environmental situation of the world that we all live in. The most prevalent definition for sustainable development is "Meeting the needs of the present generation without compromising the ability of the future generations to meet their needs" (Blutstein 2003). The world has undergone enormous technological and economic growth in many of its parts in the last century, leading to much improved quality of life. However this has also led to irreversible environmental damage. It has been realized that the current trend of technological and economic growth with total disregard of the environmental implications is not an acceptable option. Now the need of the hour is to translate this realization into action.

The analysis of the Life cycle costing of all the design alternatives in the selection process is well established in the construction sector and is generally used as the criteria for the selection of the most desirable option (ASTM E917, 2002). However Life cycle costing analysis, as is performed today, totally disregards the environmental impacts created by different competing design alternatives during their respective life spans.

On the other hand the practice of Life cycle analysis considers the environmental implications of the proposed design but disregards the economic aspects (ISO 14040, 1997). This has resulted in restricting the use of this technique mostly to academic and research domains.

In order to achieve sustainability in the construction sector it is absolutely imperative that these two practices be merged in the selection process to arrive at the most feasible solution to achieve the project objectives. This has led to the concept of Total Life cycle costing, Haddad, S., et al (2003), which proposes that all the environmental impacts associated with a particular design option be converted by to financial format and added to the life cycle cost of the option to calculate the Total Life cycle cost for the design alternative.

Design for disassembly (DfD) has emerged as an interesting concept to achieve sustainability. According to the concepts of DfD the building is treated as having layers or assemblies and subassemblies as against being considered as one whole entity. The concept of layers (Duffy, F., 1989) as quoted by Crowther (2003) has on one hand given birth to the DfD, but one the other hand has created much complications in dealing with the distribution of environmental impacts across many assemblies having varying and multiple life spans.

1.1 Research objectives

Through this research an effort has been made to present a methodology for calculating Total Life cycle cost of buildings consisting of different assemblies having individual multiple life spans.

The main research objectives are:

- To develop the Total Life cycle costing model proposed by Haddad, S., et al (2003) to incorporate the output of environmental impact assessment software.
- To propose a framework to adjust the output of existing environmental impact assessment software to asses the impacts of buildings designed for disassembly.
- To validate the proposed framework through implementation by assessing the impacts of a building designed for disassembly.

1.2 Thesis methodology and structure

In order to achieve its objectives, the research has followed five major steps:

- Step 1: Literature review

- Step 2: A detailed review of main components of the study
- Step 3: A study of Athena's environmental Impact Estimator (2002)
- Step 4: Development of a methodology to distribute environmental impacts across different assemblies of varied life cycles.
- Step 5: Validation of the proposed methodology through implementation of the frame work to assess the environmental impacts of a building designed for disassembly
- Step 6: Conclusion and recommended future work.

1.3 Limitations of the study

The main limitations of the study are

- The life cycle cost of the buildings are not discussed and are assumed to be known and only the LCA cost components to be added to LCC values are considered
- The factors to convert the environmental impacts from the outputs of the LCA database to cost format are not discussed and are left as inputs from the users of this proposed methodology
- The two factors, namely "L" and "N", proposed in this study are just concepts at this stage. These factors deal with forecasting the future and by nature a lot of work and data collection is required to make these predictions more and more accurate. Guidelines are being

provided as a part of this research to collect data for the development of these factors

- Considering the limitations of time and resources, the case study at the end of this thesis may not be considered as an exhaustive analysis of a building designed for disassembly but rather as a simple example to show the proposed methodology

Chapter 2

2.0 Literature Review

The subject matter of the research can be considered having four components and since there is next to nothing in the literature combining these four components, the literature review of these components is being done individually:

2.1 Design for Disassembly

The *longevity* of a building is determined by the building's ability to maintain structural integrity for a long time, as well as its desirability in terms of function and style. The structural integrity of a building is determined by the *durability* of materials and the quality of construction. Desirability is determined by the building's ability to adapt to change over time. Striking a balance between durability and *adaptability*, in the design of building, results in building *flexibility.*

Bowes and Golton (2001) indicate that obsolescence is the dimension that determines the timing of the demolition of a building. Buildings are not demolished only when they have reached the end of their technical design life, quite commonly they are demolished because those who control them have no further use for them. The reasons that lead to buildings having no further use include economic perspectives e.g. financial aspects and location, utility perspectives e.g. function and the environment, social perspectives e.g. style and regulatory control and of course structural perspectives e.g. structural decay (Bowes and Golton, 2001, and Craven et al, 1994).

Designing a building for durability can save costs and reduce the negative environmental impacts related to operation and maintenance i.e. the consumption of materials during renovations and the resultant waste generation. On the other hand, if a decision to demolish a building is made long before the expected end of life, the above can be reversed i.e. the incurred costs of durable materials, which may have cost more, may not be recovered because of the building's short life (Fishbein, 1998). This emphasizes the salient point that if a building is intended to have longevity, then durability must be balanced with adaptability. Adaptability in buildings refers to both the shell and interior of a building. Incorporating adaptability in building design enables the building to adapt to changing demands of the intended use as well as the ability to adapt to a different use. This flexibility in building design introduces a fresh perspective of looking at buildings, i.e. as a series of layers that can be configured in various ways to meet the changing demands of the user and the surrounding environment.

Buildings have for a long time been thought of and designed as eternal entities. Part of the reason for this is that designers and contractors perceive buildings as entities that should last forever (designers are not prepared to invest in structures that will not last and no contractor believes that his structure will be torn down) [9]. Buildings have also generally been perceived to be complete entities that are designed to perform as a whole i.e. hence the use of a building in singular (Crowther, 2001). Craven *et al* point out that such buildings lack inherent flexibility and are likely to generate more waste when modified, in extreme cases their inflexibility can leave no option but for them to be demolished under the pressures of changing demands that are placed upon them (Craven et al, 1994). The amount of waste generated through these demolitions is staggering (Table 1).

Nation	**Annual amount of construction and demolition waste - millions of tonnes**	**Percentage of total national solid waste**	**Reference**
Canada	11.2	-	Christensen, 1994
Europe- total	180	-	McGrath, Fletcher, & Bowes, 2000
France	25	-	Ruch et al., 1994
Germany	45	60%	Schultmann & Rentz, 2000 Brooks, Adams, & Demsetz, 1994
Israel	0.35 to 0.7	60%	Katz, 2000
Italy	34	-	Bressi, 1994
Japan	-	20%	Futaki, 2000
Netherlands	15	-	Van Dijk, Boedianto, Dorsthorst, & Kowalczyk, 2000
Norway	1.5	-	Myhre, 2000
United Kingdom	53	-	McGrath, Fletcher, & Bowes, 2000
Unites States of America	136	33%	Kibert, Chini, & Languell, 2000

Table 1: Quantities of construction and demolition waste [4]

Crowther takes the argument further by pointing out that the notion of a building in the singular may be a misconception resulting from the reading of a building in a limited timeframe [11]. Few, if any buildings actually remain in their initial state for more than a few years or a couple of decades at most. Building remodeling, repair, expansions and maintenance continually change the building. These changes occur both on the exterior and interior of the building in response to the demands of the user and the surrounding environment. This means that the exterior and interior of a building should be able to respond to the criteria determined by the economic, utility, social and structural perspectives mentioned earlier for the building not to be obsolete.

The theory of building layers enables the designer to incorporate flexibility into building design. This allows a building to be easily disassembled into components. It also allows the selective removal and replacement of specific components without affecting the rest of the structure. Without a doubt, this theory will be useful in the design of buildings with intent to deconstruct at the end. However, an understanding of the building design i.e. finite or eternal, material type e.g. virgin, recycled content or composite, reusability, recyclability, the various life spans of chosen materials, component connectivity and the changes in user and environmental demands, will be key to its use.

Crowther has proposed that action on the principle of environmental sustainability should necessarily take a holistic and whole life view of the consequences resulting from the design and use of buildings. Associated issues are diverse and form a broad spectrum and ranging from hard edged technical aspects of building design and construction to social issues relating to the use and reuse of facilities. One developing strand of activity has been the philosophy of design for disassembly which has seen an extension of interest and application from engineering and product design to architecture through the theoretical work of Crowther and others. Essentially, design for disassembly is based on the proposition that incorporating a methodology for dismantling a building at the end of useful service life into its design may make a meaningful contribution to *sustainability*. In terms of providing useable guidance for architects on design for disassembly, Crowther's advocacy of a performance based approach to sustainable design is reflected in his tripartite exposition of protocols based on addressing improved performance through articulating a hierarchy for disassembly and reuse based on:

Behavioural Statements – these propose gain through **reduction**, for example of

- Waste disposal and pollution
- Greenhouse gas production
- Energy consumption

Performance Standards – these propose gain through **increase**, for example of

- Material Recycling
- Component remanufacture
- Component reuse

- Building adaptability/relocatability

Prescriptive Guidelines – these propose gain through **guidance**, for example on

- Environmental benefits
- Technical benefits
- Chronological order of application

Catalli suggested that designers should consider the application of design for disassembly techniques as a function of facilitating whole life change [12]. This approach suggests strategic actions to be incorporated into the design process:

- Designing for versatility to allow components, assemblies or systems to accommodate change of function
- Design for durability to allow a material to remain unchanged over its expected life while performing its function
- Plan for easy access, which allows for a component of an assembly to be easily approached with minimal damage and impact to it and adjacent assemblies
- Utilizing simplicity of design to reduce the complexity of assembling materials, thus facilitating disassembly
- Favoring independence of materials within assemblies to allow for minimum damage during maintenance, disassembly and removal

- Making significant labeling information explicit on each component or material of an assembly to assist with reuse or disposal after disassembly
- Exposure of mechanical connections where possible to facilitate disassembly
- Making materials or components with the shortest anticipated lifestyle most accessible
- Use materials with an inherent finish and avoid contaminating material with finishes that hinder reuse or recycling activity.

2.2 Life Cycle Costing

Although concepts and practice of life cycle costing is quite well established, a lot of researchers and practitioners have given slightly varied definitions of LCC (ASTM E917, 2002). ASTM E833, 2002 defines LCC method as "a technique of economic evaluation that sums over a given study period the costs of initial investment (less resale value), replacement, operations (including energy use), and maintenance and repair of an investment decision (expressed in present or annual value terms)". Fuller and Peterson (1996) define LCC as the total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system over a period of time. Furthermore, they define LCCA as an economic evaluation technique that determines the total cost of owing and operating a facility over its assumed life.

Prior to the 1970's, most professionals, clients and developers involved with the building procurements made the decisions solely on the basis of capital costs [15]. Outside the construction industry a perceptions did exist at that time that making decision on the basis of capital cost alone can be a folly. It was believed that by possibly spending a bit more at the procurement stage, substantial long term savings can be realized over a longer term, as compared to the cheaper alternative. However, this trend was largely ignored within the construction industry with the main reasons being; an ignorance of the importance of whole life-cycle costs, lack of available data and data collection mechanisms, and the fact that those providing the capital generally had no interest in the subsequent operational costs of the buildings.

During early 1970's, the term 'cost-in-use', the expenditure related to the operation of an asset, began to appear in the literature and as being referred by the industry. Although the term was not fully adopted by the construction industry, it was recognized that the underlying principles are applicable to buildings and critical structures. Although the concept was not fully developed to appreciate the underlying importance of the accurate future cost forecasting, however it high lighted the requirement of some sort of technique to facilitate this.

It was not until late 1970s that LCC emerged as a solution to the problem. LCC encouraged the wider view or a wide ranging approach to the cost appraisal, including all foreseeable costs from planning to construction to eventual disposal

– "the whole life". A number of forecasting techniques were employed to demonstrate that the additional capital cost at the time of construction can be off-set by the long term cost saving during the life span of the investment. The concepts although being sound in theory were not widely adopted by the construction industry because of lack of reliable cost-in-use and performance data. To overcome the shortcoming, in 1971, the Royal Institution of Charted Surveyors established the Building Maintenance Cost Information Service (BMCIS) as a method to collect operation and running cost data by adopting a single classification system. In 1977, the then UK Department of Industry published *Life Cycle Costing in the Management of Assets* and LCC became widely reported on with a diversity of models and techniques existing.

In 1983, LCC came truly in its own through the work of Roger Flanagan and George Norman [16], by developing a framework for the collection of data to be subsequently used to build up the life cycle cost a project. By 1992 LCC was a familiar concept to building economist and was adopted as a British Standard BS 3843 (1992) "The costs associated with acquiring, using, caring for and disposing of physical assets, including feasibility studies, research and development, design, production, maintenance, replacement and disposal; as well as all the support, training and operation costs generated by the acquisition, use, maintenance, and replacement of permanent physical assets." In 2000, this definition was revised and incorporated into ISO 156868 Part 1 - *Service Life Planning* as "A technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs."

2.3 Life Cycle Assessment

Life assessment is defined in ISO 14040 (1997) as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". Whereas life cycle has been defined in the same standard as "consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal".

Life cycle thinking is a holistic approach to environmental and social issues. This approach is the key to sustainability concepts in the construction. Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product. The LCA method entails compiling an inventory of relevant inputs and outputs for a clearly defined system; and then evaluating the potential environmental impacts associated with those inputs and outputs. Results are interpreted in the context of the study objectives.

LCA studies environmental aspects and potential impacts throughout a product's life – from raw material acquisition through production, use and disposal. This can be conceived as flow of materials from nature, to nature, through the course of a building's life. Generally considered are impacts on

- resource use,

- human health and
- the ecological consequences associated with the input and output flows of the analyzed system.

The LCA method is not the only approach to analyzing the impact of material goods on their environment, but it is probably the most comprehensive [17].

LCA methods can be directly applied to the building sector – building products, single buildings and groups of buildings. However buildings are exceptional products and have many characteristics that serve to complicate or frustrate the application of standard LCA methods. More specifically, buildings are difficult to assess because

- the life expectancy of a building is both long and unknown, this causes imprecision. For example, the energy sources or the energy efficiency may change, thus predictions of environmental loadings cannot be precise;
- buildings are site specific and many of the impacts are local – something not normally considered in LCA;
- buildings and their components / products are heterogeneous in their composition. Therefore much data is needed and the associated product manufacturing processes can vary greatly from one site to another;
- the building life cycle includes specific phases - construction, use and demolition which have variable consequences on the environment. For

example, in the use phase, the behaviors of the users and of the services operators or facilities managers have a significant influence on energy consumption.

- a building is highly multi-functional, which makes it difficult to choose an appropriate functional unit,
- a building creates an indoor living environment that can be assessed in terms of comfort and health. To maintain a good quality indoor environment, the building needs energy (heating, ventilation, lighting, etc.) and materials. There are therefore, strong linkages between the impacts on the exterior environment and the quality of comfort, indoor air, health and productivity; and
- buildings are closely integrated with other elements in the building environment, particularly urban infrastructure like roads, pipes, wires, green space and treatment facilities. Because building design characteristics affect the demand for these other systems, it can be highly misleading to conduct LCA on a building in isolation.

Kohler and Moffatt (2003) concluded that since site-specific nature of buildings complicates the application of LCA, it has so far remained in the realm of research groups. Increasingly, however, they see LCA as an educational and policy tool that is best applied to generic buildings and building stocks rather than to particular cases.

Edwards and Bennett [19] highlighted the importance of making fair comparisons on like-for-like basis. For example for comparing the environmental impact of two internal walls of a building; one made of aerated block work and other of timber stud work with timber paneling, one might find a database that would provide the environmental impacts associated with production of one tonne of aerated block work and one tonne of kiln dried softwood. However the two options can not be directly compared on the basis of these profiles as one tonne of each would produce very different areas of wall. They thus advocated the definition of functional units to compare the two internal walls. They further proposed the use of embodied energy as most frequently cited measure of environmental impacts of building products.

Graubner and Reiche (2001) suggested to consider all factors that influence the sustainability in order to prevent problem shifting from one stage to another. They further proposed that the assessment process be repeated several times and side effects of each improvement option be highlighted till a design is optimized. It was suggested that a holistic assessment tool must calculate and asses the material and energy flow generated during the life stages of a building. As a design usually does not score best on all factors it is important to be aware of all the consequences of an improvement on one factor have on all the issues.

It may be noted that the most important aspect of the LCA is as a comparison tool, rather than being assessment of absolute values, of different design alternatives.

2.4 Total Life Cycle Costing

The concept of total life-cycle costing is relatively new and pioneering work was done by Haddad et al (2003). They proposed that in order to advance the concepts of sustainability in construction and effectively utilize the available knowledge in terms of different life cycle assessment tools and data, it is required that the practice of life cycle costing be expanded to include the cost of or cost to negate of environmental impacts of different design alternatives. It was suggested that in order to convince clients and for authorities to impose penalties or offer incentives, the environmental impacts of a design alternative be evaluated in cost estimate format and added to the traditional life cycle cost of the option.

It was deduced that the one of the primary reasons for lack of effective utilization of the collected data for environmental impacts through different available tools is their varied and some what abstract outputs, rendering them hard to use by the construction industry. It was therefore advocated that the out puts be converted to cost formats making them easier to understand and utilize by the construction industry.

Chapter 3

3.0 Main Components of the Study

The main components of the study can be described as the study of the different assemblies and sub-assemblies in a building system, calculation of total life-cycle costing through the determination of the environmental impacts associated with each sub-assembly and the distribution of these impacts across different life spans of each sub-assembly by incorporating the concepts of design for disassembly.

3.1 Assemblies and subassemblies in a building system

Applying the principle that building consists of layers rather than one entity, as proposed by the proponents of DfD, the buildings can be considered as having two basic assemblies/ components

- Base structure; consisting of floor heights, plate size and core location
- Interior structure; consisting of interior partitions, dropped ceiling, raised floors, location of fixtures and services and other interior finishes

3.1.1 Base structure

The materials behavior of the construction sector of the economy must be characterized as poor during all phases of the building materials cycle – from extraction to construction to final disposal of buildings at the end of their useful lives. Changing this situation will be quite difficult. However, the first steps in the process are under way in at least a dozen countries worldwide. Buildings are being disassembled rather than demolished, and building components and materials are being recovered or recycled for reuse in existing or new buildings. In the Netherlands, for example, at least a dozen different precast reinforced concrete systems have been developed to allow buildings to be disassembled, moved and reconfigured. One of these is the MXB-5 dry-assembly system, in which columns with steel plates at each end are connected to floor elements that have anchor bushings embedded in the concrete. The elements can be connected simply by tightening the connecting bolts. Serious efforts are also being made in several other countries to design buildings for eventual deconstruction.

Initial economic analysis indicates that resale of valuable recovered materials can far offset the additional labour costs associated with building dismantling. New industries to disassemble buildings, process used building components, and resell components and recovered materials can result from implementing deconstruction practices on a large scale. These outcomes make deconstruction an approach well worth considering for countries in which there is significant waste from demolition activities, as well as from natural hazards such has earthquakes and hurricanes.

Disassembly has several advantages over conventional demolition. It also faces several challenges. Some of the advantages are:

- an increased rate of diversion of demolition waste from landfills;
- potential reuse of building components;
- increased ease of materials recycling;
- Enhanced environmental protection, both locally and globally.

Disassembly preserves the invested embodied energy of materials, thus reducing the input of new embodied energy in reprocessing or remanufacturing materials. A significant reduction of land fill space can also be a consequence. In the United States, where construction and demolition waste represents about one-third of the total volume of materials entering landfills, a diversion rate of 80% is being experienced for deconstructed buildings [10]. In the Netherlands increasingly scarce land is being preserved for other uses. In some countries, businesses have developed the technology and techniques to turn former demolition debris into useful aggregate.

The challenges faced by disassembly are significant, but they can readily be overcome if changes in design and policy occur. They include:

- Existing buildings have not been designed for dismantling;

- Building components have not been designed for disassembly;
- Tools for deconstructing existing buildings often do not exist;
- Disposal costs for demolition waste are frequently low;
- Dismantling buildings requires additional time;
- Re-certification of used components is not often possible;
- Building codes often do not address the reuse of building components;
- Economic and environmental benefits are not well established

In order to enable the reuse of building elements or the recycling of building material on an increased scale, buildings must be separable into their original units. The environmentally sound and economically viable reuse of building elements and building material depends on the purity of waste material that arises and thus separability of different material layers and elements. By carrying out a selective demolition or by demounting / disassembling a structure instead of conventionally demolishing a building the separation of elements and materials will be taken care of during demolition process. Due to the fact that, requirements for demolition phase are often not considered in design process, building elements and component materials are usually very difficult to separate and reprocessing rates of building waste are still very low. New design concepts have to be considered in order to enable an economically viable and environmentally friendly “Selective Disassembly”.

By applying the concepts of design for disassembly (DfD) a selective demolition can be realized and allows for more sustainable separation of different materials and elements as well as optimization of maintenance process (good accessibility, non-destructive exchange of building parts). A design for disassembly allows for:

- A reduction of demolition (disassembly) cost
- A reduction of reprocessing cost by separating materials that can not be recycled together and
- A reduction of dumping cost by using recyclable material

There are three main strategies which enable a cyclic approach towards the use of building material, elements and even buildings, and the decision has to be made at the design level to select the most appropriate strategy for the eventual disassembly:

- Reprocessing of building waste material as a substitute for natural recourses which can be used for production of new elements and materials
- Reuse of building elements within the same or for a different building. In this case a standard design is required
- Reuse and mobility of a whole building. After the disassembly, the building can be reassembled at a different location for reuse [20]

3.1.2 Interior structure

The interior structure consists of basic six systems:

- Flooring systems and finishes
- Ceiling systems and finishes
- Interior partition – fixed
- Interior partitions – demountable
- Mechanical fit-up – HVAC distribution and control (excluding base building)
- Electrical fit-up – lighting distribution, communication systems (excluding base building)

Depending upon the selection of components of these systems and degree of standardization used, considerable scope exists for design for disassembly

3.1.2.1 Flooring systems and finishes

These are the major functional component in the interior structure and the primary wearing surface and consequently require significant maintenance as compared to other components. They may or may not include under floor distribution of mechanical and electric services and thereby can be subdivided into two sub-components:

- Access flooring system
- Floor finishes

In general the flooring systems should be designed and constructed continuously from one side of the floor area to the other and then partition wall created to allow the interior space reconfigured more easily without affecting the floor.

3.1.2.2 Ceiling systems and finishes

These may be of the form:

- Exposed/ Unfinished Ceiling

  Mechanical and electrical distribution systems which may typically be located in ceiling plenum can instead be located within the floor or left exposed at the ceiling level
- Tightly Attached Ceiling

  The underside of the structure is finished with tightly attached finishes to the underside of wood or steel joists or concrete slab
- Suspended Ceiling System

  With these assemblies, ensure a built in access point to the plenum space in order that duct work and lighting can be assessed without damage to the ceiling finish

3.1.2.3 Interior partitions – Fixed

Interior walls to be finished in plaster or gypsum board are typically framed in metal, though wood framing is also used where allowed within combustibility requirements of the building code. A masonry wall of concrete block may also be used. It also includes doors and horizontal wire chases.

3.1.2.4 Interior partitions – demountable

Typically demountable partition systems use concealed mechanical fasteners to affix gypsum or glass panels that can be disassembled and reassembled without damage to the system. They may be progressive or non progressives with difference being that the progressive systems have to be erected and disassembled in a specific order.

3.1.2.5 Mechanical fit-up – HVAC distribution and control (excluding base building)

Typically in fit-up or refit situation, tenant is provided access to main supply and exhaust ducts. They are of the two type:

- Ceiling based HVAC system
- Under floor Air distribution system

3.1.2.6 Electric fit-up – Lighting distribution (excluding base building)

The system consists of:

- Modular lighting
- Cable management system (excluding base building)

3.2 Total life-cycle costing

The final component of the study is to create a total life cycle costing model for a design for disassembly building and to evaluate the different scenarios involved.

Even though design for disassembly has been realized to be an interesting alternative to conventional design aiming for a sustainable development, unfortunately those concepts are not translated into action [20]. The reason for this is, that usually the whole life cycle of a building is not taken into account at the design stage and the information is generally lacking on how alternate designs can influence the whole life of the building from economic as well as environmental point of view.

In order to provide designers with more information on a "Design for Disassembly" a tool for the assessment of the building elements has to be developed that focuses on connection selection for the different building layers/ components, its influence on material and energy flow, as well as the quality of building waste materials.

All life cycle stages can be analyzed with an emphasis on those stages, where connection between elements and layers is supposed to have an influence (maintenance, refurbishment, demolition and disposal), as those are the life stages which promise the most improvement effect on the sustainability of a structure. Environmental and economic criteria are taken into account in order to optimize a structure.

Following the optimization, additional aesthetic criteria must be considered. These criteria are assessed qualitative. Aspects like acceptance of the user are considered. Especially when regarding demountable structures these criteria are of considerable importance, as the application of these structures can have negative visual side effects like external ducts and are not always accepted by the user.

3.2.1 Fundamentals of life cycle costing

LCC technique is a cost oriented method. It focuses on cost-effectiveness solutions and takes into account overall relevant cost in a specified time period. Net Present Value method is usually used to compare with the alternatives or evaluate assets. Overall costs are here considered such as gathering capital, income, operating and maintenance costs, replacement costs, and salvage costs etc. Study of asset costs performance, which includes historical costs, current costs and forecasting future costs, is one of the typical features of LCC technique.

3.2.1.1 Cost Categories and Cost Model

In office building LCC analysis, the costs (income included) are usually divided into the following five categories:

- Capital Costs; also referred to as initial cost. They are considered as *one time* negative cash flow.

- Operating and Maintenance Cost (O/M); Running costs. They are considered as *annual* negative cash flow.
- Replacement Costs; They are *one time* periodical negative cash flow.
- Income; They are considered as *annual* positive cash flow.
- Salvage Value; Resale of a building is a *one time* positive cash flow and disposal of a building is a *one time* negative cash flow.

3.2.1.2 Cash Flow and Computational Model

To set up a computational model is to establish a mathematical expression (formula normally), which can reflect the physical conditions of all relevant costs performance in a specified period of time. Cash flows are made up by relevant costs, which correspond to each cost model.

The LCC technique is a mathematical approach. Usually, it uses basic economic evaluation methods, such as Net Present Value (NPV), Annualized Equivalent Cost (AEC), Annualized Equivalent Value (AEV), Discount Benefit to Cost Ratio (BCR), and Discounted Saving to Investment Ratio (SIR) etc.

3.2.2 Life cycle assessment

Life cycle assessment is a rigorous method for assessing the environmental impact of a product, a service, or a building (Crowther, 2003). A life cycle assessment of a building involves making an environmental assessment of all of the impacts, which the project has at each of the stages of the building's life cycle. The commonly used model of life cycle assessment for materials and energy is based on a linear model of the building over time. This linear model of the building's life treats the project as a once through system in which the building progresses through a number of stages from inception, through design, construction, operation and maintenance, refurbishment, and finally to demolition.

Similarly the model of the life cycle of materials is treated as a once through system passing from raw materials extraction, through materials processing, assembly and construction, operation, and finally to demolition. This life cycle model is often referred to as a 'cradle to grave' model, where an assessment is made of all the impacts from the materials birth to its death. In performing a life cycle assessment, each of the stages of the life cycle is assessed for the potential environmental impacts at that stage. These impacts will relate to the inputs and outputs to and from the system and may include, but not be limited to, natural resource depletion, energy use, pollution and waste production, species and habitat loss, human health, and social issues.

3.2.2.1 LCA design tools

The intersection between the environmental impacts of the products and the overall impact of the building has prompted the development of integrated environmental design tools for building. These tools allow trade-offs between higher embodied impact and lower operational impact to be evaluated. These calculation tools can demonstrate the very significant trade-off between material and specification choices and the operational performance of buildings. This is important as most significant decisions about a new design are made at the beginning of the design process, so immediate feedback on energy use and material choice is crucial. Athena is one such tool developed by Athena Sustainable Materials Institute, Canada (www.athenasmi.ca) and has been used in this study for not only its extensive database but also being available to the Concordia University as a research tool. The methodology developed through this study can be similarly employed to use the output data from other LCA design tools.

Chapter 4

4.0 Athena's Environmental Impact Estimator

Before proceeding further with the discussion, it is felt, that some mention of the LCA tool employed as an example in the study is required. As already mentioned, methodology developed in this study is illustrated by Using Athena's Environmental Impact Estimator.

The Environmental Impact Estimator is a systems model for assessing the relative life cycle environmental implications of alternative building designs, intended for use by architects, engineers and researchers at the conceptual design stage. One objective is to put environmental considerations on a footing with other more traditional decision criteria. The Environmental Impact Estimator makes the process relatively simple because the Athena Sustainable Material Institute has already done the life cycle inventory (LCI) work and users of the software need not be concerned about this complex and costly step.

However many users want to be assured about the quality of the data, and to better understand how it was developed. Consequently it is desired the Environmental Impact Estimator to be more than a 'black box' so that they can feel confident using the results and advising clients accordingly. To make the process transparent, Athena Sustainable Material Institute has published different reports (also included with software in the form of a separate CD), which are intended to provide that understanding and assurance. Institute studies and publications fall into two general categories:

- investigative or exploratory studies intended to further general understanding of life cycle assessment (LCA) as it applies to building materials and buildings; and
- individual LCI studies that deal with specific industries, product groups or building life cycles stages.

All studies in this latter category are firmly grounded on the principles and practices of life cycle assessment, and follow the published Research Guidelines which define boundary or scope conditions and ensure equal treatment of all building materials and products in terms of assumptions, research decisions, estimating methods and other aspects of the work. The Research Guidelines are also provided on a CD.

However, integration of the LCI data is a primary function of the Environmental Impact Estimator itself, and therefore caution must be employed that individual LCI reports are not necessarily stand-alone documents. For example, a report may specify the amount of electricity used in production processes without taking account of the primary energy required to generate that electricity. Similarly, a report will include estimates of transportation requirements in mode and distance terms without including the energy use and emissions associated with that transportation. The essential missing energy production, conversion, and use estimates are the subject of entirely separate databases embedded in the Environmental Impact Estimator.

In some situations, the Environmental Impact Estimator also calls on related product databases to complete a calculation. For example, the report on concrete products includes estimates of reinforcing steel requirements, but the concrete report does not include the effects of producing that steel. Those effects are the subject of the separate steel report, and the Environmental Impact Estimator calls on databases from both reports to complete its calculations.

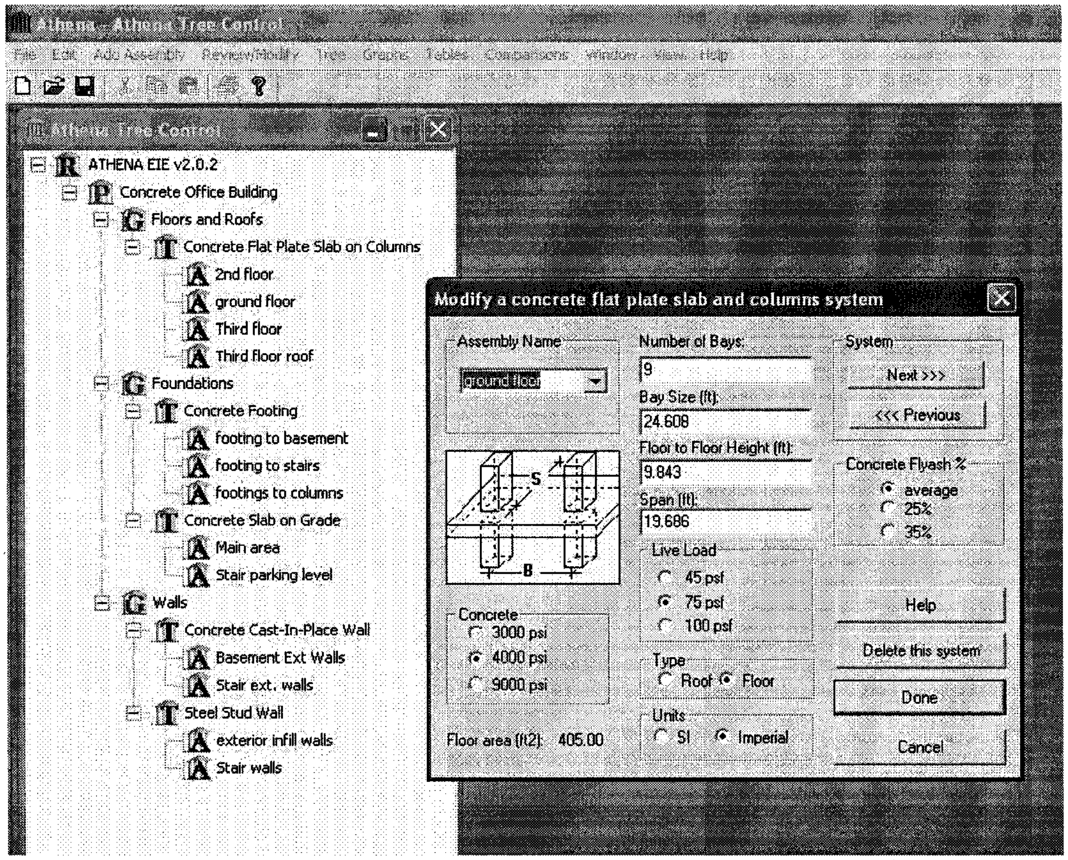
4.1 Athena's System inputs/ outputs

The details of the proposed design can be input to the system for its inbuilt database to carryout a detailed life-cycle inventory and asses the environmental impacts (Fig. 1)

The environmental impacts of the proposed design would then be calculated. Athena's output model produces a detailed life cycle inventory for an entered design. It also generates a set of summary results in graphical and tabular form (Fig. 2) showing:

- aggregate ecologically weighted resource requirements;

- embodied energy inputs by type;



- ATHENA EIE v2.0.2
  - Concrete Office Building
    - Floors and Roofs
      - Concrete Flat Plate Slab on Columns
        - 2nd floor
        - ground floor
        - Third floor
        - Third floor roof
    - Foundations
      - Concrete Footing
        - footing to basement
        - footing to stairs
        - footings to columns
      - Concrete Slab on Grade
        - Main area
        - Stair parking level
    - Walls
      - Concrete Cast-In-Place Wall
        - Basement Ext Walls
        - Stair ext. walls
      - Steel Stud Wall
        - exterior infill walls
        - Stair walls

Assembly Name: ground floor

Number of Bays: 9

Bay Size (ft): 24.608

Floor to Floor Height (ft): 9.843

Span (ft): 19.686

Concrete: ○ 3000 psi ● 4000 psi ○ 9000 psi

Live Load: ○ 45 psf ● 75 psf ○ 100 psf

Type: ○ Roof ● Floor

Units: ○ SI ● Imperial

Floor area (ft2): 405.00

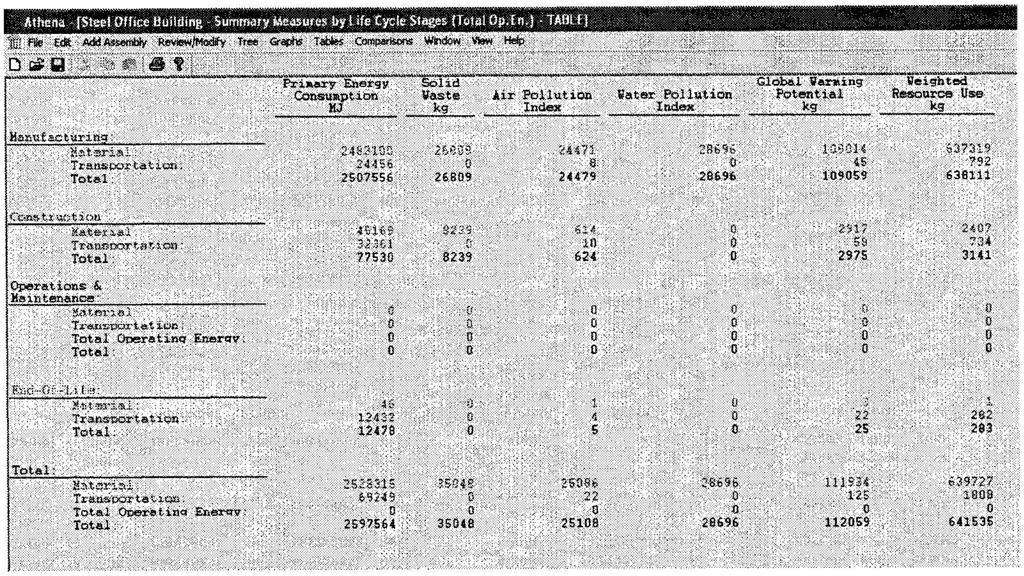
System

Concrete Flyash %: ● average ○ 25% ○ 35%

Figure2: Example of design input for a concrete office building (ground floor details).

- global warming potential;
- an index of water pollution effects;
- an index of air pollution effects; and

- solid wastes.



	Primary Energy Consumption MJ	Solid Waste kg	Air Pollution Index	Water Pollution Index	Global Warming Potential kg	Weighted Resource Use kg
Manufacturing:						
Material:	2483100	26809	24471	28696	109014	637319
Transportation:	24456	0	8	0	45	792
Total:	2507556	26809	24479	28696	109059	638111
Construction:						
Material:	45169	8239	614	0	2917	2407
Transportation:	32361	0	10	0	59	734
Total:	77530	8239	624	0	2975	3141
Operations & Maintenance:						
Material:	0	0	0	0	0	0
Transportation:	0	0	0	0	0	0
Total Operating Energy:	0	0	0	0	0	0
Total:	0	0	0	0	0	0
End-Of-Life:						
Material:	46	0	1	0	3	1
Transportation:	12432	0	4	0	22	282
Total:	12478	0	5	0	25	283
Total:						
Material:	2528315	35048	25086	28696	111934	639727
Transportation:	69249	0	22	0	125	1808
Total Operating Energy:	0	0	0	0	0	0
Total:	2597564	35048	25108	28696	112059	641535

Figure 3: Example of summary output for a steel office building.

The six environmental measures used to summarize the environmental assessment results provided by Athena™ are:

4.1.1 Embodied primary energy

Embodied primary energy is reported in Mega-joules (Mj). Embodied primary energy includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including 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.

4.1.2 Solid waste

Solid waste is reported on a mass basis in kilograms and is generally self-explanatory. In the model no attempt has been made to further characterize emissions to land as either hazardous or non-hazardous.

All other measures are indices requiring more explanation and interpretation. They have been developed because of the difficulty of using and interpreting detailed life cycle inventory results. For example, it takes considerable expertise to understand and appreciate the significance of the individual emissions to air and water. Both categories encompass a relatively large number of individual substances with varying environmental impacts. In the case of raw resource use, there is no real basis for comparison from one material to another in terms of environmental impact. The model therefore compiles related numeric results into indices that summarize the results by indicating potentials for environmental impacts.

4.1.3 Raw resource use

Raw resource use can be measured in common units such as tonnes, but a unit of one resource like iron ore is not at all comparable to a unit of another resource life timber or coal when it comes to environmental implications of extracting resources. Since the varied effects of resource extraction, (e.g., effects on bio-diversity, ground water quality and wildlife habitat, etc.) are a primary concern, it is desired to make sure they are taken into account. The problem is that while these ecological carrying capacity effects are as important as the basic life cycle inventory data, they are much harder to incorporate for a number of reasons, especially their highly site-specific nature.

Athena's approach was to survey a number of resource extraction and environmental specialists across Canada to develop subjective scores of the relative effects of different resource extraction activities. The scores reflect the expert panel ranking of the effects of extraction activities relative to each other for each of several impact dimensions. The scores were combined into a set of resource-specific index numbers, which are applied in Athena™ as weights to the amounts of raw resources used to manufacture each building product. The Weighted Resource Use values reported by Athena™ are the sum of the weighted resource requirements for all products used in each of the designs. They can be thought of as "ecologically weighted kilograms", where the weights reflect expert opinion about the relative ecological carrying capacity effects of extracting resources. Excluded from this measure are energy feedstock used as raw materials. Except for coal, no scoring survey has been conducted on the effects of extracting fossil fuels, and hence, they have been assigned a score of one to only account for their mass. The weighting factor for each raw material is set out below:

Weighted Resource Use

Same as normal resource converted to mass quantities except:

LIMESTONE * 1.5

IRON ORE * 2.25

COAL * 2.25

WOODFIBER * 2.5

4.1.4 Global warming potential

Global warming potential (GWP) is a reference measure. Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "CO_2 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 by Athena as a basis for the equivalence index:

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

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 modeling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcinations of limestone). Because Athena™ uses data developed by a detailed life cycle modeling approach; all relevant process emissions of greenhouse gases are included in the resultant global warming potential index.

4.1.5 The air and water pollution measures

The air and water pollution measures are similarly intended to capture the pollution or human health effects of groups of substances emitted at various life cycle stages. In this case Athena used the commonly recognized and accepted critical volume method to estimate the volume of ambient air or water that would be required to dilute contaminants to acceptable levels, where acceptability is defined by the most stringent standards (i.e., drinking water standards).

Athena™ calculates and reports these critical volume measures based on the worst offender -- that is, the substance requiring the largest volume of air and water to achieve dilution to acceptable levels. The hypothesis is that the same volume of air or water can contain a number of pollutants. However, there are concerns about the cumulative or synergistic effects of some substances and this so far has not been taken into account by Athena.

Athena's Environmental Impact Estimator results also subdivide these impacts totals into the life cycle stages such as:

- Manufacturing
- Construction
- Operation and Maintenance
- End-of-Life

Chapter 5

5.0 Proposed Methodology

5.1 Introduction:

This research aims at developing a methodology that utilizes the environmental impact of building materials/components (in the form of a costing element) to be used in the standard life cycle costing to establish a total life cycle costing (TLCC). This methodology will be developed in the form of a Design Support System (DSS) that enables designers to produce cost alternatives of partial and/or complete building designs that account for economic as well as environmental life cycle costing (TLCC). To achieve this objective the following sub-objectives will be fulfilled: 1) To develop a framework to quantify environmental impact (global and local) of building materials/components, 2) To convert the above environmental impact into a life cycle costing (LCC) element that could be evaluated and/or calculated along with the currently used LCC elements, and 3) To incorporate the resulted TLCC into a design support system (DSS) that helps building designers, at the design stage.

Successful completion of this research will bring identifiable benefits to members in academic consultative, manufacturing and authoritative communities. The completion of this research will also enhance the understanding of the impact of building materials on indoor and global environments. Further it will enable building designers to develop alternatives of their designs based on TLCC at different design stages to better communicate sustainable design ideas with clients.

5.2 Life cycle assessment

Further to the introduction of the basic concepts in section 3.2.2, An LCA consists of four distinct 'methodology steps' [17]. Successful application of these steps requires a clear identification of the product, its life cycle, the choice of technical systems to be represented in the system boundaries and statements of basic anticipations. These four steps are

1. Goal and Scope definition
    - Life cycle definition
    - Functional unit
    - System boundaries and data quality requirements
    - Critical review process
2. Inventory Analysis
    - Data collection
    - Refining system boundaries
    - Calculation procedures

3. Impact Assessment
    - Category definition
    - Classification
    - Characterization
    - Weighting
4. Interpretation of Results
    - Reconsider the definitions and assumptions made in the Goal and Scope definition step.

The term Life Cycle Inventory Analysis (LCI) is often used as name for steps one and two of a Life Cycle Assessment.

The term Life Cycle Impact Assessment (LCIA) is often used as name for steps one to four.

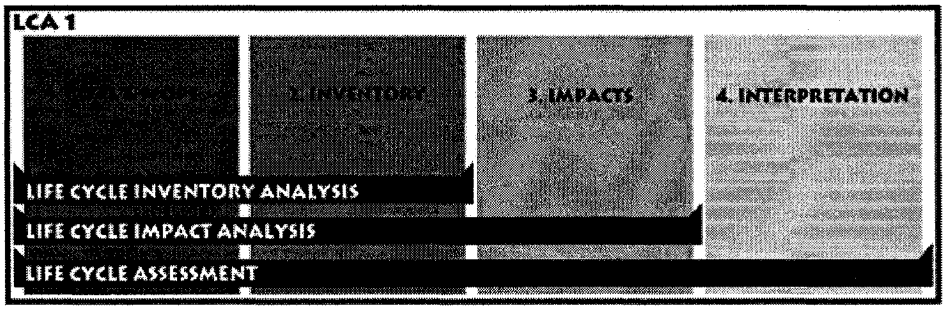


Figure 4: Life cycle inventory, analysis, and assessment methods [17]

5.3 Fundamentals of life cycle costing

Further to the introduction of the basic concepts in section 3.2.1, LCC analysis is an economic method for evaluating a project or project alternatives over a designated study period. The method entails computing the LCC for alternative building designs or systems specifications having the same purpose (functional use) and then comparing them to determine which has the lowest LCC over the study period [1].

The LCC method is particularly suitable for determining whether the higher initial cost of a building or building system is economically justified by reduction in future costs (for example operating, maintenance, repair, or replacement costs) when compared with an alternative that has a lower initial cost but higher future costs.

5.3.1 Procedure

Following steps are undertaken in the calculation of LCC:

Objectives, Alternatives, and Constraints

Design or system objective that is to be accomplished is specified and alternative designs and systems that accomplish the objective are identified. Any constraints that limit the available options to be considered are also identified at this stage.

Data and Assumptions

- **Basic Assumptions**; Establish the uniform assumptions to be made in the economic analysis of all alternative. These assumptions usually include, but are not limited to, the consistent use of the present-value or annual-value calculation method, the base time and study period, the general inflation rate, the discount rate, the comprehensiveness of the analysis, and the operational profile of the building or system to be evaluated.
- **Present-Value versus Annual-Value calculations**; the LCC project alternatives must be calculated uniformly in present-value (all costs discounted to base time) or annual-value terms (all costs converted to a uniform annual amount equivalent to the present value when discounted to the base time).
- **Study Period**; the same study period must be used for each alternative when present-value calculations are used. An annual-value LCC may, under certain restrictive assumptions, be used to compare alternatives with different study periods.
- **Inflation**; LCC analysis can be calculated in terms of constant-dollars (net of general inflation) or current-dollars terms (including general inflation). If latter is used, a consistent projection of general price inflation must be used throughout the LCC analysis.
- **Discount Rate**; it should reflect the rate of interest that makes the investor indifferent between paying or receiving a dollar now or at some future

point in time. Select a discount rate equal to the rate of return on next best available use of funds.

- **Comprehensiveness**; the appropriate level of effort comprehensiveness depends upon degree of complexity of the problem, the intended purpose of the evaluation, the level of monetary and non-monetary impacts contingent upon the investment decision, the cost of different levels of comprehensiveness, and the resources available.

Cost Data

Compile the cost data required to estimate the LCC of each alternative design or system to be evaluated. This includes the timing of each cost as it is expected to occur during the study period.

The measurement of the LCC of a building design or building system requires data in initial investment costs, including the cost of planning, design, engineering, site acquisition and preparation, construction, purchase, and installation; financing costs (if specific to the investment decision); annually and non-annually recurring operating and maintenance costs (including, for example, scheduled and unscheduled maintenance, repairs, energy, water, property taxes, and insurance); capital replacement costs; and resale value (or salvage / disposal costs). Data will also be needed for functional use costs if these costs are significantly affected by the design or system alternatives considered.

Omit from LCC evaluation costs that are not significantly affected by the design decision or system selection.

To select among design or system alternatives solely on the basis of the lowest LCC presumes that each alternative is at least capable of satisfying the project requirements and that analyses have been conducted using same operational profile.

In addition to the compiling all relevant costs, the timing of each cash flow must be determined. The time of occurrence is needed so that cost incurred at different points in time can be discounted to their time equivalent values before summation. Cash flows maybe single events, such as one time replacement cost or a resale value. They may be recurring and relatively constant in nature, such as routine maintenance costs, or they may occur at regular intervals but change over time at some projected rate of increase or decrease, such as energy costs. Costs may occur in lump-sum amounts, concentrated at a certain time of year, such as annual insurance premium. They may be spread out evenly over the year, such as salaries, or they may occur irregularly during the year. Rather than accounting for the specific pattern of each cash flow, a simplifying model of cash flow is usually adopted for an LCC analysis. In the simplified model, all cash flows in a given year are assumed to occur at the same point in time within the year, usually at the end of the year.

Compute LCC

To compute the LCC of a building or building system, all relevant cash flows in period t = 0 through t = N are discounted to a common point in time and summed. Conceptually, the computation of an LCC in present-value terms (PVLCC) can be represented as:

$$PVLCC = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t}$$

Where:

C_t = the sum of all relevant costs occurring in year t,

N = length of study period, years, and

i = the discount rate

For ease of computation, the following equivalent approach can be used instead of the above equation; find the present value (PV) of each cost category (for example, initial cost, maintenance and repair, replacement, fuel, and resale value). Then sum these present value amounts to find PVLCC;

$$PVLCC = IC + PVM + PVR + PVE - PVS$$

Where:

IC = initial cost

PVM = present value of maintenance,

PVR = present value of replacement,

PVE = present value of energy/fuel,

PVS = present value of salvage-value.

Note that resale value, when explicitly expressed as a positive cash flow, is subtracted from the other cost categories in calculating PVLCC.

5.4 Adding life cycle analysis costs

Building designers are not yet equipped with satisfactory tools to help them effectively in the process of holistic sustainable building design. As explained in section 2.4, in order for clients to be convinced, and for authorities to impose incentives and/or penalties to protect the environment, the environmental impact of buildings needs to be evaluated in cost estimate format [2]. In other words, there is a need to incorporate the environmental impacts of buildings and building materials/ components into the LCC (Fig. 4).

In particular these impacts typically include:

- depletion of scarce and non-renewable fuels such as oil and natural gas
- depletion of scarce materials such as exotic hardwood timbers
- depletion and contamination of scarce water supplies
- depletion and pollution of scarce farming land for non farming purposes
- generation of CO_2, CFC, and other airborne pollutants

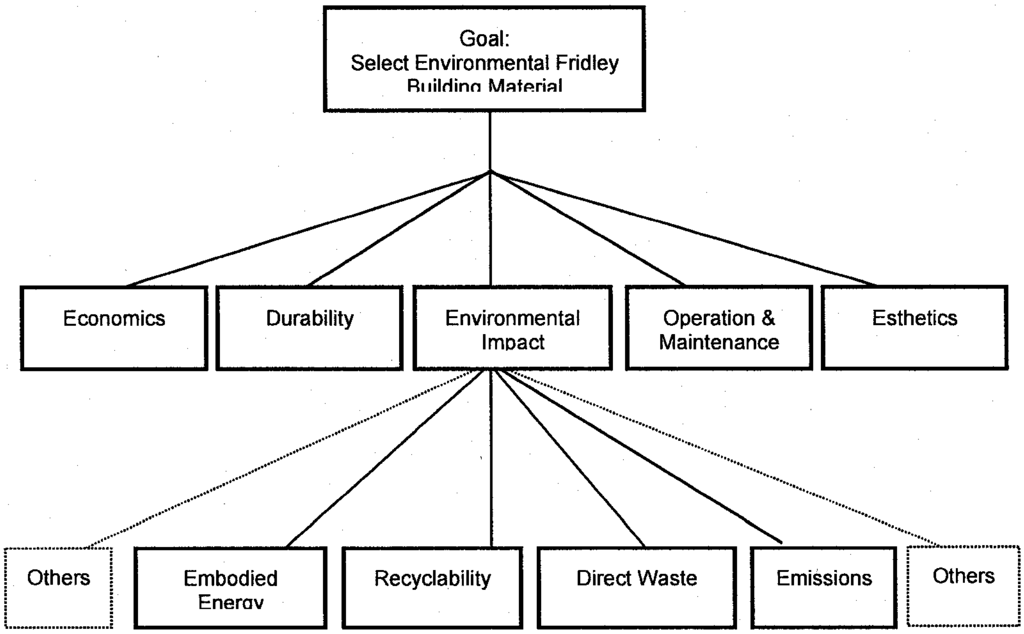


Figure 5: Example hierarchy for selecting environmental friendly building material

- destruction of rare native plant species
- destruction of native animal habitat such as rainforests
- creation of health risks in the use and disposal of toxic materials

- creation of occupational health risks through biological and chemical pollutants
- contamination of the natural and built environment through pollution generation and waste disposal

By adding these costs, relevant to each design alternative, based on the same study and base period as for already calculated LCC, in to the calculated LCC, it can be referred to as the Total Life Cycle Cost (TLCC). Therefore, if

$$LCC = IC + M + R + F - S$$

Then,

$$TLCC = IC + M + R + F - S + ELCC$$

And,

$$ELCC = EEC + EMC + WPC + REC + \ldots\ldots\text{ etc.}$$

Where:

LCC = Life cycle cost

IC = Initial cost

M = Maintenance cost

R = Replacement cost

F = Fuel/ energy costs

TLCC = Total Life cycle cost

ELCC = Environmental Life cycle cost

EEC = Embodied energy cost

EMC = Emission costs

WPC = Water pollution costs

S = Resale/ salvage value REC = Recycling costs

If the values for different environmental costs are known or are available to the designer, the same can directly be put in the TLCC equation to calculate the combined value for LCC and ELCC, which would be of great benefit to the designer/ decision maker in selecting the overall best alternative among all the possible options.

However if these values are not directly known, the designer would be able to get the relevant values for these parameters from the proposed design support system (DSS) Fig. 5, which would be based on the existing environmental impact estimating software (for example Environmental Impact Estimator developed by

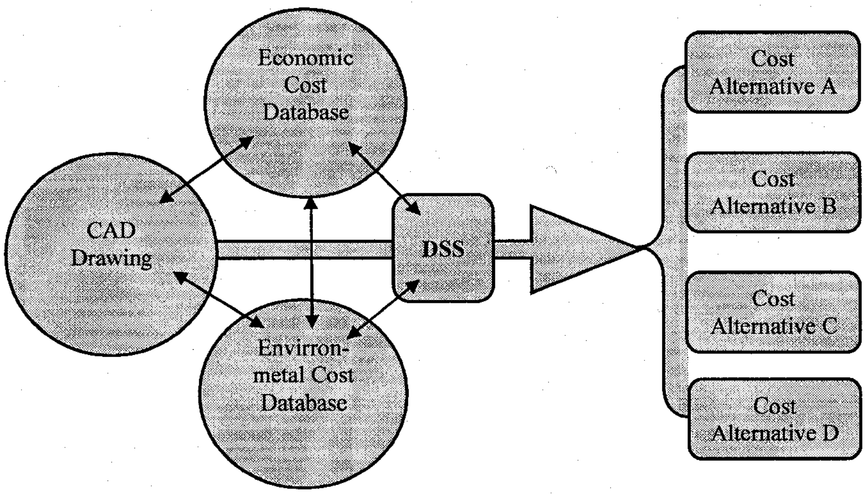


Figure 6: Schematic of environmental and economic life cycle costing design support system.

Athena Sustainable Materials Institute, Canada) and would convert the environmental impact of the proposed design alternative into a life cycle costing (LCC) element to be used as ELCC in the above equation.

In order to associate design and material considerations into the proposed methodology while using the existing environmental impact estimating software (for example Environmental Impact Estimator developed by Athena Sustainable Materials Institute, Canada), it is proposed based on the characteristics of the design alternative, such as:

1. Design Considerations
    - Component accessibility
    - Convertibility
    - Building systems independence
    - Versatility
    - Simplicity
    - Flexibility
    - Expandability
    - Re-furbish ability
2. Material Considerations
    - Exposed, reversible and universal connections

- Inherent finishes
- Compatibility
- Re-usability
- Re-cycle ability
- Durability
- Re-furbish ability

5.4.1 Required designer inputs

The user/designer would be required to define/ input following three parameters:

1. Degree/ Level of conformity (L):

   Define a level best describing as per his judgment the degree (expressed on a scale of 0 to 100) to which the proposed design conforms to the basic principles of design for disassembly

2. Number of expected uses (N):

   The number of times, according to his best judgment, the assembly components would be used during their serviceable life

3. Monetary value to unit environmental damage:

   User would be required to input relative $ value per unit of each of the environmental impacts assessed by Athena, in order to convert each into a life cycle costing (LCC) element.

5.4.2 Calculation of the environmental impacts

It is proposed that depending upon the degree/ level of designed for disassembly and number of expected uses selected by the user, the component effects on environment, per life cycle, for Manufacturing and End-of-Life stage are reduced by that extent. For example a building designed for 100% disassembly (ideal situation) will have a net negative effect on environment after useful life of assembly equal to the total impact divided by the number of expected design assemblies of the components as compared to another design for 0% disassembly.

It is also proposed that the environmental consequences of the Construction and Operational and Maintenance stages of the life cycle would be considered to be unaffected by the choice of degree of designed for disassembly.

Then,

$$TLCC = IC + M + R + F - S + ELCC$$

And,

$$ELCC = R\,(EI_{MS}) + EI_{CS} + EI_{OMS} + R\,(EI_{EOLS})$$

Where:

TLCC : Total Life cycle cost

IC : Initial cost

M : Maintenance cost

R : Replacement cost

F : Fuel/ energy costs

S : Resale/ salvage value

ELCC : Environmental Life cycle cost

R : Recyclability factor; $R = (1 - \%L + \%L / N)$

L : Level of conformity to design for disassembly

N : Number of expected uses of components of design assembly

EIMS : Athena's total environmental impact for Manufacturing stage

EICS : Athena's total environmental impact for Construction stage

EIOMS : Athena's total environmental impact for Operation and Maintenance stage

EIEOLS : Athena's total environmental impact for End-of-Life stage

Therefore it is proposed that the environmental impacts (local and global) of the building materials/ components have to be quantified into standard costing format and included into standard life cycle costing evaluations to achieve a total life cycle costing, which is absolutely essential for the comparison of different design/ system alternatives in order to select the most sustainable building solution.

5.4.3 Example of calculation of R factor

The user/ designer selected the following value, based on his judgment;

L = 75 (75% of material is expected to be recovered for further use after disassembly)

N = 4 (Recovered material can be expected to be used in 4 different assembly cycles; environmental impacts due to recoverable material has to be divided into 4 assembly cycles)

Then,

$$\begin{aligned} R &= (1 - \%L + \%L/N) \\ &= \{1 - 75/100 + (75/100)/4\} \\ &= \underbrace{1 - 0.75}_{\text{Environmental impact factor due to unrecoverable material}} + \underbrace{0.1875}_{\text{Environmental impact factor due to recoverable material per each assembly cycle}} = 0.25 + 0.1875 = 0.4375 \end{aligned}$$

5.5 Guidelines for the determination of "L" and "N" factors

The two factors, namely degree/ level of conformity (L) and number of expected uses (N), introduced in the section 5.4.1, are the basis of the calculations to distribute the environmental impacts across different assemblies and to calculate these impacts per each assembly cycle of the buildings designed for disassembly. Since these factors deal with the prediction of the performance of the assemblies/ subassemblies in future, in order to predict their value as accurately as possible, it is proposed that these values should be determined in two stages (Fig. 6).

	Step 1	**Step 2**
Stage I	Specification ▪ Assemblies and sub-assemblies ▪ Materials ▪ Component size and weight ▪ Connections (number and type) ▪ Method and sequence of assembly and disassembly including plant and equipment to use ▪ Finishes ▪ Tolerances	Estimation ▪ Manufacturers ▪ Construction companies ▪ Consultants
Stage II	Standardization ▪ Standardization across construction industry of specifications of assemblies and subassemblies	Data collection and usage ▪ Manufacturers ▪ Construction companies ▪ Consultants ▪ Professional bodies ▪ Commercial organizations ▪ Regulatory bodies

Figure 7: Two stages in the determination of the values for L and N factors.

In stage I, as a first step detailed specifications of each and every assembly/ sub-assembly should be developed. These specifications should include materials, component sizes and weights, types and number of connections used, method and sequence of assembly; including plant and equipment to use, finishes and allowable tolerances. As a second step manufacturers of these systems and/ or construction companies and consultants should estimate the values for these factors to the best of their judgment. It should be noted that with the passage of time, repeating the same specifications over time and checking the actual performance of the previous assemblies, these estimates will become more and more accurate.

In stage II, the specifications will become standardized across construction industry, facilitating the wide spread data collection and usage. It is hoped that at such stage in addition to previously mentioned manufacturers, construction companies and consultants, this data will be collected and distributed through professional bodies, commercial organizations (like R.S. Means) and probably some regulatory bodies. This will lead to more accurate credible and accurate values and greater acceptance of the results by the construction industry.

Chapter 6

6.0 Case study

In order to elaborate the methodology presented in this research, a short case study is undertaken.

6.1 Case study data

A 16,113 ft^2 three story steel office rental building in Montreal, designed for disassembly, with a life expectancy of 30 years was analyzed.

Following assembly-wise design data was assumed:

6.1.1 WF steel beams and HSS steel columns

Assembly name	# of bays per row	# of rows	Bay size (ft)	Floor to floor height (ft)	Supported span (ft)	Live load (psf)
Basement	3	3	30	9.843	20-30	75
Ground	3	3	30	11.812	20-30	75
Second	3	3	30	11.812	20-30	75
Third (roof)	3	3	30	11.812	20-30	45

6.1.2 Floors and roofs

Concrete flat plate slab on columns

Assembly name	Concrete (psi)	Area (ft^2)	# of bays	Bay size (ft)	Floor to floor height (ft)	Bay span (ft)	Live load (psf)	Type	Concrete fly-ash (%)
Ground	3000	2700	3	30	11.812	30	45	Floor	average
Second	3000	2700	3	30	11.812	30	45	Floor	average
Third	3000	2700	3	30	11.812	30	45	Floor	average

Envelope definition

Roof

Category	Material	Type	Thickness (in)
Insulation	Fiberglass	Batt	2
Vapour Barrier	Polyethylene	6 mill	
Gypsum board	Gypsum	Moisture resistant 5/8”	
Roof system	4 ply built-up asphalt	Cellulose glass felt	5

Floors

Category	**Material**	**Type**	**Thickness (in)**
Gypsum board	Gypsum	Fire-rated type x 1/2”	
Paint	Alkyd	Solvent based	

6.1.3 Foundations

Concrete footings

Assembly name	**Length (ft)**	**Width (ft)**	**Thickness (ft)**	**Rebar (#)**	**Concrete (psi)**	**Concrete fly-ash (%)**
Footing to basement	187.0Q	1.969	7.880	5	3000	average
Footing to stairs	66.932	1.969	11.820	5	3000	average
Footings to columns	104.992	6.562	23.640	6	3000	average

Envelope definition

Category	Material	Type	Thickness (in)
Vapour Barrier	Polyethylene	6 mill	

Concrete slab on grade

Assembly name	Length (ft)	Width (ft)	Thickness (inch)	Concrete (psi)	Concrete fly-ash (%)
Main Area	73.823	70.870	4.0	3000	average
Stair parking level	19.686	12.468	4.0	3000	average

Envelope definition

Category	Material	Type	Thickness (in)
Vapour Barrier	Polyethylene	6 mill	

6.1.4 Walls

Concrete cast-in-place walls

Assembly name	Wall type	Length (ft)	Height (ft)	Total opening area (ft^2)	# of window units	Concrete (psi)	Rebar (#)
Basement exterior wall	Exterior	187.0Q	9.843	0.00	8	3000	5
Stair exterior wall	Exterior	49.215	45.934	209.898	8	3000	5

Concrete cast-in-place walls (continued)

Assembly name	Thick. (inch)	Concrete fly-ash (%)
Basement exterior wall	8	average
Stair exterior wall	8	average

Envelope definition

Exterior walls

Category	Material	Type	Thickness (in)
Insulation	Cellulose	blown	2.5
Vapour Barrier	Polyethylene	6 mill	
Gypsum board	Gypsum	Fire-rated type x ½"	
Paint	Alkyd	Solvent based	
Cladding	Brick	(Metric) Modular	
Other	Polypropylene		

Interior walls

Category	Material	Type	Thickness (in)
Insulation	Cellulose	blown	2.5
Gypsum board	Gypsum	Fire-rated type x ½"	
Paint	Alkyd	Solvent based	

Steel stud walls

Assembly name	**Wall type**	**Length (ft)**	**Height (ft)**	**Total opening area (ft^2)**	**# of window units**	**Sheathing type**
Exterior infill walls	Exterior	566.957	11.812	3000	80	plywood
Stair wall	Exterior	137.802	11.812	210	8	plywood

Steel stud walls (continued)

Assembly name	**Stud thick. (in)**	**Stud spacing**	**Stud weight**
Exterior infill walls	1 5/8 x 3 5/8	16 o.c.	Heavy (20 Ga)
Stair wall	1 5/8 x 3 5/8	16 o.c.	Heavy (20 Ga)

Envelope definition

Exterior walls

Category	Material	Type	Thickness (in)
Insulation	Cellulose	blown	2.5
Vapour Barrier	Polyethylene	6 mill	
Gypsum board	Gypsum	Fire-rated type x ½"	
Paint	Alkyd	Solvent based	
Cladding	Brick	(Metric) Modular	
Other	Polypropylene		

Interior walls

Category	Material	Type	Thickness (in)
Insulation	Cellulose	blown	2.5
Gypsum board	Gypsum	Fire-rated type x ½"	
Paint	Alkyd	Solvent based	

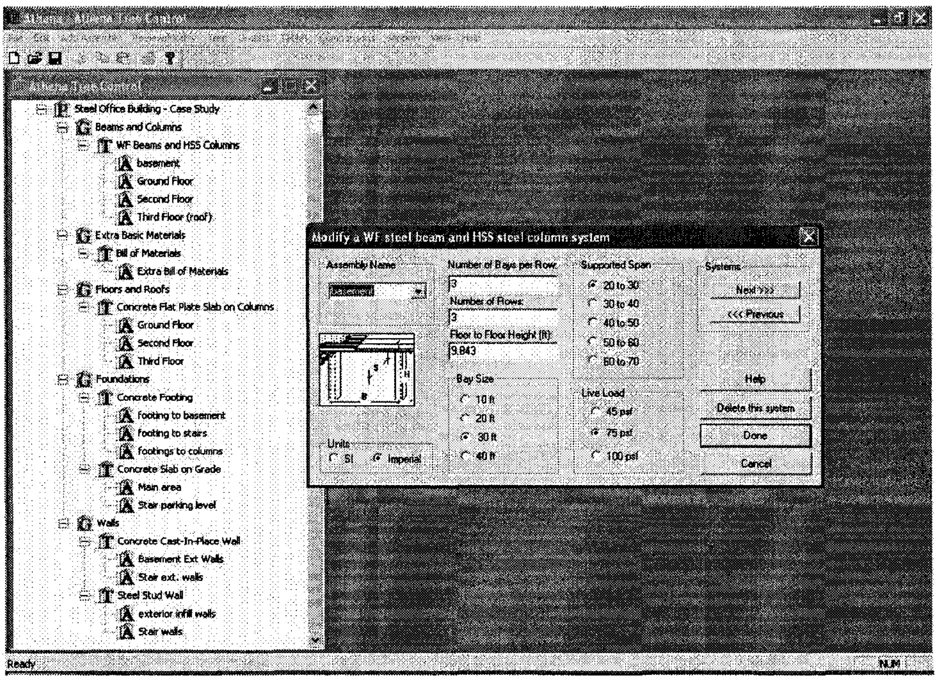
6.1.5 Operating energy consumption (per year)

Electricity: 24,000 kWH

Natural Gas: 600 m^3

6.2 Data input to Athena

The design data was input to Athena (figure 7).



Modify a WF steel beam and HSS steel column system

Assembly Name: basement

Number of Bays per Row: 3

Number of Rows: 3

Floor to Floor Height (ft): 9.843

Units: ○ SI ● Imperial

Bay Size: ○ 10 ft ○ 20 ft ● 30 ft ○ 40 ft

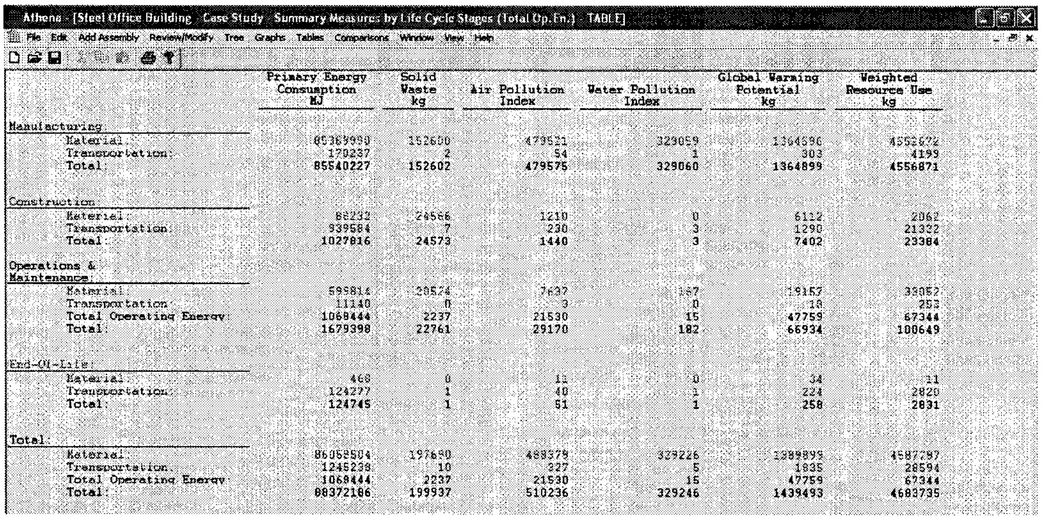
Supported Span: ● 20 to 30 ○ 30 to 40 ○ 40 to 50 ○ 50 to 60 ○ 60 to 70

Live Load: ○ 45 psf ● 75 psf ○ 100 psf

Figure 8: Data input to Athena's Environmental Impact Estimator

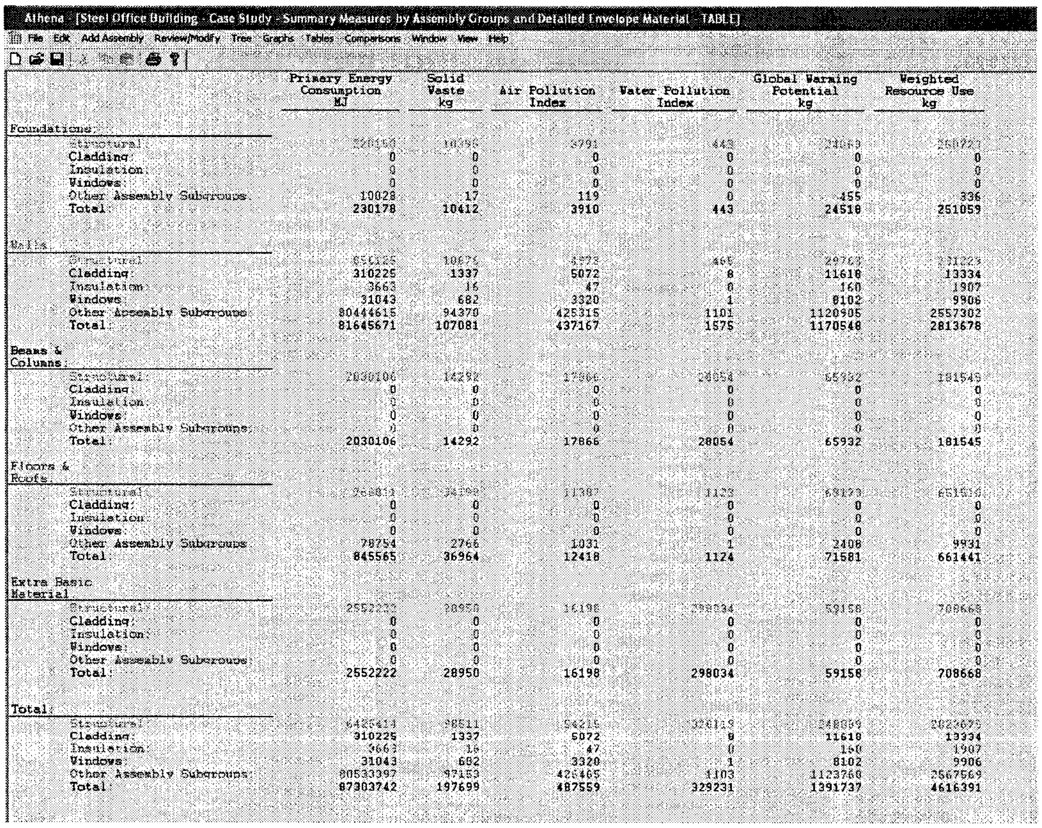
6.3 Result outputs/ summary tables

Summary measure table by life cycle stages for total operating energy (figure 8) along with summary measures by assembly groups and detailed envelope material table (figure 9) was obtained from the Athena's Environmental impact Estimator.



	Primary Energy Consumption MJ	Solid Waste kg	Air Pollution Index	Water Pollution Index	Global Warming Potential kg	Weighted Resource Use kg
Manufacturing:						
Material:	85369990	152600	479521	329059	1364596	4552672
Transportation:	170237	2	54	1	303	4199
Total:	85540227	152602	479575	329060	1364899	4556871
Construction:						
Material:	88232	24566	1210	0	6112	2062
Transportation:	939584	7	230	3	1290	21322
Total:	1027816	24573	1440	3	7402	23384
Operations & Maintenance:						
Material:	599814	20524	7637	167	19157	33052
Transportation:	11140	0	3	0	18	253
Total Operating Energy:	1068444	2237	21530	15	47759	67344
Total:	1679398	22761	29170	182	66934	100649
End-Of-Life:						
Material:	468	0	11	0	34	11
Transportation:	124277	1	40	1	224	2820
Total:	124745	1	51	1	258	2831
Total:						
Material:	86058504	197690	488379	329226	1389899	4587797
Transportation:	1245238	10	327	5	1835	28594
Total Operating Energy:	1068444	2237	21530	15	47759	67344
Total:	88372186	199937	510236	329246	1439493	4683735

Figure 9: Summary measures by life cycle stages (total operating energy)



	Primary Energy Consumption MJ	Solid Waste kg	Air Pollution Index	Water Pollution Index	Global Warming Potential kg	Weighted Resource Use kg
Foundations:						
Structural:	220150	10395	3791	443	24063	250723
Cladding:	0	0	0	0	0	0
Insulation:	0	0	0	0	0	0
Windows:	0	0	0	0	0	0
Other Assembly Subgroups:	10028	17	119	0	455	336
Total:	230178	10412	3910	443	24518	251059
Walls:						
Structural:	856125	10676	3413	465	29763	231229
Cladding:	310225	1337	5072	8	11618	13334
Insulation:	3663	16	47	0	160	1907
Windows:	31043	682	3320	1	8102	9906
Other Assembly Subgroups:	80444615	94370	425315	1101	1120905	2557302
Total:	81645671	107081	437167	1575	1170548	2813678
Beams & Columns:						
Structural:	2030106	14292	17866	28054	65932	181545
Cladding:	0	0	0	0	0	0
Insulation:	0	0	0	0	0	0
Windows:	0	0	0	0	0	0
Other Assembly Subgroups:	0	0	0	0	0	0
Total:	2030106	14292	17866	28054	65932	181545
Floors & Roofs:						
Structural:	766811	34198	11387	1123	69173	651510
Cladding:	0	0	0	0	0	0
Insulation:	0	0	0	0	0	0
Windows:	0	0	0	0	0	0
Other Assembly Subgroups:	78754	2766	1031	1	2408	9931
Total:	845565	36964	12418	1124	71581	661441
Extra Basic Material:						
Structural:	2552222	28950	16198	298034	59158	708668
Cladding:	0	0	0	0	0	0
Insulation:	0	0	0	0	0	0
Windows:	0	0	0	0	0	0
Other Assembly Subgroups:	0	0	0	0	0	0
Total:	2552222	28950	16198	298034	59158	708668
Total:						
Structural:	6425414	98511	52655	328119	248089	2023675
Cladding:	310225	1337	5072	8	11618	13334
Insulation:	3663	16	47	0	160	1907
Windows:	31043	682	3320	1	8102	9906
Other Assembly Subgroups:	80533397	97153	426465	1103	1123768	2567569
Total:	87303742	197699	487559	329231	1391737	4616391

Figure 10: Summary measures by assembly groups and detailed envelope material table

6.4 Selection of 'L' and 'N' values for each assembly

Following values of 'L' and 'N' were selected for each assembly

Assembly Name	L (selected)	N (selected)	R (calculated)
Foundations	0%	1	1.00
Walls	70%	3	0.53
Beams & Columns	95%	5	0.24
Floors & Roofs	60%	2	0.70
Extra Basic Material	50%	2	0.75

Where

L : Level of conformity to design for disassembly

N : Number of expected uses of components of design assembly

R : Recyclability factor; R = (1 - %L + %L / N)

6.5 Calculation of environmental life-cycle cost (ELCC)

The output from the Athena along with the selected values for 'L', 'N' and 'R' were input into the developed decision support system (DSS) to calculate the ELCC value. A monetary conversion factor of $1.00 per each unit of environmental impact was also assumed.

Summary Measures by Life Cycle Stages

(Primary Energy Consumption, Solid Waste, Air Polution Index and Water Pollution Index)

	Primary Energy Consumption MJ		Soild Waste kg		Air Pollution Index		Water Pollution Index	
	Value	%Age	Value	%Age	Value	%Age	Value	%Age
Manufacturing	85540227	96.80%	152602	76.33%	479575	93.99%	329060	99.94%
Construction	1027816	1.16%	24573	12.29%	1440	0.28%	3	0.00%
Operations & Maintenance	1679398	1.90%	22761	11.38%	29170	5.72%	182	0.06%
End-Of-Life	124745	0.14%	1	0.00%	51	0.01%	1	0.00%
Total	88372186	100.00%	199937	100.00%	510236	100.00%	329246	100.00%

Summary Measures by Life Cycle Stages (continued)

(Global Warming Potential and Weighted Resource Use)

	Global Warming Potential kg		Weighted Resource Use kg	
	Value	%Age	Value	%Age
Manufacturing	1364899	94.82%	4556871	97.29%
Construction	7402	0.51%	23384	0.50%
Operations & Maintenance	66934	4.65%	100649	2.15%
End-Of-Life	258	0.02%	2831	0.06%
Total	1439493	100.00%	4683735	100.00%

Summary Measures by Assembly Groups

(Primary Energy Consumption, Solid Waste, Air Polution Index and Water Pollution Index)

	L	N	R	Primary Energy Consumption MJ	Soild Waste kg	Air Pollution Index	Water Pollution Index
Foundations	0%	1	1.00	230178	10412	3910	443
Walls	70%	3	0.53	81645671	107081	437167	1575
Beams & Columns	95%	5	0.24	2030106	14292	17866	28054
Floors & Roofs	60%	2	0.70	845565	36964	12418	1124
Extra Basic Material	50%	2	0.75	2552222	28950	16198	298034
Total				87303742	197699	487559	329230

Summary Measures by Assembly Groups (continued)

(Global Warming Potential and Weighted Resource Use)

	L	N	R	Global Warming Potential kg	Weighted Resource Use kg
Foundations	0%	1	1.00	24518	251059
Walls	70%	3	0.53	1170548	2813678
Beams & Columns	95%	5	0.24	65932	181545
Floors & Roofs	60%	2	0.70	71581	661441
Extra Basic Material	50%	2	0.75	59158	708668
Total				1391737	4616391

Environmental Life Cycle Costing (ELCC)

(Primary Energy Consumption, Solid Waste and Air Polution Index)

	Primary Energy Consumption MJ			Soild Waste kg			Air Pollution Index		
	%Age	Total	Adjusted	%Age	Total	Adjusted	%Age	Total	Adjusted
Foundations									
Manufacturing	96.80%	222802	222802	76.33%	7947	7947	93.99%	3675	3675
Construction	1.16%	2677	2677	12.29%	1280	1280	0.28%	11	11
Operations & Maintenance	1.90%	4374	4374	11.38%	1185	1185	5.72%	224	224
End-Of-Life	0.14%	325	325	0.00%	0	0	0.01%	0	0
		230178	230178		10412	10412		3910	3910
Walls									
Manufacturing	96.80%	79029269	42148943	76.33%	81730	43589	93.99%	410897	219145
Construction	1.16%	949583	949583	12.29%	13161	13161	0.28%	1234	1234
Operations & Maintenance	1.90%	1551569	1551569	11.38%	12190	12190	5.72%	24993	24993
End-Of-Life	0.14%	115250	61467	0.00%	1	0	0.01%	44	23
		81645671	44711562		107081	68940		437167	245395
Beams & Columns									
Manufacturing	96.80%	1965050	471612	76.33%	10908	2618	93.99%	16792	4030
Construction	1.16%	23611	23611	12.29%	1757	1757	0.28%	50	50
Operations & Maintenance	1.90%	38580	38580	11.38%	1627	1627	5.72%	1021	1021
End-Of-Life	0.14%	2866	688	0.00%	0	0	0.01%	2	0
		2030106	534490		14292	6002		17866	5102

(contnued on next page)

Environmental Life Cycle Costing (ELCC)

(Primary Energy Consumption, Solid Waste and Air Polution Index)

	Primary Energy Consumption MJ			Soild Waste kg			Air Pollution Index		
	%Age	Total	Adjusted	%Age	Total	Adjusted	%Age	Total	Adjusted
Floors & Roofs									
Manufacturing	96.80%	818468	572928	76.33%	28213	19749	93.99%	11672	8170
Construction	1.16%	9834	9834	12.29%	4543	4543	0.28%	35	35
Operations & Maintenance	1.90%	16069	16069	11.38%	4208	4208	5.72%	710	710
End-Of-Life	0.14%	1194	836	0.00%	0	0	0.01%	1	1
		845565	599666		36964	28500		12418	8916
Extra Basic Material									
Manufacturing	96.80%	2470434	1852825	76.33%	22096	16572	93.99%	15225	11418
Construction	1.16%	29684	29684	12.29%	3558	3558	0.28%	46	46
Operations & Maintenance	1.90%	48502	48502	11.38%	3296	3296	5.72%	926	926
End-Of-Life	0.14%	3603	2702	0.00%	0	0	0.01%	2	1
		2552222	1933713		28950	23426		16198	12391
Total		87303742	**48009610**		197699	**137280**		487559	**275715**
Monetary value per unit			**$1.00**			**$1.00**			**$1.00**
ELCC		**$48,009,610.02**			**$137,279.89**			**$275,714.70**	

Environmental Life Cycle Costing (ELCC) - continued

(Water Pollution Index, Global Warming Potential and Weighted Resource Use)

	Water Pollution Index			Global Warming Potential kg			Weighted Resource Use kg		
	%Age	Total	Adjusted	%Age	Total	Adjusted	%Age	Total	Adjusted
Foundations									
Manufacturing	99.94%	443	443	94.82%	23247	23247	97.29%	244259	244259
Construction	0.00%	0	0	0.51%	126	126	0.50%	1253	1253
Operations & Maintenance	0.06%	0	0	4.65%	1140	1140	2.15%	5395	5395
End-Of-Life	0.00%	0	0	0.02%	4	4	0.06%	152	152
		443	443		24518	24518		251059	251059
Walls									
Manufacturing	99.94%	1574	840	94.82%	1109891	591942	97.29%	2737467	1459982
Construction	0.00%	0	0	0.51%	6019	6019	0.50%	14048	14048
Operations & Maintenance	0.06%	1	1	4.65%	54429	54429	2.15%	60463	60463
End-Of-Life	0.00%	0	0	0.02%	210	112	0.06%	1701	907
		1575	840		1170548	652501		2813678	1535400
Beams & Columns									
Manufacturing	99.94%	28038	6729	94.82%	62515	15004	97.29%	176628	42391
Construction	0.00%	0	0	0.51%	339	339	0.50%	906	906
Operations & Maintenance	0.06%	16	16	4.65%	3066	3066	2.15%	3901	3901
End-Of-Life	0.00%	0	0	0.02%	12	3	0.06%	110	26
		28054	6745		65932	18411		181545	47225

(contnued on next page)

Environmental Life Cycle Costing (ELCC) - continued

(Water Pollution Index, Global Warming Potential and Weighted Resource Use)

	Water Pollution Index			Global Warming Potential kg			Weighted Resource Use kg		
	%Age	Total	Adjusted	%Age	Total	Adjusted	%Age	Total	Adjusted
Floors & Roofs									
Manufacturing	99.94%	1123	786	94.82%	67872	47510	97.29%	643525	450468
Construction	0.00%	0	0	0.51%	368	368	0.50%	3302	3302
Operations & Maintenance	0.06%	1	1	4.65%	3328	3328	2.15%	14214	14214
End-Of-Life	0.00%	0	0	0.02%	13	9	0.06%	400	280
		1124	787		71581	51216		661441	468264
Extra Basic Material									
Manufacturing	99.94%	297866	223399	94.82%	56092	42069	97.29%	689473	517105
Construction	0.00%	3	3	0.51%	304	304	0.50%	3538	3538
Operations & Maintenance	0.06%	165	165	4.65%	2751	2751	2.15%	15229	15229
End-Of-Life	0.00%	1	1	0.02%	11	8	0.06%	428	321
		298034	223567		59158	45132		708668	536193
Total		329230	**232383**		1391737	**791778**		4616391	**2838140**
Monetary value per unit			**$1.00**			**$1.00**			**$1.00**
ELCC		**$232,382.71**			**$791,778.30**			**$2,838,139.75**	

Total ELCC	**$51,493,127.07**

Chapter 7

7.0 Conclusion and recommended future work

7.1 Conclusion

Tremendous advancements in the industrialization and urbanization accompanied by the massive construction have taken place over the last century. These changes have occurred at a huge environmental cost. In order to sustain the global environment as we know it, it is absolutely essential that we rethink our strategies of technological advancement. These new strategies have to include the way we construct.

To achieve the goal of "greener" construction techniques a lot of different avenues are being explored. Design for disassembly or DfD as it is commonly known, is one of the most promising ideas to have being put forward to accomplish this objective. DfD involves a total rethinking of the traditional designing process of the building construction. In DfD, the plan to convert the building or any component that of, at the end of its useful life, into elements that can effectively be used in another construction is crucial to its basic design concept. It in that sense totally revolutionizes the way buildings are traditionally conceived with only the purpose or function during its useful life being considered. We have seen that the practice of total disregard of the disposal strategies of buildings or their components once they have served the design function has led to enormous amount of demolition waste being generated with according to estimates 136 million tonnes of such waste being generated in United States alone. With landfill sites becoming hard to find and at a more and more economic and environmental cost, across board acceptance of the practice of DfD can result in the reduction of demolition waste and consequent savings in terms of economic and environmental benefits by up to 80%.

Another major advantage of DfD is in terms of substantial savings of invested embodied energy of materials, thus reducing the input of new embodied energy in reprocessing or remanufacturing materials and thus reducing the production of green house gasses in these processes.

Design for Disassembly has thus a great potential for renovation and deconstruction of base as well as interior structures, thereby making good use of existing and future building stock in the face of a dynamic ever-changing work force and rapidly evolving technologies and workplace standards. It is the need of the hour to have more flexibility in the built environment to cater for these changing requirements and save the built environment from becoming obsolete at an alarming rate.

For the application of the concepts of sustainability in the construction sector the practice of evaluating the competing design options through the life-cycle costing alone is not enough and environmental costs assessed through a life cycle assessment have to be converted in to economic format and directly added to LCC to achieve total life cycle cost which is a more realistic representation of all costs associated with a particular design option. First steps in determining of the factors to convert environmental costs to economic format have already being taken through the efforts of United Nations Framework Convention on Climate Change (UNFCCC) by establishing the framework for international emissions trading.

The databases to calculate the environmental costs of a particular design options through the application of life cycle assessment techniques have been developed at the expenses of enormous amounts of money, time and effort. These databases however lack any modality to adjust their results for a building designed for disassembly with substantial number of its elements being reused as such in other assemblies rather than being recycled. Through this research an effort is being made to present a methodology to overcome this shortcoming of these existing databases and to adjust their results to truly reflect the environmental costs of DfD buildings.

It is hoped that this research will result in stimulating more efforts in adoption of the design for disassembly and the application of total life cycle costing as the evaluating criteria of different design options by the construction industry.

7.2 Recommended future work

Through this research a frame work has been suggested to distribute the environmental impacts associated with buildings designed for disassembly across its different assemblies and as such calculate these impacts per each assembly cycle of the building. In order to make use of this framework and to meaningfully employ the methodology presented, the future scholars should continue the work to overcome the limitations of the research as mentioned in section 1.3, I would recommend that immediate work should be carried out on two fronts:

- The factors to convert the environmental impacts from the outputs of the LCA database to cost format, which were left as inputs from the users of this proposed methodology, have to be determined and agreed upon in order to calculate the total life cycle cost and make practical use of this research.
- Fundamental to the proposed framework are the two suggested factors, namely "L" and "N". These factors, as explained, deal with forecasting the future and by nature a lot of work and data collection is required to make these predictions more and more

accurate. As suggested in section 5.5 of the guidelines these should be developed in the two suggested stages

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