EMERGY-BASED LIFE CYCLE ASSESSMENT (EM-LCA) FOR SUSTAINABILITY APPRAISAL OF BUILT ENVIRONMENT

by

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Abstract

Construction and operation of built environment including various types of buildings (such as commercial, residential, institutional) and urban infrastructures are facing challenges because of accelerated pace of resource depletion, waste generation, high energy consumption, greenhouse gas (GHG) emissions and climate change impacts. Several new practices and efforts are underway to develop technical basis to assess the environmental and associated socio-economic impacts due to the design, construction, operation, and disposal of the built environment, and achieve sustainable development goals. In recent years, sustainability assessment or appraisal of a built environment has gained increasing focus and led to integrate sustainable development goals and guidelines in day-to-day decision-making. However, developing a pragmatic sustainability appraisal tool for built environment systems is a key challenge facing planners, policy makers, asset managers, and engineering professionals worldwide.

This research developed a comprehensive framework, based on the integration of emergy synthesis and life cycle assessment (LCA), for sustainability appraisal of built environment systems. The main objective of Emergy-based Life Cycle Assessment (Em-LCA) framework is to support decision-making for asset management by quantifying sustainability performance principles (environmental protection, and socio-economic development) throughout the life cycle of the built environment systems.

The developed Em-LCA framework is applied to selected built environment systems (i.e., linear infrastructure and building systems) using cradle-to grave approach (i.e., from design and project planning to the end-of-life). The Em-LCA framework is implemented to classify life cycle inflows/outflows (e.g., matter, energy/waste, and emission) of the selected built environment systems and to deliver a quantitative characterization of the associated impacts (e.g., natural resources depletion, wastes generation, GHG and toxic emissions, and life cycle costs). Further, the results of Em-LCA are integrated for different sustainability performance indicators to estimate the overall environmental and socio-economic impacts. To address the uncertainty issues, fuzzy-based uncertainty modeling has been used to validate the reliability of the Em-LCA results.

The results of this research clearly prove that, Em-LCA offers a realistic and pragmatic sustainability assessment framework that will overcome several challenges of existing sustainability assessment and traditional asset management frameworks by providing quantitative and transparent results to facilitate informed decision-making.

Keywords: Sustainability appraisal, built environment, emergy synthesis, life cycle assessment, fuzzy uncertainty modeling.

Preface

Six journal papers have been prepared, submitted (under review), or published from this PhD research. Complete references are provided below:

1. Reza, B., Sadiq, R., and Hewage, K., 2011. "Sustainability assessment of flooring systems in the city of Tehran: An AHP-based life cycle analysis". *Construction and Building Materials*, 25(4), 2053-2066.
2. Reza, B., Sadiq, R., and Hewage, K., 2013. "Emergy-based life cycle assessment (Em-LCA) for assessing the sustainability of infrastructure systems: A case study on paved roads". *Journal of Clean Technologies and Environmental Policy* (*In Press*).
3. Reza, B., Sadiq, R., and Hewage, K., 2013. "Uncertainty characterization in emergy synthesis: Fuzzy-based approach". *Journal of Cleaner Production* (submitted April 2013).
4. Reza, B., Sadiq, R., and Hewage, K., 2013. "Comparing multi-unit and single-family residential buildings in Canada: An emergy-based life cycle assessment (Em-LCA)". *Building and Energy* (submitted May 2013).
5. Reza, B., Sadiq, R., and Hewage, K., 2013. "Promise and problems of sustainability assessment tools in the context of built environment – A critical review (to be submitted May 2013).
6. Reza, B., Sadiq, R., and Hewage, K., 2012. "Sustainability assessment of built environment – A review of rating systems" (to be submitted May 2013).

Versions of Chapter 2 (including Appendix A) have been prepared as two review papers (i.e. paper (5) and (6)). A version of Chapter 3 has been submitted as paper (2). A version of Chapter 4 has been submitted as paper (4). A version of Chapter 5 has been submitted as paper (2). A version of Chapter 6 has been submitted as paper (3). In addition, Appendix B is based on a primary research work of the author and published as paper (1). All papers have been written by the author of this thesis, while Dr. Sadiq and Dr. Hewage provided review and feedback and finalized the manuscript.

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Chapter 1 Introduction

Distinct from the natural environment, the term built environment refers to manmade components of people's surroundings including different types of building (such as residential and commercial) and their supporting infrastructures and utilities (such as bridges, roads, water supply, wastewater systems, and transit systems), as well as other built structures and modifications to the natural environment (Brandon and Bentivegna 1997). Kibert et al. (2002) have recognized the built environment as not merely an industrial product while as the most significant artifacts of human culture with historic and heritage value. Younger et al. (2008) stated that the built environment not only encompasses small-scale settings such as offices, houses, hospitals, shopping malls, and schools but also comprises large-scale settings such as neighborhoods, communities, and cities, as well as roads, sidewalks, green spaces, and connecting transit systems. Numerous sectors involve in built environment development such as local and regional governments, urban planning, engineering, architecture, transportation design, land conservation, and environmental psychology (Younger et al. 2008).

In general, the built environment and building process depend on natural resources and services (Graham 2003). Decline of natural resources as a result of the development, aging, and decay of the built environment has significantly increased the importance of developing sustainability assessment/ appraisal[1] tools to evaluate environmental damages and socio-economic consequences. The built environment as systems metabolizing matter and energy and producing waste and emissions substantially affects the natural environment and human health in variety of ways (Baccini 1997).

[1] It is necessary to mention that in this thesis the terms *sustainability appraisal* and *sustainability assessment* are used as identical taxonomies and identified as evaluation and/or comparison of environmental impacts and socio-economic consequences of different alternatives or strategies.

The construction and operation of built environment systems not only may impact human safety and health (mostly due to physical activities such as construction) but many current built environment design practices also adversely contribute to the global environmental burdens. The built environment consumes energy and raw materials to construct and operate, release CO_2, generate waste, and occupy land. On a global scale, the built environment is responsible of ~70-80% of all resources entering into the world economy (Baccini 1997). Building industry, including housing, accounts for ~44% of all extracted materials from the earth's biological or mineral resources (Roodman and Lenssen 1994), one-third of the total landfill waste stream (Kibert et al. 2001b), 25-40% of energy consumption of the society (Perez-Lombard et al. 2008) and around 30% of greenhouse gas emissions release (UNEP SBCI 2009).

Built environment systems are critical assets that are subject to the aging effects and deterioration during their service lives, increasing demand and cost, and random extreme events and damaging effects such as floods and earthquakes. The built environment moreover facing challenges of fast urbanization, landscape changes and development of new material and structural types. The impacts of these pressures can bring about deficiencies in their condition, reduction in their capacity and the level of services over time. The consequence of these burdens are alarming increase in the risk of failures (e.g., fatalities, injuries, health problems, traffic congestion) which in turn may have very serious impacts on the environment, public safety & health, and the remaining service lives of these assets. To develop a sustainable built environment all these issues must be addressed holistically to ascertain the short- and long-term effects on the service life of the built environment.

In order to create a balance between the environment, society and the economy, and to reduce the extent of resource depletion and greenhouse gas emissions, all the sectors of built environment should be replaced by more resource and energy efficient solutions (Dimitrokali et al. 2010). This action is recognized as "*sustainable development*" that has been accepted internationally and been defined in the United Nations Commission Report on Environment and Development (1987) as "*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Troyer 1990).

Development of modern civilization depends on construction and development of the built environment by optimizing the usage of finite resources and applying new industrial products and materials. As a result, construction and operation & maintenance (O&M) of the built environment and asset management have become a cornerstone of sustainable development. However, a clear-cut answer to the questions of how sustainable is our built environment systems or asset management plans and how can we improve them is not an easy task (Forsberg and Malmborg 2004). Moreover, the sustainability paradigm requires multidisciplinary actions and involvement of all stakeholders in the decision-making process.

It has been accepted globally that potential impacts of the built environment and its related activity needs to be determined to plan necessary control and opt asset management strategies to make policy decisions. An integrated sustainability assessment framework for the built environment can help to find a plausible compromise between socio-economic growth of modern societies and environmental protection for all industry stakeholders. In general, a sustainability assessment framework implies *Triple Bottom Line* (TBL) evaluation criteria that include environmental protection, economic prosperity, and social acceptability and equity of an activity as a result of short- and long-term policy decisions.

Rebitzer et al. (2004) stated that, "*achieving sustainable development requires methods and tools to help quantify and compare the environmental impacts of providing goods and services ("products") to our societies"*. In general, every product including built environment encompass a life cycle that begins with the design of the product, followed by resource extraction, manufacturing and production, use/consumption, and finally end-of-life process that includes activities such as collection/sorting, reuse, recycling, and waste disposal (Rebitzer et al. 2004). All the stages of a built environment system's life cycle and related activities and processes can be brought about several environmental impacts due to consumption of resources, emissions of substances into the natural environment, and other environmental exchanges such as radiation (Rebitzer et al. 2004).

A state-of-the-art review of literature shows that there is an urgent need for innovative techniques to facilitate sustainability assessment at various levels of built environment development (Horvath and Hendrickson 1998; Keoleian et al. 2005; Zhang et al. 2010a). However, lack of integrated methodologies for sustainability assessment compel designers/

engineers to employ existing alternatives that were not necessarily the most sustainable solution (Ugwu et al. 2006).

In the last decade, several attempts have been made to reduce the environmental and socio-economic impacts due to activities related to construction and O&M of built environment systems and to achieve sustainable asset management solutions. However, the quantitative sustainability assessment of a built environment system is always a challenge (Forsberg and Malmborg 2004). Many of existing sustainability assessment tools (these tools are reviewed in Chapter 2) provide only a qualitative measurement of the examined built environment system or offer a subjective rating scale (e.g. green building rating systems). These subjective/qualitative sustainability appraisal tools do not provide any reliable quantitative information on sustainability performance of the examined built environment system. The use of such subjective and qualitative approaches to performance assessment can be totally inadequate especially for safety- and health- critical built environment (e.g. highways, bridges, and water mains). Providing reliable quantitative predictions of the current and future performance of the built environment systems can help to meet new demands within a fiscally responsible and environmentally sustainable framework, while preserving quality of life and ensure adequate level of services (LOS).

1.1 Research scope

The motivation for the proposed research stems from the recognition of the fact that a reliable sustainability assessment framework to measure the short- and long-term performance of the built environment systems is critical. Developing a reliable sustainability assessment framework will help in providing effective asset management plans that ensure desired safety, serviceability, functionality and an optimal allocation of available resources throughout the built environment systems life cycle. The main goal of the proposed research is to develop a quantitative sustainability assessment framework based on emergy synthesis and LCA to assess the performance of the built environment systems in meeting TBL sustainability criteria over their useful life span. Emergy can be defined as the energy of one type (usually solar energy) that was used up directly and indirectly in order to generate a resource, product, service, or activity. The proposed sustainability assessment framework aims to address all aspects of sustainable development (in contrast to common economic frameworks such as life cycle costing) of a built environment system.

This is necessary to emphasize the focus of this research is only on sustainability assessment of two main elements of built environment and urban systems, i.e. linear infrastructure systems (road systems) and building systems, however has an ability to be applied for other systems as well. The proposed sustainability assessment framework aims to support decision-making for asset management by quantifying sustainability performance principles (environmental protection and socio-economic development) throughout the life cycle of the built environment systems (roads and buildings). This research is not considering the technical and engineering aspects of designing road and building systems; however it provides a reliable and accurate basis to compare different design alternatives based on life cycle environmental and socio-economic impacts.

The proposed research consolidates the vast body of existing knowledge and shapes it into best practices that can be used by decision makers, asset managers, and practitioners in the public and private sectors. It provides instruments to plan long-term sustainable strategies for the built environment systems and to improve their performance at minimal cost and with the least environmental impacts.

It is anticipated that the proposed research will address the knowledge gaps in current sustainability assessment frameworks and informed decision-making tools in the context of built environment and asset management. The result of this research will assist asset owners and managers to make policy decisions for effective resource allocation and capital investment and design sustainable built environment systems. The result of this research can be used as a reference work to assist designers, builders, operators, and all other professionals to create, maintain, and operate built environment systems that will ensure environmental protection, improving the quality of life, health & safety, and socio-economic viability.

1.2 Research objectives

The overall objective of this research is to develop a systemic sustainability assessment framework, based on emergy synthesis and LCA, to evaluate a broad spectrum of life cycle TBL impacts of the built environment systems. Accordingly, this research proposed an innovative Em-LCA technique, which is a comprehensive sustainability assessment framework, aims to quantitatively investigate the metabolism (resource use and emission release) of the built environment systems, with different design alternatives, and under different scenarios. Specific objectives of this research are as following:

i. Conduct a comprehensive survey of state-of-the-art sustainability assessment methods, tools, and paradigms that can be applied to the built environment and civil infrastructure systems. This will address, but not limited to, the following sub-objectives:
    - Improve and enhance our understanding of existing sustainability assessment tools in the context of built environment
    - Identify possible shortcomings and deficiencies in existing sustainability assessment tools
    - Identify the knowledge gaps in current sustainability assessment frameworks and decision-making tools
    - Apply shortlisted innovative techniques and methods in proposed sustainability assessment framework.

ii. Develop a quantitative and comprehensive sustainability assessment framework based on emergy synthesis coupled with LCA to estimate the contribution of life cycle inflows/outflows and their associated TBL impacts in a single energy-based unit.

iii. Integrate the sustainability performance objectives by developing emergy-based *sustainability performance indicators* to estimate an overall environmental loading (ELR) and sustainability index (ESI) of the examined built environment systems. The sustainability performance indicators must be capable to provide a holistic view of the built environment system performance in meeting TBL sustainability criteria and provide adequate information to support informed decision-making for asset management.

iv. Characterize uncertainties in emergy synthesis and Em-LCA framework, by providing detailed information about different sources of uncertainty in emergy analysis process. Employ fuzzy-based modeling for emergy synthesis in the proposed Em-LCA framework.

v. Apply Em-LCA framework for selected built environment systems (i.e., linear infrastructure and building systems) over their life cycle from cradle-to grave (i.e., from design and project planning to the end-of-life) by classifying life cycle inflow/outflow (e.g., matter, energy/waste, emission) and their associated TBL impacts characterization (e.g., natural resources depletion, wastes generation, toxic emissions, pollutions, and life cycle costs).

The objectives of this research will be achieved in four main phases as it was shown in Figure 1-1.

1.3 Thesis structure

This thesis contains seven chapters and two supplementary appendices. Following this introduction chapter, Chapter 2 provides a comprehensive review of a broad spectrum of sustainability assessment tools in the context of built environment, focusing on scope, approach and practicability of each tool. Chapter 3 developed the methodology, Em-LCA framework, and builds a framework in a step-by-step manner. Chapter 4 explores implementation of the developed Em-LCA framework for assessing the sustainability of building systems. Chapter 5 investigates implementation of the developed Em-LCA framework for assessing the sustainability of linear infrastructure, i.e., road systems. Chapter 6 explores the use of fuzzy-based methods in emergy synthesis within Em-LCA framework to address uncertainty issues. Finally, Chapter 7 summarizes research outcomes and provides recommendations for future research.

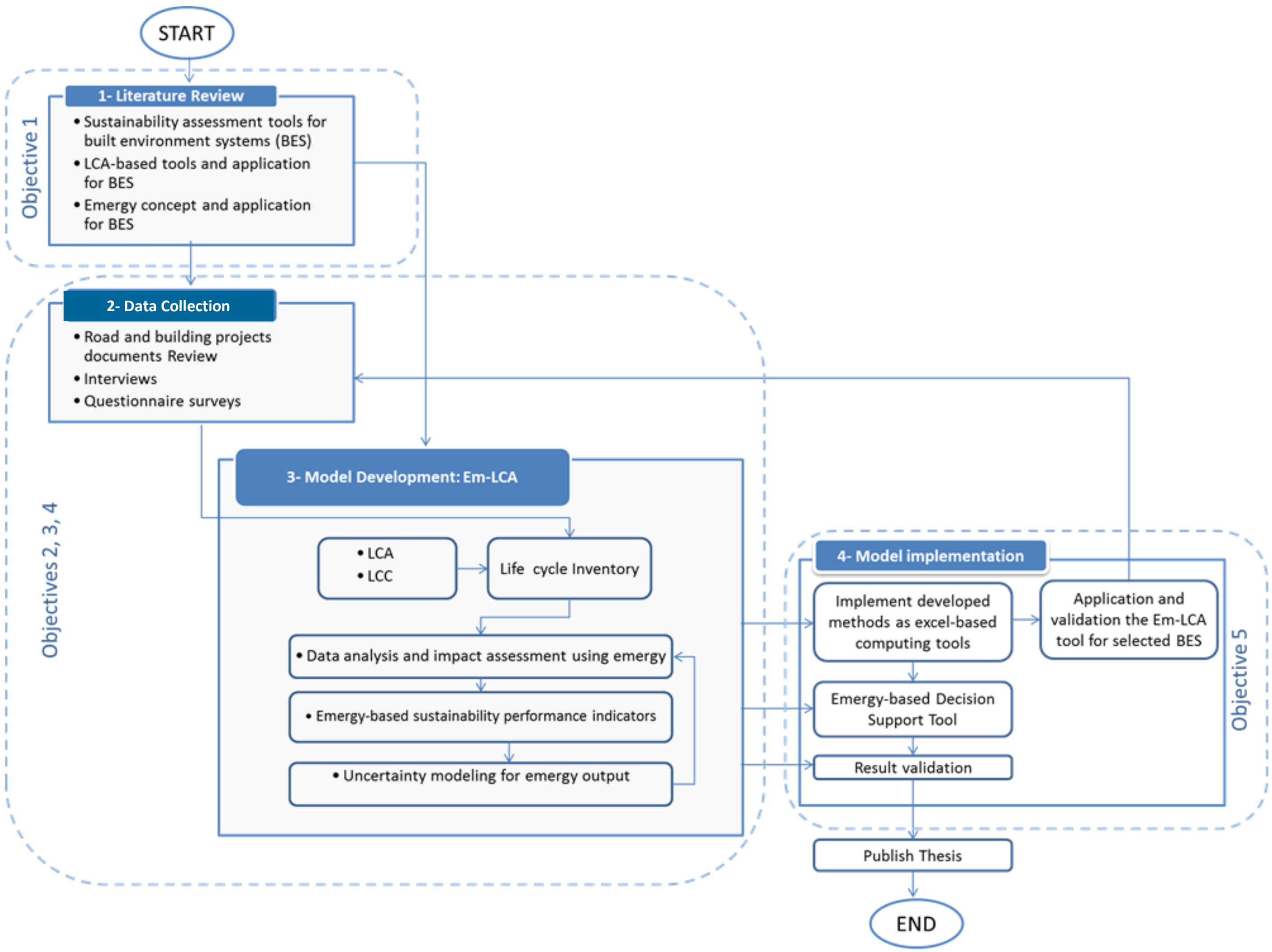


Figure 1-1 Thesis organization

Chapter 2 Sustainability Appraisal Tools for Built Environment

2.1 Overview

Considering the continuous and dynamic impacts of built environment, sustainability refers to reducing environmental impacts and ensuring economic viability, comfort, and safety over the life cycle. In recent years, sustainability appraisal of a built environment has gained increasing focus and led to integrating sustainable development policies and legislations in day-to-day decision-making for a modern society. However, planning for sustainable built environment is a complex process that deals with multitude of issues related to risks, costs, benefits, and interests of various stakeholders. Developing an applicable sustainability appraisal tool for buildings and cities is a key challenge facing planners, policy makers, asset managers, and engineering professionals worldwide.

With regard to the goal of sustainable development, the built environment construction and operation process would shift from using nonrenewable to renewable resources and fuels and from waste productive options to reuse and recycling alternatives. Moreover, sustainability assessment systems would shift from “primary cost” emphasis to “life cycle cost” emphasis, where hidden costs of a built environment such as waste, emission and human health related costs were considered (Kibert et al. 2001).

Therefore, ideally an effective sustainability appraisal tool should address the complete life cycle sustainability issues including design, construction, operation, maintenance as well as demolition and disposal (Chew and Das 2007). Graham (2003) argued that, performing a more holistic and system-based sustainability appraisal can provide improved understanding to make informed decisions on the basis of choosing lower impact materials and design alternatives, and to create the built environment in balance with the local climate, traditions, culture, and surrounding environment.

In general, in the field of construction and infrastructure process the sustainability appraisal and design tools can be classified into three main categories:

- Sustainability rating systems and guidelines such as: LEED (US), BREEAM (UK), SBTool (international), Green Globes (Canada and US), Greenstar (Australia), CASBEE (Japan);

- Environmental Systems Analysis (ESA) tools such as: material flow analysis (MFA), embodied energy analysis (EEA), cost-benefit analysis (CBA), ecological footprint (EF), emergy synthesis
- LCA based tools such as: BEES (US), ATHENA (Canada), ESCALE (France), Eco-Quantum (Netherlands), EcoEffect (Sweden), and EVENTS (UK)

This chapter aims to comprehensively review all sustainability appraisal tools, in the context of built environment from both academic and practical perspective. Focusing on scope, approach and practicability, this review covers a broad spectrum of standardized frameworks, procedures, and paradigms assessing sustainability performance of built environment.

2.2 Sustainability rating systems for built environment

Reijnders and van Roekel (1999) classified this category of sustainability assessment tools as guidance type instruments. Rating systems have been developed worldwide to address the need for a straightforward and simple method of integrating sustainable built environment practices into a common standard. These qualitative tools address sustainability performance based on scoring some building parameters to calculate the overall score to rate and classify them. In general, the rating systems develop a framework to design, build and operate so called "green buildings" by presenting a set of *qualitative performance criteria* to determine level of environmental performance of an understudied built environment.

The performance criteria of different standards vary widely from considering single indicator, such as indoor quality or recycled material, to encompassing broad range of performance criteria in the built environment (Calkins 2009). Rating systems award credits for optional building features that support sustainable design criteria, those were defined under different categories such as location and maintenance of building site, conservation of water, energy, and building materials, and occupant comfort and health. In fact, the number of credits indicates the level of achievement (British Columbia Forest Facts 2011).

Fowler and Rauch (2006) defined sustainable building rating system as "*tools that examine the performance or expected performance of a 'whole building' and translate that examination into an overall assessment that allows for comparison against other buildings*." They further described that, systems that can satisfy four factors of relevancy (providing whole building evaluation), measurability (using quantifiable characteristics), applicability (applicable to the large scale of buildings), and availability (adaptable to the local market), can fit the needs of sustainable building rating system. Applying rating systems to address sustainability performance is becoming increasingly popular (Soderlund et al. 2008). For assessing the environmental performance of built environment, only in the USA, more than 60 rating systems have been developed (Economist 2007). Table 2-1 summarized some of the sustainability rating systems across the world. Five of those tools (LEED, BREEAM, Green Globs, SBTool, and CASBEE) that have been recognized and applied widely as an accepted sustainable building rating system have been compared in this section (these tools have been reviewed in detail in Appendix A).

Table 2-1 Common sustainability rating systems across the world

Rating System	*Country of Origin*	*Organizations Providing Rating Tools*	*Year of Release*
BREEAM	United Kingdom	Building Research Establishment (BRE)	1990
LEED	United States	United States Green Building Council's (USGBC's)	1998
Green Globes	Canada	ECD Energy and Environment Canada Green Building Initiative (GBI)	2002
SBTool	International	International Initiative for a Sustainable Built Environment (iiSBE)	1996
CASBEE	Japan	Japan Green Build Council (JaGBC)	2001
Green Star	Australia	Green Building Council Australia (GBCA)	2003
HK BEAM	Hong Kong	BEAM Society	1996
Living Building Challenge	United States	International Living Future Institute	2006
BCA-GM	Singapore	National Environment Agency	2005
ESGB	China	Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD)	2006

Building **R**esearch **E**stablishment **E**nvironmental **A**ssessment Method (BREEAM) is the first building environmental certification system and the most widely recognized measures of a building's environmental performance that was established and operated by the Building Research Establishment (BRE) in 1990 in the UK. The number of buildings certified with BREEAM reached to 200,000 in total by 2011 (BREEAM 2011). Recently, BREEAM certification has been become mandatory for all new housing projects in the UK.

Leadership in **E**nergy and **E**nvironmental **D**esign that known more commonly by its acronym of LEED has been developed by United States Green Building Council's (USGBC's), a national coalition of building industry professionals, contractors, policy makers, owners and manufactures. LEED is a standardized green building certification system that was issued and released in 1998 (LEED NC v1.0) and is now being used to rate specific building typologies, sectors, project scopes.

The inception of Green Globes^{TM} assessment and rating system rooted in the BREEAM publishing in Canada in 1996, by the Canadian Standards Association (CSA), for Existing Buildings. One of the original intentions of Green Globes development was to allow building professionals and owners to self-assess the performance of their existing building (Kubba, 2009). For this purpose, Green Globes system has been established as a web-based self-assessment performance assessment software tool that delivers an online assessment protocol, rating system and a user-friendly interactive guidance for green building design, operation and management (Smith et al. 2006). The Green Globes system is now applied in Canada and the USA.

Sustainable **B**uilding **Tool** (SBTool), formerly known as GBTool (Green Building Tool), is an international generic framework for rating the sustainable performance of buildings and projects. It established qualitative and quantitative measures to evaluate sustainable design achievements and assess energy and environmental performance of buildings. SBTool is the software implementation of the Green Building Challenge (GBC) assessment method that has been under development since 1996 through the work of more than 20 countries, and is currently led by the members of International Initiative for a Sustainable Built Environment (iiSBE). SBTool is a computer support system in the form of a spreadsheet (Ruiz and Fernández 2009a) that involves a consensus of different viewpoints from participants operating in widely differing environmental, climatic, economic, and socio-cultural regions (Cole 2001).

Comprehensive **A**ssessment **S**ystem for **B**uilding **E**nvironmental Efficiency (CASBEE) is a tool for assessing and rating the environmental performance of buildings and built environment and was release in 2001. CASBEE has been developed to provide suitable consideration for issues and problems peculiar to Japan and Asia (CASBEE 2012). Xiaoping et al. (2009) stated that CASBEE development has been deeply influenced by the GBTool. CASBEE has been established as a joint industrial/government/academic project under the support of the Japanese ministry of Land, Infrastructure, Transport and Tourism.

In general, sustainability rating systems can be compared, and classified according to following five different aspects:

- Performance criteria that used by different rating system to measure and rate sustainability performance of a understudied built environment
- Built environment life cycle levels or scope, i.e. cradle to grave or cradle to stage
- Weighting, grading, and rating methods
- Practicability and flexibility for different types of project and built environments (e.g., commercial, residential, industrial, infrastructure,…) and geographical regions

Table 2-2 lists the performance criteria that are covered in the five building performance rating systems. From Table 2-2 it can be realized that, some performance criteria are the same in all 5 rating system: operation energy, material use, recycled content, portable water use, greenhouse gas emission, solid waste, and site selection. However, there are some criteria categories that mostly emphasized in one of the rating systems, such as socio-economic issues that were mostly considered by SBTool.

Table 2-3 indicates life cycle phases can be assessed by each rating system. From this table it can be realized that all rating systems cover all three phases of design, construction, and operation & maintenance phase. While BREEAM cover entire life cycle, Green Globs only consider three life cycle phases.

Table 2-2 Performance Criteria for different sustainable built environment rating system

Performance Criteria	*Rating System*				
	LEED	**BREEAM**	**Green Globes**	**SBTool**	**CASBEE**
Energy consumption					
Embodied energy				✓	
Total life cycle primary non-renewable energy use		✓		✓	
Operation energy	✓	✓	✓	✓	✓
Life cycle energy	✓			✓	
Energy efficient equipment	✓	✓	✓		✓
Renewable energy sources	✓	✓	✓✓	✓	✓✓
Energy monitoring	✓	✓			✓
Management and control of energy					✓
Material selection					
Material life cycle impact		✓	✓		
Materials reuse	✓	✓	✓	✓	✓
Recycled content	✓	✓	✓	✓	✓
Rapidly renewable material	✓		✓	✓	✓
Materials with low health risks					✓
Regional materials	✓		✓		✓
Construction waste management	✓	✓			
Reduction, reuse and recycling of demolition waste	Only for installation		✓		✓
Insulation	✓	✓			✓
Water					
Use of portable water, storm water and gray water	✓	✓		✓	✓
Rainwater us					✓
Water conserving features	✓	✓	✓		✓
Water monitoring		✓			
Water leak detection and prevention		✓			
Water efficient equipment	✓	✓			✓
On-site water treatment	✓		✓		
Environmental loading and pollution					
Greenhouse gasses emission	✓	✓	✓	✓	✓
Ozone depletion substances emission	✓	✓	✓	✓	
Heat island effect	✓				✓
Acidification substances emission				✓	
Photo-oxidant substances emission				✓	
Waterborne emission				✓	
Liquid waste/wastewater	✓			✓	
Stormwater and sewage pollution	✓	✓	✓	✓	
Solid waste	✓	✓		✓	✓
Toxic substance and hazardous waste			✓	✓	
Noise attenuation		✓			✓
.Light pollution					✓
Wind damage & sunlight obstruction					✓

Consideration of the surrounding environment					✓
Indoor environment and comfort					
Air quality and ventilation	✓	✓	✓	✓	✓
Noise and acoustic		✓	✓	✓	✓
Thermal comfort	✓	✓	✓	✓	✓
Day-lighting and illumination	✓		✓	✓	✓
Visual quality	✓	✓	✓	✓	
Controllability of system	✓		✓	✓	✓
Space optimization			✓		
Maintenance of core functions			✓	✓	
Ensuring a long service life					
Basic life performance					✓
Maintenance of operating performance					✓
Functionality & usability				✓	✓
Design for maintenance of core functions during power outages	✓				
Flexibility & adaptability			✓	✓	✓
Durability & reliability					✓
Service ability & amenity					✓
Fire-resistant structure and fire detection					✓
Resistance against natural disasters					✓
Land use & ecology					
Land use	✓		✓	✓	✓
Site selection	✓	✓	✓	✓	✓
Protection of ecological feature	✓	✓	✓	✓	✓
Mitigating ecological impact		✓	✓		✓
Maintenance of heritage buildings				✓	✓
Long term impact on biodiversity		✓		✓	✓
Watershed features			✓	✓	
Commuting transport					
Public transport accessibility	✓	✓	✓	✓	✓
Green vehicles	✓				
Parking capacity	✓	✓			✓
Cycling facility	✓		✓		✓
Local characteristics & outdoor amenity		✓			✓
Community connectivity	✓				✓
Travel plan		✓			
Urban development					
Infrastructure	✓	✓			✓
Affordable housing	✓	✓			✓
Business, economy and employment	✓	✓			✓
Quality of life					✓
Social infrastructure					✓
Urban context					✓
Retrofitting existing sites	✓	✓			
Preservation of the existing natural environment					✓

Control of the burden on the local infrastructure					✓
Management					
Sustainable procurement		✓	✓		
Construction process planning	✓	✓			
Maintenance of performance		✓			✓
Commissioning			✓		
Emergency response plan			✓		
Economics					
Life cycle cost and service life planning		✓		✓	
Economic performance				✓	
Investment risk				✓	
Social aspects					
Quality of service				✓	
Safety and security				✓	
Affordability				✓	
Cultural and perceptual aspects				✓	
Other					
Innovation in design	✓				
Accredited professional	✓				
Stockholder participation		✓			✓

Table 2-3 Life cycle coverage in different sustainable built environment rating system

Life cycle phase	***Rating System***				
	LEED	**BREEAM**	**Green Globes**	**SBTool**	**CASBEE**
Plan	-	✓	-	✓	✓
Design	✓	✓	✓	✓	✓
Construction	✓	✓	✓	✓	✓
Operation and maintenance	✓	✓	✓	✓	✓
Renovation or rehabilitation	-	✓	-*	✓	✓
Demolition and decommissioning	✓	✓	-	-	✓

* Significant renovation is considered as new building in Green Globes

In addition, a list of project and building types that are evaluated by each rating system provided in Table 2-4 to compare their practicability. According to this table, the number of different building type that can be covered by CASBEE is more than other rating system, that followed by SBTool and BREEAM. On the other hand Green Globes has less usage domain as compared to 4 other rating systems. Finally, a comparison of assessment frameworks that are applied in these tools indicated in Table 2-5. With regard to this table, it can be realized that LEED and Green Globes do not follow any weighting system to address relative importance of different performance criteria. It was moreover realized that, except CASBEE, which rate a built environment based on environmental quality and load or BEE value (see

Appendix A), 4 other rating systems rate a built environment based on overall grade of building performance.

Table 2-4 Sustainable built environment rating system usage domains or building types

Project and Building Types	***Rating System***				
	LEED	BREEAM	Green Globes	SBTool	CASBEE
New Construction	✓	✓	✓	✓	✓
Major Renovation	✓	✓	✓	✓	✓
Existing Building	✓	✓	✓	✓	✓
Building emergency management			✓		
Intelligent Building			✓		
Temporary Construction					✓
Mixed-use Project	✓	✓		✓	✓
Neighborhood development	✓				
Urban Planning		✓		✓	✓
Infrastructure systems				✓	✓
Commercial sector					
Office	✓	✓	✓	✓	✓
Retail	✓	✓	✓	✓	✓
Industrial		✓	✓	✓	
Public Sector					
Educational Building	✓	✓		✓	✓
Healthcare/Hospital	✓	✓	✓	✓	✓
Prison and court house	✓	✓	✓	✓	✓
Multi Residential					
Residential apartment	✓		✓	✓	✓
Dormitory residence	✓	✓	✓		
Hotel/Hostel	✓	✓	✓	✓	✓
Residential care home	✓	✓	✓		✓
Other building sector					
Homes/Single occupancy	✓	✓		✓	✓
Bespoke		✓			
Interiors	✓		✓		
Indoor Parking				✓	
Shell & Core	✓				
Library	✓	✓		✓	✓
Manufacturing plants	✓				✓
Art Gallery/Museum	✓	✓		✓	✓
Worship place/crèche		✓			
Theatre/music/concert hall		✓		✓	✓
Exhibition/conference hall		✓			✓
Sports/fitness /recreation		✓		✓	✓
Transport hub		✓			
Restaurant an Café				✓	✓
Governmental Buildings					✓
Border Stations	✓	✓	✓	✓	✓

Table 2-5 Sustainability appraisal framework for built environment rating system

Assessment Method	***Rating System***				
	LEED	BREEAM	Green Globes	SBTool	CASBEE
Scoring	Points specified for each criterion; Project can award scores for applicable criteria	Credits are allocated to each criterion; Project can award credits for applicable criteria	Credits are allocated to each criterion; Project can award credits for applicable criteria	Scale from -1 to +5 on all criteria; all criteria are scored based on target value	Scale from level 1 to 5 on all criteria; Project can award scores for applicable criteria
Weighting	No weighting system; Equal weighting for all criteria; Simple additive	Weighting has been defined based on relative importance of issues categories	No weighting system; based on score percentage	Weighting system for three level; default weights can be modified by national team	Weighting major items based on building stakeholders opinion and using AHP
Rating benchmark	Based on percentage of points; Certified, Silver, Gold, Platinum	Based on percentage of weighted scores; Pass, Good, Very Good, Excellent, Outstanding	Based on score percentage; One to four/five globes	Based on overall score from -1 to +5; Acceptable practice, Good Practice, Best practice	Based on BEE value; Poor, Fairly poor, Good, Very good, Excellent

In short, various rating systems and sustainable design tools for the general guidance of sustainable built environment have been developed. Sustainable design tools and rating systems provide frameworks that are potentially applicable for the design of built environment depending on the goals and requirements that are identified by user. These emerging tools advocate environmental friendly practices and have superseded traditional economic evaluation methods. Rating systems are the most generic sustainability assessment tools in the field of construction and infrastructure. However, sustainability apprasial tools are not limited to rating system and include two other categories of assessment tools as it was classified in section 2.1 and will be described in the subsequent sections.

2.3 Environmental Systems Analysis

Review of literature shows that, many environmental problems can be directly related to flows of energy, materials/substances and products through the economy (Bouman et al. 2000). Over the years, researchers from different disciplines and policy makers have created integrated methods, standardized frameworks and holistic sustainability appraisal tools to evaluate different processes and products including built environment and related building and construction activities. Consequently, several *Environmental Systems Analysis* (ESA) tools have been developed to quantify environmental performance by estimating detailed energy flow, material flow characteristics as well as emission impacts associated with a product or activity.

In general, ESA tools applied some source of analysis to measure environmental damaging effects (environmental impacts) associated by a system studied (e.g., a product, service, economy, or project), at a specific location and period of time, in the basis of mass, energy, or money values (Dimitrokali et al. 2010; Moberg 1999). The main purpose of these tools are to assist decision makers to identify the environmental burdens caused by the understudied system and to ensure that decision makers deliberate the ensuing environmental impacts when deciding whether to carry on with a project. Hence, a suitable ESA tool can be applied as a decision-support tool to provide certain detail information to support strategic decision with regard to sustainable development goals.

Many of ESA tools are under continuous development and have been in use in different disciplines including engineering in general and building, and construction industries in particular. Some comparative studies about different ESA tools pointed out that many of these tools applied similar analysis methods under separate names and some of those implicated with almost the same advantageous and weakness (Moberg 2006) . However, many of these tools have been focusing on different environmental impacts and analysis scopes, while only a few of them incorporating social and economic aspects besides environmental considerations (Moberg 2006). Some of the most commonly used ESA tools include:

- Environmental Impact Assessment (EIA)
- Ecological Footprint (EF)
- Cost-Benefit Analysis (CBA)
- Environmental Risk Assessment (ERA)
- Material Flow Accounting (MFA)
- Embodied Energy Analysis (EEA)
- Emergy Synthesis

The above ESA tools have been applied to evaluate different products, services, and economic activities in different disciplines around the world. They have also been applied to evaluate built environment products and related activities. A brief description of ESA tools have been provided in following sections.

2.3.1 Environmental Impact Assessment (EIA)

EIA is a strategic decision-support method that has been developed in order to incorporate environmental aspects and human well-being considerations into a proposed project planning. EIA approach has been primarily established with the 1969 US National Environmental Policy Act (NEPA), and then followed by Canada, Australia, and some European countries such as Germany, Sweden, and France. Currently, EIA is used in many countries around the world and became an obligatory element of licensing procedures for certain public or commercial projects in some European countries.

The International Association for Impact Assessment (IAIA 1999) defined EIA as "*the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made*." The main propose to apply EIA is to investigate the direct and indirect impacts of a proposed project (e.g. construction of an airports or ship yards) on humans, animals, vegetation, air, climate, water, ground, landscape and cultural environment, and other natural resources. In other word, theoretically EIA tool should investigate all environmental impacts associated by a proposed project.

However, EIA have often been criticized for having too limited system boundary (spatial and temporal scope) as practically almost all EIAs only address the direct and on-site environmental impacts (Lenzen et al. 2003). Accordingly, several indirect environmental effects of developments through consumption of goods and services, mining of resources, production of building materials and machinery, additional land use for activities of various manufacturing and industrial services ignored by EIAs studies. However, the indirect environmental impacts of developments should be taken into consideration during the decision-making process as they are often more severe than the direct impacts assessed by EIA.

So, EIA is a suitable ESA tool when applied for site-specific issues of projects, while it's less effective for assessing techniques or operating procedures (e.g. operation phase of a residential building or a roadway). Consequently, EIA has less frequently been applied particularly as a generic sustainability appraisal tool for a built environment project; since it's formulated to assess the site specific environmental impacts of an object located on a given site and in a given context. Whereas, some other sustainability appraisal tools such as LCA-based tools have been formulated to assess the non-site specific potential environmental impacts of a product regardless of where, when or by whom it is used (Crawley and Aho, 1999). Accordingly, often EIA has been used as a part of other sustainability assessment tools such as LCA-based tools or emergy synthesis to assess environmental performance of a built environment (e.g., Liu et al. 2011; Li et al. 2010). The step-by-step process of an EIA can vary substantially; important steps that are commonly applied in an EIA process have been indicated in Figure 2-1.

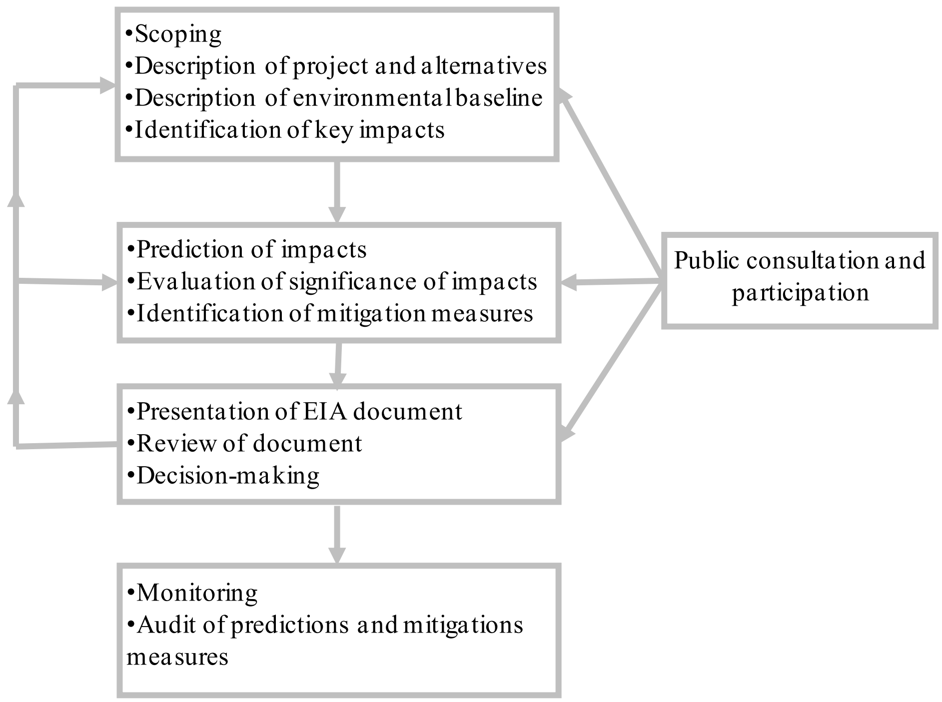


Figure 2-1 Important steps of EIA process (adopted from Glasson et al. 2005)

2.3.2 Ecological Footprint (EF)

EF is a standardized indicator tracking human demand for ecological goods and services (natural capital) that may be distinguished with the biosphere's ecological capacity to regenerate (Ewing et al. 2010). EF analysis is an accounting framework to measure the biosphere capacity (biocapacity) that is needed to preserve minimum sustainability conditions. Bio capacity represents the planet's capability to meet human demand for material depletion and waste disposal and can be defined as an area of biologically productive land or sea available/ necessary to support a certain population or economy (Ewing et al. 2010). By applying EF assessment, it is possible to approximate the quota of planet required to support humanity if every person followed a particular lifestyle.

Initially, in 1992 William Rees published the first academic work about EF concept (Rees 1992). Later Wackernagel (1994) developed EF concept and calculation process as the PhD dissertation under Rees' supervision at the University of British Columbia in Vancouver, Canada, from 1990–1994. Based on Wackernagel study on EF concept, an urban area dose not only occupies the actual ground that is covered by built environments (buildings and or infrastructures). But, an urban system requires agricultural land (for food products), sea areas (denitrification of sewage water, for fishing, etc.), forests (for wood production, assimilation of GHG emission, etc.) to support human population (Wackernagel 1994). So, by applying EF to evaluate a city or built environment all natural services can be taken into account while those are often not included in usual sustainability assessment idea of a built environment.

Over the years, EF analysis has been applied mainly for communication and learning proposes (not for strategic or policy decision) and to measure the use of resources throughout the economy. In addition, EF can be applied to examine the sustainability of different goods and services, various industry sectors, as well as urban neighborhoods, cities, regions and nations. Some examples of initiative studies of applying EF to evaluate sustainability of built environment and urban design include (Bastianoni et al. 2006; Doughty and Hammond 2004; Rees 1999) and some recent studies are (Bin and Parker 2012; Gondran 2011; Wang et al. 2012).

Although EF standards[2] are emerging to make EF methodology and results more comparable and consistent the methods used to calculate EF in different studies vary significantly. Methodology disagreements include data sources, accounting for fossil fuels, sea areas, nuclear power, imports/exports, and in using global numbers or local numbers.

EF analysis mostly focuses on human population or economics and calculates the sum of biologically productive lands and water areas needed to supply goods and services and absorb wastes generated continuously, to obtain the footprint indicator. In other words, EF calculates environmental impact in two categories; input side (e.g. areas of forestry, crops, or built-up area) and output side (e.g. dominated areas required for uptake of CO_2), and describes both input-output sides in terms of m^2. Ecologically productive sector that can be analyzed by EF are the following:

- Forest (planting or natural) to measure EF for timber products and some ecological services

[2] EF standards are available at www.footprintstandards.org

- Sea surface area to measure EF for sea products
- Pasture to measure EF of grazing land
- Arable land (ecologically most productive area) to measure EF of crops production
- Fossil energy land to evaluate EF for CO_2 sequestration
- Built-up areas (built environment) to evaluate EF for human settlements, roads, etc.

There are two other methods that developed analogous to the EF concept, namely Carbon Footprint (CF) and Water Footprint (WF). Galli et al. (2011) investigated strengths and weaknesses, linkages, overlaps, and differences among the three "Footprint Family" indicators. The CF accounts for the overall amount of GHG emissions that are directly and indirectly produced through a process or are accumulated over the life cycle of a product (Galli et al. 2011). The WF is a measure of the appropriation of natural capital in terms of the direct and indirect water use actuated by the consumption or production of goods and services (Hoekstra et al. 2009). The WF concept is closely linked to the *virtual water* concept which defined by Allan in the early 1990s as the volume of water required to produce a commodity or service (Allan 1998).

It should be noted that the EF mostly focus on one main aspect of sustainability: the human appropriation of the Earth's biological capacity. One of the criticisms surrounded this EF model is dangers of double-counting which may lead to overestimates. For example the pasture or grazing land might be provided the same area required for CO_2 sequestration. Grazi et al. (2007) have conducted a systematic comparison of the EF and an economic-based ESA method and pointed out that EF and economic-based ESA methods may *lead to very distinct, and even opposite, rankings of different spatial patterns of economic activity*. Some critics argue that EF analysis for densely populated areas (cities or countries such as New York, and Singapore with little intrinsic biocapacity) may lead to erroneous result (Gordon and Richardson 2003).

In addition several studies pointed out that the results of EF can vary with the results from more common ESA method such as LCA. For example EF model treated nuclear power in the same manner as coal power (Global Footprint Network 2008), while long term environmental impacts of the two powers can be radically different (Hertsgaard 2011). Some studies argue that EF is a strong communication tool from an educational point of view which can produce transparent indicator showing unsustainable behavior. However, they acknowledge EF analysis shortages including EF incapability of converting several environmental aspects (mainly impacts of emissions, other than Co_2, such as toxicological aspect, ozone depletion) into EF indicator (area m^2 or ha), limited EF role within a policy context, and EF limited analysis scope (Wiedmann and Barrett 2010).

2.3.3 Cost-Benefit Analysis (CBA)

CBA is a socio-economic based ESA method which estimates the total impacts (including environmental impacts) of a project, investment, or decision on society by measuring social costs and benefits. In CBA, costs and benefits are expressed on a basis of monetary values, and are adjusted based on the time value of money. Primarily, CBA applications tended to ignore environmental impacts or provided only a partial monetization of impacts (Pearce 1998). Currently, applications of CBA in environmental policy have gone through several stages, and CBA used to make environmental policy by governments and other organizations. Hanley and Barbier (2009) conducted on of the initiative studies in CBA applications for environmental management.

The main propose of CBA is to predict if the benefits of a policy outweigh its costs, and by how much relative to other alternatives (Cellini and Kee 1994). CBA is one of the well-established decision-support tools used for economic evaluation of projects on higher strategic level. As presented by Boardman et al. (2006) following is a list of steps that comprise a generic CBA:

1. Identification of alternative projects/programs.
2. Identification of project stakeholders.
3. Identification and valuation of social costs and benefits for each option (this step can include identification and evaluation of environmental impacts).
4. Allocation of cost and benefits over project time period.
5. Converting of all costs and benefits into a common currency.
6. Applying discount rate.
7. Calculation of net present value (NPV) of project alternatives.
8. Performing sensitivity analysis.
9. Presenting recommended choice.

Hanley et al. (1993) describe environmental impact analysis using CBA in four following steps:

1. Identification of project impacts resulting from its implementation. For example, environmental impacts of a bridge project include a list of all resources used in constructing the bridge (e.g. steel, concrete, labor hours); effects on local unemployment level; impacts on traffic movement; effects on local property prices; impacts on the quality of landscape and so on.
2. Determining economically relevant impacts. In CBA framework an environmental impact is economically relevant if it affects social utility and can be described by market value. Positive effects can be considered as project benefits while negative impacts can be counted as project costs.
3. Physical quantification of relevant impacts. This step aims to determine the physical amount of cost and benefit flows for a project. For the case of bridge example physical amount of can include: time saving for people using the bridge compare to using other alternatives; the number of years bridge will last (without rehabilitation) as compare to other alternatives; the number of vehicles crossing the bridge annually, etc.
4. Monetary valuation of relevant impacts. In order to compare physical values of different impacts they must be converted into common measure.

The most important advantage of CBA as compare to other ESA methods is presenting “a single” result in monetary value which is understandable by all society stockholders. However, presenting a single result by converting entire benefits and costs of a complex process or product into a common currency is not quite transparent. On the other hand, one of the most controversial criticisms of CBA is that it evaluates ecosystem services to humans, such as air and water pollution using economic analysis. In addition, many environmental impacts such as human life and some irreversible effects on ecology are not convertible into monetary values.

Reza et al. (2013c) recommended inclusion of environmental impacts and benefits in monetary values by incorporating LCA-based techniques. In addition, converting intangible benefits of public policies such as market penetration, business reputation, or long-term enterprise strategy alignment can cause huge uncertainty in CBA result. Accordingly, some studies recommended applying an uncertainty modeling (e.g. Monte Carlo simulations) beside sensitivity analysis (which is part of CBA standard procedure) to evaluate the reliability and accuracy of CBA results (Campbell and Brown 2005).

CBA has less frequently been applied as a single ESA method to evaluate environmental performance of built environment. Some recent studies of CBA application for sustainability appraisal of built environment conducted by Carter and Keeler (2008); Issa et al. (2010); Mahlia and Iqbal (2010); Pulselli et al. (2009). Review of literature on the application of CBA for built environment indicates that CBA has usually been applied as a part or complement of other sustainability appraisal tools such as emergy synthesis (e.g., Pulselli et al. 2009) or LCA-based tools (e.g., Carter and Keeler 2008).

2.3.4 Environmental Risk Assessment (ERA)

In general, risk assessment (RA) is a systematic procedure to determine quantitative or qualitative value of risk related to recognized hazards that can treat life or environment. Risk can be described as the probability or likelihood of an adverse effect to occur multiply by the magnitude of the potential loss. So, RA is an ESA tool that deals with two fundamental concepts: probability/ likelihood and consequence.

Over the years RA has being extended into the environmental field. ERA has been performed in many different ways, applied for various areas and industries (e.g. food, aerospace, oil and gas, nuclear, military, medical, etc.). Society of Environmental Toxicology and Chemistry (SETAC 2004) describe ERA as "*the practice of determining the nature and likelihood of effects of our actions on animals, plants, and the environment*". In general ERA deal with human-caused changes that can affect ecological systems and alter important features of lakes, streams, forests, or watersheds (SETAC 2004).

ERA mostly focus on two main aspects: ERA for human health effects which also called human health risk assessment (HHRA) and ERA for environmental impacts assessment which also called ecological risk assessment (EcoRA). In fact, EcoRA aims to evaluate the potential adverse effects of human activities on the living organisms that make up ecosystems (US EPA 2012), while HHRA evaluates toxicological effects of a chemical substance on human health.

Environmental risks are usually attained by characterizing two basic elements, exposure and effects, and varying degrees of uncertainty (SETAC 2004). Exposure is the interaction of stressors with receptors (e.g. concentrations of contaminants or physical changes in habitat) (SETAC 2004).While effects analysis aims to evaluate changes in the nature and magnitude of effects as exposure changes (SETAC 2004). Integrating exposure and effects information leads to an estimation of risk, the likelihood that adverse effects will result from exposure (SETAC 2004).

ERA has less frequently been applied as a single ESA method to assess sustainability of a peace of built environment. However, it has often been used as a part EIA and/or LCA in studies related to sustainability appraisal of built environment (e.g. see Erlandsson and Borg 2003; Hauschild et al. 2008; Reza et al. 2011). Reza et al. (2011) stated that environmental risk for a piece of built environment refers to the likelihood of impacts on the natural environment throughout the building/infrastructure life cycle. In that research (see Appendix B) ERA has been conducted as a part of life cycle impact assessment (LCIA) and environmental risk of built environment over its life cycle classified into three main categories (Reza et al. 2011):

1. Human health risk (HHR) due to material toxicity or toxic emissions during material life cycle. HHR has been determined based on material toxicity index which usually represented by USEPA's reference dose (RfD) for non-carcinogenic and by slop factor (SF) for carcinogenic effects. HHR furthered has been subdivided into two main categories: cancer and non-cancer risks. Building alternatives (flooring system) have been compared relatively based on chemical RfD for non-cancer and chemical SF for cancer chronic effects (the unit of both factor is milligrams of substance per kilogram body weight per day (mg/kg/day)].
2. Ecological risk (ECR) has been determined based on pollutant hazard index. The hazard index for each pollutant has been compared to air emission standards and water quality criteria of understudy region to assess their potential threat to ecological entries.
3. Safety risk (SR) has been subdivided into two categories: injury potential and fire risk. Building alternatives have been compared based on their relative safety risks.

Despite frequent use of ERA as a part of EIA or LCA, some researchers found ERA as a very complex methodology for sustainability assessment studies. They argue that, making an accurate prediction (likelihood and consequence) can be very time and resource consuming (SETAC 2004). In addition, because of the complexity of nature and its inherent variability (such as rainfall and temperature variations), ERA process will include some degree of uncertainty that must be quantified and communicated properly. SETAC (2004) moreover found that, conducting ERA that encompass large areas and involve multiple stressors is very challenging. As a result, developing standard tools and approaches to provide more effective links through ERA to risk management still needs a lot of efforts.

2.3.5 Material Flow Accounting Method

The Material Flow Accounting (MFA) method is applied to evaluate the environmental burden associated from the diversion of material flow through the natural ecosystem pathways. The theoretical basis of this method is based on input–output analysis (IOA) framework that originally developed by Leontief (1966). This method was mostly applied to obtain a picture of the economic system by addressing the major flows of money and/or goods on the national level (Bouman et al. 2000). Subsequently, the concept has been extended by many researchers to involve environmental aspects (see e.g., Faber et al. 1997; Perrings 1987; Ruth 1993). Later by recognition the fact that materials should be considered not only as a medium to carry economic services, but also as a system of the metabolism between nature and human beings, the concept was applied for environmental accounting and sustainability issues (Haberl et al. 2004; Moriguchi 1999). Finally, an officially approved standard of MFA was established by the European Statistical Office after the publication of a methodological guide “Economy-wide material flow accounts and derived indicators” in 2001 (Teresa Torres et al. 2008).

Bringezu and Moriguchi (2002) recognized MFA as an essential link between the paradigms and the practices of sustainability. They declared that a sustainable system is characterized by minimized and consistent physical exchanges between human society and the environment. Daniels (2003) recognized MFA as *one of the most valuable devices for encouraging and implementing a global green technoeconomic paradigm*. MFA has been developed to study the metabolic characteristics of social - economic system, and refers to the analysis of the set of activities comprising extracting materials from nature, chemical transformation, manufacturing, keeping as society's stock for a certain amount of time, consumption, recycling, and at the end of the production-consumption chain, disposing in the natural environment (Amann et al. 2002). It is based on common paradigm of industrial metabolism, principle of mass balancing and applying physical units to quantify the inputs and outputs of those processes (Bringezu and Moriguchi 2002).

Moriguchi (1999) described MFA as a systematic tool that comprehensively addresses the material inputs to a system, the material outputs from that system, and the material throughputs throughout the system. He furthered explain that, typical inputs comprise raw materials and energy resources, while typical outputs consist products and by-products, including undesirable ones such as emissions, wastes and pollutants. The material input/output consists of five main categories of environmental compartments (GRDC 2012): (1) abiotic raw materials, (2) biotic raw materials, (3) moved soil (agriculture and forestry), (4) water and (5) air. Accordingly, the term “materials” not only covers raw materials (mineral or metal) but also any other materials or substances in a broader sense, such as, fossil fuels, soil and aggregate, agricultural, forestry, and fishery products, manufacturing products, solid wastes, and so on (Moriguchi 1999).

According to MFA method different categories of material flows can be considered. Direct flows represent the actual weight of the products while indirect flows refer to the whole materials that have been used for manufacturing and production process consisting both used and unused materials (SERI 2011). On the other hand, used materials refer to the amount of extracted resources, which enters to the economic system for further processing or direct consumption while unused materials or extractions represent overburden and parting materials that have been derived from soil excavation, dredged materials from construction activities, mining, as well as fishing, wood, and agricultural harvesting losses that never enter the economic system (SERI 2011). Unused and indirect material flows also are referred to the terms "ecological rucksacks" that represents hidden flows.

MFA has been developed based on the laws of thermodynamics (law of conservation of mass) and material balance principles which states that total incoming flows into a biological system are equal with the total flows leaving the system plus net accumulation of materials in the system (SERI 2011). Consequently, waste generation and emissions are directly related to the scale of material input. So, a reduction in the use of materials (i.e. dematerialization) by means of increasing resource efficiency could reduce issues associated with waste generation and emissions and provide a successful strategy to combat global environmental crisis such as climate change, loss of biodiversity, and desertification (SERI 2011).

In this method, applicable material intensity factors (g/unit) are multiplied by each input. Intensity factor is quantity of materials moved from nature to create a unit of the resource. The total mass transfer supporting a process directly or indirectly is calculated from material inputs of five main environmental compartments, abiotic raw materials, biotic raw materials, moved soil (agriculture and forestry), water, and air that is directly or indirectly required to produce that input to the system (GRDC 2012). Then, the resultant material intensities (MIs) of the specific inputs are distinctly aggregated together for each environmental compartment, and allocated to the system's output as a quantitative measure of its cumulative environmental impact from that compartment (Ulgiati et al. 2006). The resulting total MIs of the product constitutes a quantitative measure of the present ecosystem disturbance associated with the withdrawal and use of natural resources (Bargigli et al. 2004).

MFA has been applied in both macro- and micro-level when the method aggregated total of all the material flows which accompany a national economy (national level) or limited to a smaller units of human activities such as a specific building. At national level MFA is used as a basis to develop framework of integrated environmental and economic accounting, and sustainability indicators. Accordingly, variety of MFA indicator systems such as the Direct Materials Inputs (DMI), Direct Materials Consumption (DMC) and Total Materials Requirements (TMR), have been proposed in order to monitor and assess the environmental performance of national and regional economies (Bringezu and Moriguchi 2002; Hoekstra and Van Den Bergh 2006). The first MFA application for the national level has been established at the early 1990s for Austria (Steurer 1992), Japan (Japanese Environmental Agency 1992) and Germany (Schuetz and Bringezu 1993). On the other hand, at microscopic level, MFA is developed as a complementary tool in the field of life cycle assessment (LCA).

Special session on MFA was conducted by OECD (2000) distinguished two types of analysis for MFA method (Bringezu and Bleischwitz 2009):

- Type I that determine specific environmental problems related to certain impacts per unit flow of substances, materials, or products. Type I, can be further described in three different approach; Type Ia: Substance Flow Accounting (SFA), that traces the flows of specific substances of priority concern (e.g. heavy metals, toxic chemicals or nutrients). Type Ib: bulk-MFA, that studies selected bulk material flows (e.g. wooden products, energy carriers, excavation, biomass, plastics). Type Ic: that analyses selected products or services consisting of several materials (e.g. cars, furniture). Type Ic can be also classified under the heading of LCA
- Type II that can support policy decisions related to natural resources and eco-efficiency and deals with problems of environmental concern related to the throughput of firms, sectors, or regions. Type II, also comprised three different approaches; Type IIa: represents the analysis of metabolic performance of firms such as plants or companies. Type IIb: considers metabolic performance of certain industrial sectors or filed of activities such as construction industry or production sector. Type IIc: is a major filed of MFA that analyze the metabolism of cities, regions and nationals, or supranational economics. This MFA type can consider total or main throughput, mass flow balance, and total material requirement of a city or region.

Different analysis types of MFA can be applied as a measure of sustainability to assess environmental and socio-economic performance of the built environment in both macro- and micro-level studies. However, more frequently, MFA, Type IIc, have been applied by urban planners to evaluate urban metabolism and sustainability of built environment in regional/ national scale. To apply MFA as a measure of sustainability for built environment, a building or infrastructure system can be assumed as stocks of construction materials those composed of chemical elements. First practices of MFA application for built environment and urban metabolism in national scale can be seen in a research by Baccini and Brunner (1991) and was followed by a substantial textbook on regional material flow analysis by Baccini and Bader (1996). Baccini (1997) further applied MFA to determine sustainability of urban region's in the Swiss Lowlands by monitoring the region metabolism and related material/energy flux. Table 2-6 summarizes the characteristics of some published MFA case studies for urban metabolism and sustainable built environment.

2.3.6 Energy Analysis and Embodied Energy Analysis Method

Energy analysis or *Embodied Energy Analysis* (EEA) is an environmental accounting methodology which aims to find sum of the total direct and indirect energy inputs (fuels/power, materials, human resources, etc.) that was used through the life cycle of a product. The term embodied energy also rooted in Leontief input–output analysis (IOA) framework. Initially, IOA framework was adapted to embodied energy analysis method by tracing the direct and indirect energy flows through an ecological system by Hannon (1973). Miller (2001) stated that the term embodied energy has various interpretations according to different literatures and publications and implications of what has been included in the total measurement are quite unclear. In its most conventional form, EEA method is expressed as the amount of "gross energy requirement" (GER), the total non-renewable or commercial energy input that was used directly and indirectly in the life cycle process of one unit of output (good or a service), in terms of their heat equivalents (Herendeen 1998). Accordingly, to calculate the embodied energy of a system's output, all different inputs to the system, in forms of material and energy, are multiplied by appropriate oil equivalent factors (kg oil/unit). Cumulative embodied energy of a product can be derived as the sum of the oil equivalents of different inputs and can be then converted to energy units multiplying by the standard calorific value of oil fuel (41,860,000 J/kg) (Ulgiati et al. 2006).

Review of literature shows that embodied energy that have been estimated for specific product can vary widely, sometimes significant variation by hundred percent. These discrepancies reflect the complex nature of calculating embodied energy that deals with the number of factors and variables include regional and national conditions, manufacturing processes, number and type of processing steps, energy sources, recycled content, and life cycle boundaries i.e. cradle to gate or cradle to grave (Calkins 2009). Dixit et al. (2010) stated that EEA is gaining great attention among researchers, professionals, builders and material manufacturers. However, they further explain that current practices in field of EEA are suffering of inaccuracy and unreliability of energy data.

Table 2-6 MFA studies for urban metabolism and sustainable built environment

Reference	***Content***	***Country***	***Key analysis area***
Baccini 1997	Sustainable development of urban systems (ecological objectives of sustainability was considered)	Switzerland	Regional water, biomass, construction materials and energy carriers of the buildings and transportation networks of a urban region in the Swiss Lowlands
Newman 1999	Sustainability and cities: study of the metabolism of Sydney	Australia	Resource inputs consumed and waste outputs discharged from Sydney. Proposing an extended metabolism model including social indicators
Stimson et al. 1999	Investigating quality of life and sustainable development in the Brisbane-Southeast Queensland metro region	Australia	Connections between urban metabolism and quality of life
Hendriks et al. 2000	MFA application as an environmental policy decision-making tool for Vienna and part of the Swiss Lowlands	Switzerland	Analyzing material flows and stocks for recognition of resource depletion and environmental quality
Decker et al. 2000	Energy and material flow through the urban ecosystem	world's 25 largest cities	Stored inputs thorough construction and waste of the urban built environment. Social and environmental costs of building
Warren-Rhodes and Koenig 2001	Escalating trends in the urban metabolism	Hong Kong	City's load on the natural environment by highlighting trends in resource consumption and waste generation total air emissions, municipal solid wastes, and sewage discharges
Barrett et al. 2002	Urban material stocks and flows of the City of York	UK	Total material demand for housing, road/footpath construction and resurfacing, and passenger transport
Huang and Hsu 2003	MFA and emergy evaluation of o investigate Taipei area's urban construction sustainability	Taiwan	MFA for constructing major urban engineering projects such as roads, bridge, MRT, flood prevention projects, storm drainage and sewerage pipes, and buildings
Sahely and Dudding 2003	Estimating the urban metabolism of Canadian cities	Canada	Overall fluxes of energy, water, material, and waste generation pollutant emissions, solid wastes, and wastewater of an urban region
Kytzia 2003	MFA as a tool for sustainable management of the built environment	Switzerland	Estimate the availability and qualities of dwelling space on a regional scale to support sustainable built environment development
Daniel B. Müller 2006	Stock dynamics for forecasting material flows for housing	Netherlands	National resource and energy consumption as well as waste and emission generation associated with concrete

			diffusion in the Dutch dwelling stock
Schulz 2007	Resource consumption associated with economic and urban development trends	Singapore	Domestic material extraction, trade, and consumption
Sartori et al. 2008	Dynamic MFA for Norwegian residential sector	Norway	Dwelling stocks' construction, renovation and demolition activities considering population and socio-economic lifestyle indicators
Federici et al. 2008	A thermodynamic, environmental, and MFA approach for Italian highway and railway transport systems	Italia	Resource consumption and emission associated by Italian transportation infrastructure: highways, railways, and high-speed railways
Niza et al. 2009	Urban MFA to characterize the urban metabolism of the city of Lisbon	Portugal	Resource management; Sustainable city; Urban planning building construction, public transportation, etc
Barles 2009	Urban metabolism of Paris and its region	France	Analysis of central city, suburbs and region to capture the impacts resource consumption, waste generation, and emission to air and water of regional and urban activities
Krausmann et al. 2009	Studying patterns and trends of changes in the global social metabolism to understand the dynamics of human environment relations	-	Environmental pressures and sustainability problems associated with global extraction of biomass, fossil energy carriers, metal ores, industrial minerals and construction bulk minerals
Mingming Hu 2010	Dynamic MFA: Sustainable built environment development, for Chinese housing stock dynamics	China	Rapid urbanization, economic development, and housing in China; Long-term metabolism of the built environment stocks; Beijing's demand for construction materials and demolition waste generation
Cochran and Townsend, 2010	MFA approach for estimating C&D debris generation and composition for a large region	USA	Waste management, construction and demolition C&D debris
M Hu et al. 2010	Iron and steel in Chinese residential buildings	China	Rural and the urban housing systems; iron and steel demand and scrap availability for different life span of residential buildings in China
Woodward and Duffy 2011	Irish Cement and concrete flow analysis	Ireland	Concrete, production cradle to gate , usage and waste management disposal or recovery

One of the important characterizations of EEA framework is the embodied carbon can be also analyzed besides embodied energy measure. Accordingly, the total CO_2 emission can be roughly estimated by multiplying all the energy used in life cycle stages with emission factors. However, embodied energy has been mostly recognized as only one measure of sustainability rather than as a sole basis of material, component or system selection. One of the reasons is that EEA methodology is usually concerned with the depletion of non-renewable fossil energy. Accordingly, renewable energy inputs, such as sunlight, wind, rainfall, as well as the indirect environmental support embodied in labor and services, resources provided for free by the environment including topsoil, spring water, and environmental support from the biosphere, e.g., absorption of the waste and emission associated with human activities, are not considered and counted in the EEA framework (Ju and B. Chen 2010).

Comparing to the other environmental accounting methods, EEA framework most widely have been applied as a measure of sustainability for built environment. EAA framework has been not only used to evaluate built environment as a whole but also used frequently as a criterion for evaluating green building materials and products. For instance, embodied energy used besides other performance indicators (such as recyclability, operational energy, etc) in green building standards (e.g. UK Code for Sustainable Homes), building rating systems (e.g. SBTool) and generic LCA sustainability tool (e.g. BEES and Athena). Embodied energy has been also recognized as a significant component of the buildings life cycle impact in various LCA studies for built environment (e.g. Chang and Ries 2011; Monahan and Powell 2010; Reza et al. 2011).

In general, there are two forms of embodied energy can be evaluated for a building (Ramesh et al. 2010):

1. Initial Embodied Energy: this term represents total non-renewable energy pathways required for the raw materials extraction, processing, manufacturing, transportation to site, and assembling building materials to construct a building. The Initial Embodied Energy can further be subdivided into two different categories: (1) Direct energy that is consumed in various on-site and off-site operations such as building products

transportation to the site and then prefabrication, on-site transportation, and building construction and assembly. (2) Indirect Energy consumed in the process of building materials acquiring, processing, and manufacturing as well as any transportation related to these activities.

2. Recurring Embodied Energy: this form represents total non-renewable energy expended to maintain, repair, restore, refurbish or replace of materials, components, or systems through building life cycle.

Accordingly, the total embodied energy of a building can be achieved from the sum of the initial and recurring embodied energy. In addition, the total life cycle energy of a building (from raw material extraction to deconstruction and disposal) can be obtained as the sum of the life-cycle *embodied energy*, *operational energy* that required in the building for operating various electrical and mechanical services, and demolition energy that required to demolish the building and transporting the waste material to landfill sites and/or recycling plants (Ramesh et al. 2010). As a result to mitigate the environmental impacts of a built environment through its lifetime it's necessary to reduce both embodied energy and operating energy, latter is usually much higher than the embodied energy (Kotaji and Schuurmans 2003). Table 2-7 summarizes the characteristics of recent published EEA studies related to the sustainable built environment (To find older EEA article review see Ramesh et al. 2010; Sartori and Hestnes 2007).

2.3.7 Emergy Synthesis

In the 1980s, Odum and co-researchers at the University of Florida proposed and developed the groundbreaking idea of emergy as a way of understanding the behavior of self-organized systems, valuing ecological products and services, and altogether analyzing ecological and economic systems (Hau and Bakshi 2004). Emergy, spelled with an 'm', *is a universal measure of real wealth of the work of nature and society made on a common basis* (Odum 2000). Campbell (1998) stated that emergy can be a true measure of relative importance which expresses different forms of environmental, economic and human system flows in terms of equivalent ability to do work (exergy). By definition, emergy is "*the available energy (exergy) of one kind (usually solar energy) that was used up directly and indirectly to generate a resource, product, services or activity*". Based on this basic definition, emergy concept seems quite straightforward, while its implications can be potentially profound (Hau and Bakshi 2004).

In order to apply emergy concept to analyze a system, that system should be considered as the networks of energy flows, then the emergy value should be determined for each stream through the system (Odum 2000). The theoretical basis for emergy synthesis is rooted in thermodynamics, general system theory (von Bertalanffy 1968), and system ecology (Odum 1983). Evolution of the emergy theory over the thirty years was documented by Odum in Environmental Accounting (Odum 1996) and in the volume edited by C.A.S. Hall titled Maximum Power (Odum 1995). Emergy evaluates the energy which used in the past by the universe to do work of production of a product or service (Odum 1995, 1996, 2007). In the last 30 years, the research by Odum and his colleges on emergy accounting confirms that, *emergy is the 'memory' of the total exergy that was previously required and thus is different from a measure of energy now* (Odum 1996).

Emergy is an expression of all the environmental supports (direct/indirect energy and resources) including 'freely available' ones, as well as money and human services spent in the work process that produce a good or service in the unit of solar energy (Brown and Buranakarn 2003). The most interesting characteristic of emergy approach that makes it exceptional among other ESA tools is that, it attempts to develop a link to connect economic and ecological systems and assign an "unbiased" emergy value to ecological and economic products and services. This emergy value is accounted based on the theory of energy flow in systems ecology and its relation to systems survival (Hau and Bakshi 2004). Accordingly, by applying emergy approach, it is possible to objectively evaluate the contribution of environmental, economic, and social aspects of a system with an energy-based unit. This will help to directly compare socio-economic and environmental aspects of every system (Odum 2007).

Table 2-7 EEA studies for sustainable built environment

Reference	Content	Region of study	Type of built environment	Embodied energy		Operation energy	Key analysis area
				Energy	Emission		
Treloar et al. 2001	Embodied energy of building materials to reduce life cycle GHG emission	Australia, Melbourne	Residential and commercials building	✓			Using IOA and hybrid methods to evaluate life cycle embodied energy, comparing materials and components and their recycled content
Thormark 2002	A low energy building in a life cycle	Sweden	Apartment housing	✓		✓	Embodied energy, operating energy and recycling potential of the most energy efficient apartment housing
Lenzen and Treloar 2002	EEA for two design options, wood- and concrete-framed building	Australian based data for Swedish building	Wood- and concrete-framed multi-storey building	✓	✓		Embodied energy and embodied emission using a hybrid input–output technique
Venkatarama Reddy and Jagadish 2003	Embodied energy alternative building materials and technologies	India	multi-storey residential building	✓			Total embodied energy to compare different types of alternative roofing systems, masonry, building materials
Scheuer et al. 2003	Life cycle energy and environmental performance	USA, Michigan	University building	✓		✓	Embodied energy and LCA for building materials, structure, envelope, interior structure, finishes, utility and sanitary systems
Mithraratne and Vale 2004	Life cycle energy model for houses	New Zealand	Housing with 3 construction types	✓		✓	Embodied energy, operating energy, life cycle energy and cost for generic constructions and space heating
Yohanis 2006	Embodied energy conceptual stage of building design	UK	Non-domestic buildings	✓	✓		Comparative impact of operational energy, capital, and embodied energy on the building cost
Pullen 2007	Embodied Energy of the Urban Environment	Australia, Adelaide metropolitan area	Urban residential buildings and supporting infrastructures	✓		✓	Mapping of embodied and life cycle energy consumption in the urban environment to analyze urban energy consumption
Asif et al. 2007	Dwelling home LCA	Scotland	Typical semidetached	✓	✓		Embodied energy and associated emission impact of main construction

			three-bedroom house				materials
Y. L. Langston and C. A. Langston 2008	Reliability of building embodied energy modeling	Australia, Melbourne	Thirty different residential and commercial buildings	✓			The relationship between initial embodied energy and capital cost
Huberman and Pearlmutter 2008	Life-cycle energy analysis LCEA of building	Southern Israel, Negev desert	A dormitory complex that characterized as a climatically responsive building	✓		✓	Analyzing both embodied and operational energy consumption to compare a number of possible material composition alternatives
Dimoudi and Tompa 2008	Energy and environmental indicators of different construction and structure materials	Greece	Office buildings	✓	✓		Initial embodied energy and equivalent CO2, SO2 emissions compared with the overall building energy performance
Utama and Gheewala 2008	Life cycle energy of a house	Indonesia	Single landed houses	✓		✓	Embodied and operating energy of a residential enclosure comparing two typical clay and cement house
Utama 2009	High rise apartment life cycle energy of building envelope	Indonesia	High-rise residential building	✓		✓	Thermal properties, embodied and operating energy of building envelope; Comparing typical double wall and single wall envelopes
Shukla et al. 2009	EEA for building with low energy intensive materials	Indian Institute of Technology, New Delhi	Adobe house at Solar Energy Park	✓		✓	Embodied energy involved in construction of main structure, finishes, furniture, maintenance and electric work
Kofoworola and Gheewala 2009	Life cycle energy assessment of a typical office building	Thailand, district of Bangkok	38-storey office building	✓		✓	Whole life cycle embodied and operating energy; Assessment of potential energy saving
Chang et al. 2010	Economic I–O LCA model to evaluate the embodied energy and environmental emissions	China	24 Construction sectors: buildings and infrastructure	✓	✓		Analyzing buildings and infrastructure embodied energy and related emissions in macro-level: Chinese society
Hernandez and Kenny	Building optimization towards life cycle	-	Low-energy domestic building	✓		✓	Evaluate life cycle zero energy building LC-ZEB based on primary energy use

2010	zero energy						in operation plus the energy embedded in materials and systems over the life of the building
Haynes 2010	Embodied energy calculations Within life cycle analysis	Australia	Residential buildings	✓	✓	✓	Life cycle embodied energy, operational energy and embodied carbon
Duffy et al. 2011	Embodied emissions using stochastic analysis Monte-Carlo simulation	Ireland, Dublin	Seven apartment buildings with different structural characteristic		✓		Input–output and embodied CO2-eq analysis for main building materials and construction activities

Emergy synthesis technique is based on basic thermodynamics laws, general system theories (Von Bertalanffy 1973), energetics[3] (Lotka 1945) and system ecology (Odum 1988). To develop emergy synthesis, a system is converted into a network of energy streams and a measure of solar emergy assigned to energy flows (Hau and Bakshi 2004). Solar emergy represents the total amount of available solar energy that was directly or indirectly used in order to generate or support a given product or service, and calculated in solar equivalent joules (sej) (Pulselli et al. 2009). Therefore to quantify the solar emergy for ecological goods and services, the analyzer need to trace back through all the energy and resources flows (energy supply chain) that contributed to generate these input flows in the amount of solar energy that came into their production (Brown and Ulgiati 2002).

A key concept in emergy evaluation process is *solar transformity* or *unit emergy value (UEV)*. The amount of emergy required to produce one joule of an input will be determined by its solar transformity from Equation (1). For example, if 12E+04 solar emjouls[4] (sej) of coal and 4E+04 sej of service are required to generate 1 Joule electricity, the solar transformity of electricity is 16E+04 (sej/J) (Odum 1996).

$$\text{Solar transformity} = \frac{\text{Solar emergy flow (sej)}}{\text{Available energy flow (exergy)(J)}} \qquad \textbf{(1)}$$

Transformity can therefore be considered as a *quality factor* that functions as a major of *intensity of the biosphere support* to the product under study (Sciubba and Ulgiati 2005; Ulgiati et al. 2006). Moreover, the total solar Emergy, *U*, can be derived from Equation (2).

---

[3] The "*maximum power principle*" has been suggested as the 4th energetics principle in open system thermodynamics, where a case of an open system is a biological cell. Referring to Odum (1995), "*The maximum power principle can be stated: During self-organization, system designs develop and prevail that maximize power intake, energy transformation, and those uses that reinforce production and efficiency*."

[4] Solar equivalent joules

$$U = \sum_{i=1}^{n} E_i \times Tr_i \quad \textbf{(2)}$$

where U is the total emergy calculated over all the independent input flow, E_i is the available energy or exergy and Tri is the solar transformity of the ith input flow of a product or service.

Figure 2-2 shows an energy system diagram of a work. In this figure, *Js* shows a source energy flow while Jp indicates the product energy flow, *Jq* refers to lost or degraded energy flow, based on thermodynamics 2nd law, and *Jf* presents feedback energy flow. For better understanding of emergy accounting and solar transformity calculation, an example is provided in Figure 2-3.

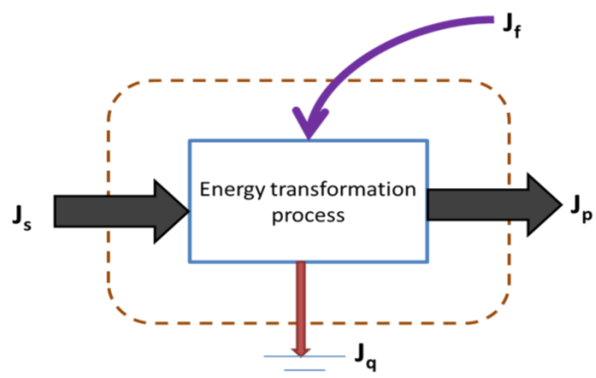


Figure 2-2 Energy system diagram of a work

To conduct a complete emergy synthesis, a 5-step process is required:

i. Developing system diagram and a conceptual model

ii. Providing emergy evaluation table

iii. Extracting raw data and energy content specific for a given project

iv. Converting raw data to emergy unit using unit UEVs form relevant database (e.g. ISAER 2012); and

v. Summarizing results and calculating emergy indices

These five steps are discussed in detail by Campbell et al. (2005) and Odum (1988, 1995, 1996, 2000, 2007). A brief description of emergy synthesis five steps are discussed in in the following sections.

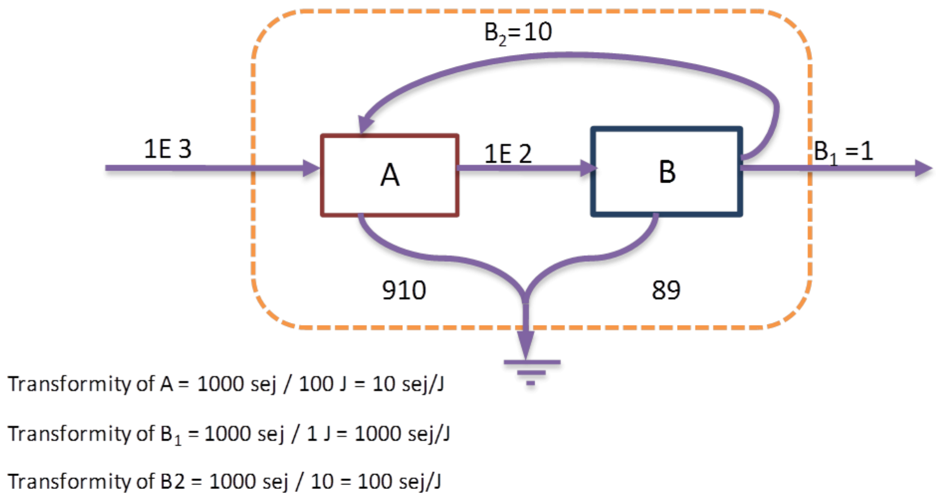
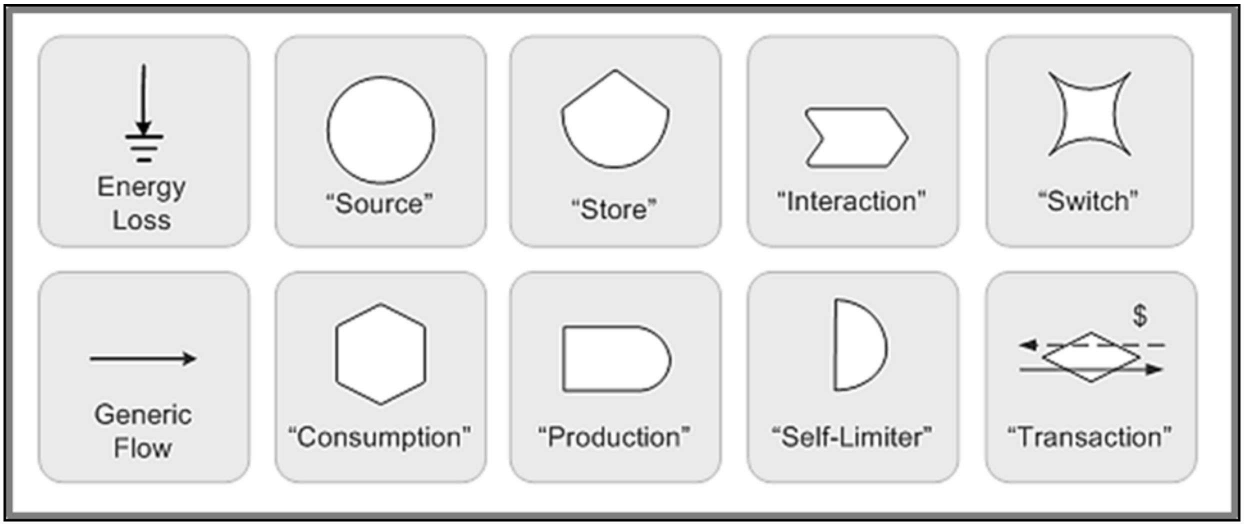


Figure 2-3 Example of emergy accounting

2.3.7.1 Diagramming and developing a conceptual model

In the first step, a detailed system diagram of a given product is developed, considering all inflow and outflow pathways. An energy system diagram represents a visual mathematic of a product inflow and outflow and their interactions using a network of symbols. In general, a product/resource system diagram should include all interaction among natural, human and economic pathways and components. These inflows and outflows and their interactions are presented using energy system language symbols and their inherent mathematics. Main energy system language symbols and short description of their meaning was shown in Figure 2-4. A network of these symbols can be translated directly to a set of simultaneous 1st order differential equation (Campbell et al. 2005).

An energy system diagram usually documents all system physical flows (such as raw material or electricity) as well as properties component (such as aesthetics and information) and any possible interaction/connection and pathway between these system components. The main purpose of developing an energy system diagram for an examined system is to perform a critical inventory of processes, flows, and storages that are important "drivers" of that system. This includes all streams that flow across the system boundary and are therefore necessary to take into account. A basic energy system diagram of an urban system and its regional support area has been indicated in Figure 2-5[5]. Important components to develop an energy system diagram was summarizing as following (Campbell et al. 2005):



Energy loss or heat sink: Represents loss of potential energy from further use by system
Source: Source of energy delivering forces to the system from outside the system boundary
Store or tank: A compartment of energy storage inside the system boundary storing a quantity as the balance of inflows and out flows
Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both
Switch: A symbol that indicates one or more switching actions
Generic flow: A pathway proportional to the quantity in the storage or source upstream
Consumption: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow
Production: Unit that collects and transforms low-quality energy under control interactions of high-quality flows
Self-limiter: A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within
Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source

Figure 2-4 Energy system language symbols

[5] Numerous examples of energy system diagrams can be found at the EmergySystems.org web site

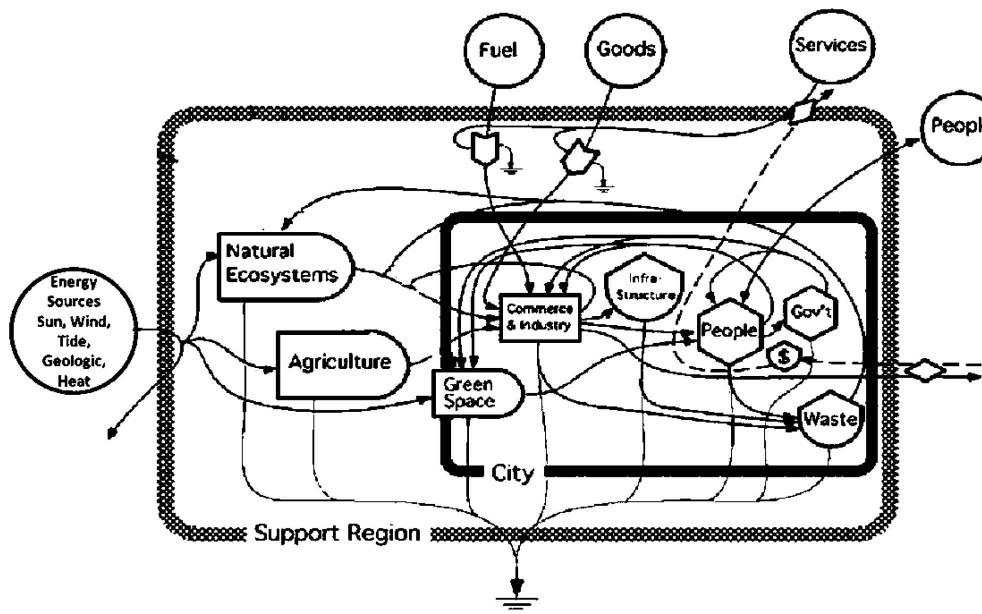


Figure 2-5 Energy system diagram of an urban system (adopted from EmergySystems.org)

System boundary: System boundary determines the spatial and temporal scale of the analysis which is represented as a rectangular box surrounded by all system diagrams components.

Forcing functions: Any inflow that crosses in the boundary is an energy source for the system, including pure energy, materials, machinery, work and human services, money, as well as information.

Pathway lines: Interaction flows are represented by arrowheads line that includes energy, materials, information and money.

Outflows: Any outflow that still has available energy can show as pathways leaving the system from the upstream borders. Moreover, degraded energy can be indicated with pathway exiting at the bottom of the diagram.

2.3.7.2 Emergy evaluation table

In this step, the description of different pathways from product system diagram is transferred into the emergy evaluation table, where the calculations needed to quantitatively evaluate these pathways are compiled. Generally, the emergy evaluation table has six columns as it was shown in Table 2-8. Often an additional column is added to list emdollars (Em$), or emprice values that express emergy flows in equivalent monetary flows.

Table 2-8 Emergy evaluation table

Note	*Item(name)*	*Data (flow/time)*	*Units*	*UEV (seJ/unit)*	*Solar Emergy (seJ/time)*
1.	First item	xxx.x	J/yr	xxx.x	Em_1
2.	Second item	xxx.x	g/yr	xxx.x	Em_2
--					
n.	nth item	xxx.x	J/yr	xxx.x	Em_n
O.	Output	xxx.x	J/yr or g/yr	xxx.x	$\sum_{n}^{1} Em_i$

2.3.7.3 Data sources and model evaluation

In the third step, data sources and model evaluation, and raw data and energy content of different sources and materials that needed to complete the emergy analysis tables are extracted and summarized in the table. The information related to all inflows such as different forms of energies, materials, services and money will be collected from different resources and documents[6]. The raw data needed for emergy most often reported as flows of energy (Joule, Kcal), mass (gr, kg, tone) and/or money (Dollar, Euro, etc.).

2.3.7.4 Unit Emergy Values (UEVs)

In the fourth step, UEVs or conversion factors are calculated or collected from previous studies[7] to convert raw data (energy content) into emergy unit.

UEV of a pathway can be fall into the following categories (Odum 1996):

- *Solar transformity*: Represents emergy investment per unit process output of available energy with the unit of seJ/J.
- *Specific emergy*: Represents emergy investment per unit process output of dry mass with the unit of seJ/g or seJ/kg.

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[6] The type of documents is related to case study; e.g. bill of materials or metric computation for a particular construction project can be used.

[7] UEV data often can be collected from reference emergy accounting studies (e.g., Odum 1996).

- *Emergy-money ratio*: Emergy investment per unit of GDP generated in a country, region or process with the unit of seJ/currency. Emergy values can be converted to emergy-dollars (EM$) by using emergy-money ratio (Odum 1996).

Although, UEVs have been calculated for numerous goods and products[8], in some cases the calculation of new UEVs or the updating of old UEVs is required. To obtain UEV of a particular item, its production process is analyzed and then emergy inputs to the process are summed and divided by the available energy in the product.

After completing the emergy evaluation table and estimating all the inputs to a system, the UEV of the under studied product or process can be calculated. In order to obtain the UEV of the under studied system, the output (row "O" in Table 2-8) is estimated in units of energy or mass. Then the input emergy is summed and the UEV is determined by dividing the emergy by the units of the output. The UEV that result for the examined system (product or process) can be also useful for future emergy evaluations.

2.3.7.5 Flow summary and calculation of emergy indices

In the final step all data in emergy evaluation table are summarized to calculate some emergy indices. Emergy indices are usually calculated to compare systems, suggest optimized alternatives, predict trends and reduce environmental burdens. So far several emergy indices have been presents in different studies that are used to evaluate the *global/regional performance* of a process (Brown and Ulgiati 1997, 2010; Campbell et al. 2005; Meillaud et al. 2005; Ulgiati et al. 1995).

2.3.7.6 Emergy synthesis applications

Emergy synthesis has been employed in different areas and to evaluate complex systems at all scales humanity and nature. Some emergy synthesis applications have been summarized in Table 2-9. In the context of built environment, emergy synthesis has been used by urban

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[8] Recently a complete list of UEVs have been gathered by ISAER that can be found at the http://emergydatabase.org web site

planners and ecologists to evaluate spatial organization, urban development, and urban metabolism at a regional/ national scale (macro level studies). Some recent applications of emergy accounting method for urban planning is reported by Duan et al. 2011; Liu et al. 2009; Su et al. 2009; Zhang et al. 2011. However, review of the literature shows that emergy synthesis has been rarely used as a standard tool for assessing sustainability of built environment, engineering decision-making, and specifically for micro scale and project specific case studies related to the built environment. In addition, current practices in emergy synthesis are suffering of inaccuracy and unreliability of UEV data.

2.4 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is the third group of sustainability assessment tools that is reviewed in this chapter. In recent years, the LCA has successfully been applied to integrate environmental concerns like climate change and resource depletion (Khan et al. 2004). Rebitzer et al. (2004) explain LCA as a methodological framework to assess an estimate the environmental impacts associated over life cycle of a product, process or activity, such as resource depletion, climate change, acidification, eutrophication, ozone depletion, tropospheric ozone (smog) creation, and toxicological stress on human health and ecosystems.

LCA "cradle-to-grave" approach makes it unique among other sustainability appraisal tools (Finnveden et al. 2009). LCA methodology is based on the axiom that all phases in the life of a product cause environmental impacts and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste management (Lippiatt 2000).

LCA is a standard procedure to evaluate the environmental performance of human-dominated products and processes (Rugani and Panasiuk 2012), and has been widely used in diverse areas including construction and infrastructure industry (Wang et al. 2010). Although LCA has become the recognized international approach to assess the comparative environmental performances of products or processes, many aspects of the LCA technique are still under development (e.g. ultimate impacts on human and ecosystem health) (Finnveden et al. 2009).

Table 2-9 Emergy different fields of study

Ecosystems		*Economy*		*Urban systems & cities*		*Resources*		*Policy making*	
Field	**Example**	**Field**	**Example**	**Field**	**Example**	**Field**	**Example**	**Field**	**Example**
Self-organization	Odum, 1986;1988	Sustainability	Odum and Odum, 2002; Brown et al. 2009	Spatial organization and urban development	Huang and Chen, 2005; Ascione, et. AB2009	Fossil fuels	Odum, 1996; Bargigli et al., 2004;Bastianoni et al. 2009	Tools for decision makers	Almeida, et al. 2007; Giannetti et al., 2010
Biodiversity	Brown et al. 2006	Development policies	Odum, 1980b	Urban metabolism	Huang et al.,2006; Zhang et al., 2009	Renewable and nonrenewable electricity	Brown and Ulgiati, 2001; Peng et al. 2008; Brown and McClanahan, 1992	Conservation and economic development	Lu et al.2007
Complexity	Brown and Cohen, 2008	Tourism	Lei and Wang, 2008; Vassallo et al., 2009	Transportation modes	Federici et al., 2003; 2008; 2009	Biofuels	Carraretto et al., 2004; Dong et al. 2008; Franzese et al., 2009		
Ecosystems health	Brown and Ulgiati, 2004	National and international analyses	Lomas et al., 2008			Material flows and recycling	Brown and Buranakarn, 2003		
Food webs and hierarchies	Brown and Bardi, 2001	Trade	Brown, 2003						
Forest ecosystems	Doherty et al., 1995; Lu et al. 2006								
Watersheds	Agostinho et al., 2010								
Aquatic and marine	dum and Arding,1991								

LCA approach not only includes environmental assessment but also may consider economic and risk evaluations in the analysis. The life cycle costing (LCC) is a technique to estimate overall cost of different products (e.g. construction and building) design options over the life of the project (Khan et al. 2004; Wang et al. 2010).

The United States Environmental Protection Agency (USEPA 1995) defined LCA "*as a methodology for estimating the environmental burdens of processes and products (goods and services) during their life cycle from cradle to grave*". The Society of Environmental Toxicology and Chemistry (SETAC 1993) defined LCA "*as a process to evaluate the environmental burdens associated with products, processes, or activities by identifying and quantifying energy and material used and waste released to the environment; to assess the impact of this energy, and materials used and wastes released to the environment; and to identify and evaluate opportunities to affect environment improvements*". The fundamental aim of LCA is to provide pragmatic indications to aid policy decisions (Raugei et al. 2012)

Since early 1990s, the LCA has been used for estimating environmental impacts of the construction industry (Fava 2006). A comprehensive review on the development of LCA in the construction industry has been reported (Ortiz et al. 2009), which suggests that the LCA can guide decision-making in construction industry using principles of sustainable development. In the context of construction and building sector, LCA is a complex process and several studies have been performed to identify framework deficiencies and improve the evaluation process for building LCAs (Rajendran et al. 2007; Zhang et al. 2010a). However, some review of the literature in this field indicate that there are still notable framework gaps and inconsistencies amongst existing studies, including issues with the functional units, system boundaries, goals, scopes, and data (Santero et al. 2011).

Some previous studies on building LCAs do not have comprehensive systems boundaries and are subjected to lack of transparency (e.g. ignoring building service life and maintenance activity during service phase), and are based on solid weighing approach, that can lead to unrealistic result of building life cycle impacts. As a result, there is a need for a movement towards a more reasonably transparent methodology and reliable building LCA framework that will provide designers, researchers, and other stakeholders the ability to accurately and consistently characterize the impacts of buildings construction, operation and maintenance.

A comprehensive effort has been made towards the standardization of LCA by the International Standardization Office (ISO 14040 2006). However, the final results of LCA are still based on subjective evaluations that leave the choice of the impact assessment method to the analyst (Ulgiati et al. 2006). SETAC, ISO 14040 and CML (Center of Environmental Sciences of Leiden University) have provided best practices and guidelines for an LCA framework. Though these organizations worked independently, general consensus on the LCA framework has been evolved that can be described by following four phases (Bahareh Reza et al. 2011):

- Goal definition and scope assessment
- Inventory analysis
- Impact assessment (evaluation)
- Improvement assessment

2.4.1 Goal definition and scope assessment

In this stage, the understudied system and its boundaries, the functional unit to be applied for life cycle calculation and the procedure to be followed for the study are determined. In particular, in this stage the main purpose of the study, the people to which the study is addressed, and the future use of the results must be defined. Defining goal and scope assessment consists of following steps:

- Defining the purpose; this step helps to obtain the existing process/ product information and analyze process/ product improvement strategies.
- Setting the scope and depth; a decision has to be made that how many factors and processes need to be investigated in the study.
- Defining reference system; a system for which all the inputs and outputs are recorded and the total environmental impacts of a product or process are determined. A Schematic representation of a LCA system has been illustrated in Figure 2-6.
- Selecting LCA system boundaries; determination of the processes or units in sequence (subsystems) that will be included in the studied system. Figure 2-7 illustrates cradle-to-grave system boundary of built environment.

- Establishing the LCA functional unit; a reference unit or a measure of performance to which all the inputs and the outputs of the system will be referred. Defining an appropriate functional unit is essential in order to compare different systems.

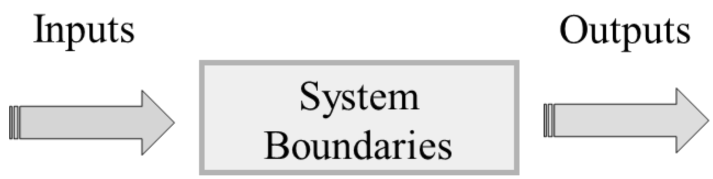

Figure 2-6 Schematic representation of a LCA system

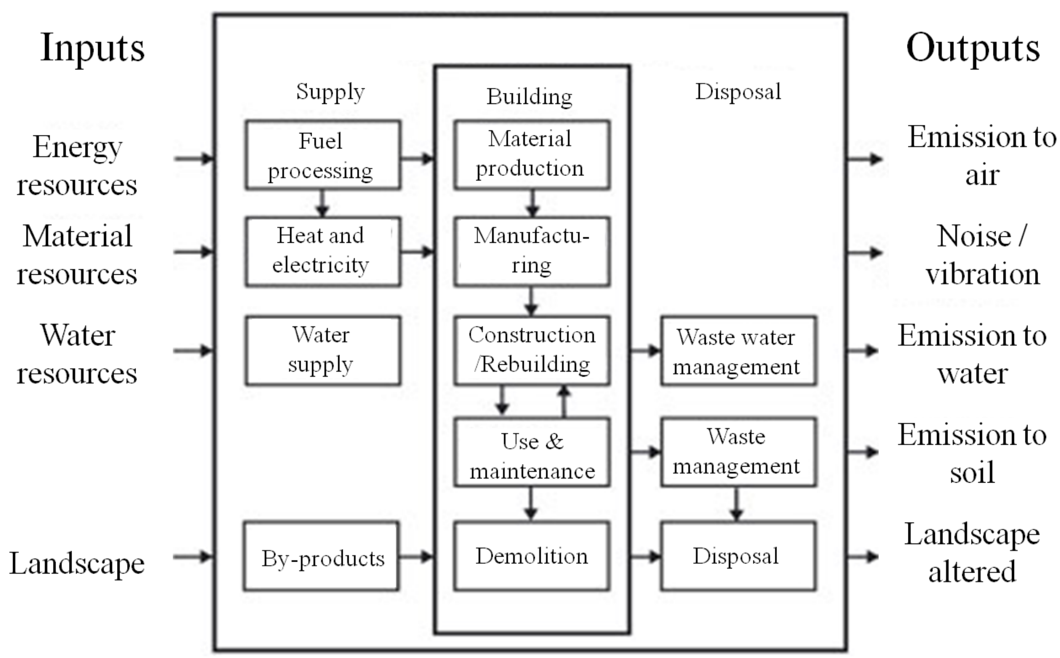

Figure 2-7 Life cycle system boundary for built environment

2.4.2 Life Cycle Inventory (LCI)

LCI is a methodology for estimating the resources consumption and the emissions and waste flows quantities associated by or attributable to a product's life cycle (Rebitzer et al. 2004). The main purposes of LCI are establishing baseline information for specific product or activity, ranking relative contribution of life cycle stages, and understanding the relative environmental burdens of examined products or activities (Scientific Applications International Corporation (SAIC) 2006).

LCI analysis requires gathering data for all process units and their associated energy and mass flows, as well as the data on emissions and discharges into the receiving waters, soil, and air (Reza et al. 2011). LCI analysis is very complex and encompasses tracking numerous of discrete unit processes in a supply chain (e.g., the extraction of raw resources, various primary and secondary production processes, transportation, etc.) as well as dozens of related mass, energy, and substances (Trusty and Horst 2003). Consequently, collecting LCI data is costly and challenging, and is most frequently retained confidential by those manufacturers that do undertake studies (Trusty and Horst 2003).

Finnveden et al. (2009) stated that performing an LCI requires a lot of data that can be vary based on geographical, temporal, and technological differences. Accordingly, preparing inventory data is the most work- and time-consuming stages of an LCA. On the other hand, LCI can often be challenging due to the lack of appropriate data for the examined system (Finnveden et al. 2009). As a result, many databases have been developed in order to facilitate the LCI and avoid duplication in data compilation. LCI databases include public national or regional databases, industry databases, and consultants' databases that are often offered in combination with LCA software tools (Finnveden et al. 2009).

In order to conduct LCI for an examined system, the system boundaries are established, and the system is described through a process flow chart (Khan et al. 2001). Usually the outcome of LCI phase can be summarized in an inventory table. The functional unit defined in the previous stage is ascribed to each factor. Then the results of LCI can be characterized in terms of impact potentials as it will be described in the next step.

2.4.3 Life cycle impact assessment (LCIA)

LCIA involves following steps (Pennington and Potting 2004):

i. Impact categories selection: this step includes choosing different impact categories (e.g. climate change, acidification, resource depletion, etc.) and appropriate indicators for each impact category (e.g. kg of CO_2 equivalent). Impact categories usually identified based on three main groups of "areas of protection" as reported by Haes and Lindeijer (2002):
   - Human health
   - Natural environment (resources and life support functions—climate regulation, soil fertility)
   - Man-made environment (monuments, forest plantations)

ii. Classification: assigning the inventory data to the relevant impact categories that are selected in previous step.

iii. Characterization: calculating impact category indicators using characterization factors. Characterization factors usually express the contribution of an inventory data to an impact category (e.g. contributions of different gases to climate change relative to CO_2 equivalent)

iv. Normalization: calculating category indicator results relative to reference values(s).

v. Grouping and/or weighting: in this step, cumulative effects of environmental burden on human and ecology is estimated. The impacts of various categories are aggregated into a single index using relative weights assigned to them.

vi. Data quality analysis.

Grouping and/or weighting is the most challenging and controversial step of the LCA technique, since it involves human subjectivity (Khan et al. 2004). Azapagic (1999) and Fava (1993) argued the philosophical and conceptual validity of such aggregation. Consequently, weighting is not being allowed when following ISO14042 in comparative assertions disclosed to the public. However, weighting is explicitly allowed for other applications, thus it is LCA practitioner responsibility to use weighting in a proper way.

Dealing with non-commensurate units of varying environmental impacts (e.g., gram of CO_2 equivalent, kcal of energy equivalent, kg of solid waste generated) is a major issue of the LCIA (Brown and Buranakarn 2003). This issue makes the calculation of the cumulative effects very difficult and leads to a complicated multi-criteria problem. In addition, as discussed by Reza et al. (2011), aggregating and weighting to calculate cumulative effects for product alternatives is essential, in order to use the results of LCA for decision-making and comparative analysis (see Appendix B).

Therefore, several LCA studies and commercial LCA software employ Multi-Criteria Decision-making (MCDM) techniques to address this issue (Reza et al. 2011; Khan 2004; Zealand 2001). On the other hand, MCDM methods need to apply weighting schemes to make comparison between different impacts. There is no widely agreed method to determine the relative importance of different impacts (Reza et al. 2011). Table 2-10 compares two different weighting schemes for relative importance of different environmental impacts for a well-known LCA tools (BEES). It should be noted that assigning different weight to a particular life cycle impact, often can completely alter the design options (Calkins 2009).

Table 2-10 Comparing different weighting schemes for BEES (Calkins 2009)

Impact	*USEPA Science Advisory Board (SAB) Study (2000) Relative Important Weight*	*BEES Stakeholder Panel (2006) Relative Important weight (%)*
Global warming	16	29
Acidification	5	3
Eutrophication	5	6
Fossil fuel depletion	5	10
Indoor air quality	11	3
Habitat alternatives	16	6
Water intake	3	8
Criteria air pollutants	6	9
Smog	6	4
Ecological toxicity	11	7
Ozone depletion	5	2
Human health	11	13

Another important issue that LCA and some ESA tools are facing is aggregating environmental impacts with socio-economic factors (TBL sustainability performance). Environmental impacts are usually described in terms of physical units such as grams of chemical pollutants emitted to the air, kilometers of degraded streams, or the number of endangered species in a particular region. On the other hand, human related issues (socio-economic impacts) commonly account for in dollars. However, to make a policy decision related to environmental systems, both environmental impacts and its associated socio-economic consequences must be expressed by a unified measure to compare and evaluate equitably (Campbell et al. 2005).

2.4.4 Interpretation and improvement assessment

The purpose of this stage is to recommend any possible improvement in the system (Reza et al. 2011). This phase is also mentioned as interpretation in ISO 14040. In addition, identification of substantial issues and appraisal to reach conclusions and preparing final report are integral parts of this stage. Figure 2-8 illustrates four phases of LCA framework. According to (ISO 14040 2006), the interpretation should include:

- Identification of substantial concerns based on the results of the LCI and LCIA phases of an LCA
- Evaluation of the study considering completeness, sensitivity and consistency checks
- Conclusions, limitations and recommendations.

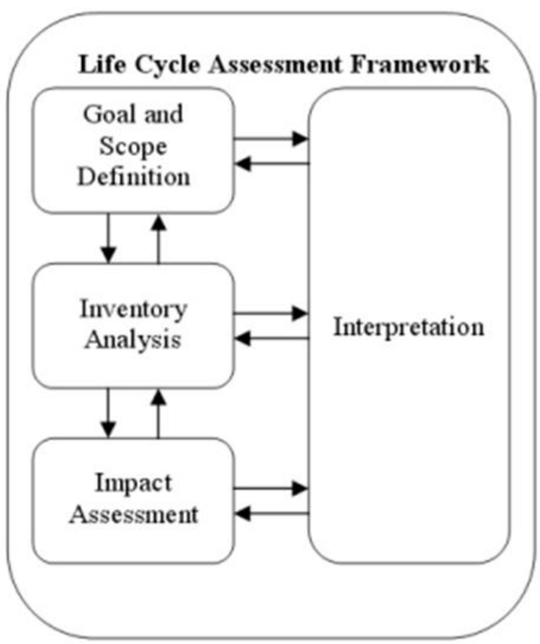

Figure 2-8 Four main phases of LCA framework ISO 14040

2.4.5 LCA tools for modeling built environment

LCA can be applied to assess sustainability performance of built environment with different purpose:

- Strategic planning and decision-making (e.g. rehabilitating or reconstructing a bridge)
- Product development (e.g. innovating a new building material),
- Alternative comparison for purpose of decision-making (e.g. comparing different flooring system)
- Ecolabeling (e.g., labeling a new construction material)
- Policy and regulations (e.g. Road and Highway Code).

There are a number studies as well as commercially available software for building and infrastructure LCA. A rough division into two classes of LCA commercially available databases and software can be made as following:

i. Generic LCA software, typically designed to compare different products including built environment such as SimaPro and GaBi. These tools they are not designed for building and infrastructure systems and often require considerable effort on user part
ii. Specialized LCA-based software for built environment such as BEES and Athena that intended to use by designers, builders, and building product manufacturers.
iii. Tailored LCA software systems to be used for building or specific infrastructure (e.g. highway or bridge). Usually these tolls are firm-specific adaptations of generic LCA software packages that are programmed directly for the needs of the firm.

Some of the LCA commercially available databases and software that have been used in the context of built environment have been listed in Table 2-11. Review of literature shows that LCA have been applied more often as compared to ESA tool for sustainability appraisal of built environment systems. LCA indeed is a powerful tool for analyzing and environmental system and estimating environmental impacts of built environment and related products. However, social implications of building and infrastructure systems are lacking in LCA.

Table 2-11 Some of the LCA databases and tool

Database name	*Geographical region*	*Supported by*	*Generic*	*Built env. specific*	*Description*
Athena	Canada and USA	Athena Institute		✓	Whole building design level, Impact Estimator for Buildings and EcoCalculator for Assemblies
BEES[1]	USA	National Institute of Standards and Technology (NIST)		✓	Selecting environmentally and economically balanced building products, follows ISO 14040 series of standards and ASTM standard life-cycle cost
BLCC	USA	National Institute of Standards and Technology (NIST)	✓		Economic analysis, buildings and building-related systems life cycle cost program, energy escalation rate calculator, annual supplement to handbook 135
CMLCA[2]	Netherlands	Institute of Environmental Sciences (CML) - Leiden University	✓		Aims to support the technical steps of LCA procedure, focus on advanced computational aspects of LCI calculations
Eco-Quantum	Netherlands	IVAM University of Amsterdam		✓	Whole building design decision, quantifies environmental impacts of a building based on seven impact categories
Envest	UK	Building Research Establishment		✓	Whole building design decision, predicts the environmental and cost impact of various strategies for heating, cooling and operating a building
eTool	International	eTool®		✓	Modeling both buildings (residential and commercial) and infrastructure globally
Ecoinvent	Swiss	The Swiss Centre for Life Cycle Inventories	✓		Database of LCI and LCIA data, used in more than 40 countries worldwide
ECO-it	Netherlands	PRé Consultants	✓		Modeling life cycle of complex products, scoring based on Eco indicator 99 guideline, SimaPro complement
GaBi	Germany	PE Europe GmbH and IKP University of Stuttgart	✓		Generic LCA tool and database for product comparison, evaluates life cycle environmental, cost and social profiles of products, processes and technologies
LISA[3]	Australia	BlueScope Steel		✓	LCA decision support tool for construction (multi-storey offices, high rise, wide span warehouse, road, and rail bridges)
SimaPro	Netherlands	PRé Consultants	✓		Product comparison tool, Ecoinvent database, 17 different impact assessment methods, following the ISO 14040 series

[1] BEES: Building for Environmental and Economic Sustainability
[2] CMLCA: Chain Management by Life Cycle Assessment
[3] LISA: LCA in Sustainable Architecture

Furthermore, LCA is based on utilitarian *user-side* perspective (Raugei et al. 2012), and only focus on environmental impacts due to resource consumption and emissions and ignores the work of ecosystems to provide ‘freely available’ services and products (e.g. rainfall, soil organic matter, etc.). A critical review by Zhang et al. (2010c) indicates that, to apply life cycle oriented methods to address sustainable development, the role of ecosystem goods and services must be accounted, as they form the basis of planetary activities and human well-being. Accordingly, the system boundary needs to be considered large enough to account for all the ecosystem goods and services that support the entire technological activities in the life cycle (Zhang et al. 2010d). Rigid system boundaries of LCA practices make accounting for changes in the system difficult. This issue sometimes referred to as the *boundary critique* to *systems thinking*. Ortiz et al. (2009) reviewed some recent development and researches on LCA methodology and tools employed in the built environment over the last 7 years, from 2000 to 2007. They compared and discussed the differences between the LCA of building materials and components combinations versus the LCA of the full building life cycle.

Review of literature shows that, LCA studies most often consider two environmental aspects, i.e. energy consumption (embodied or primary) and CO_2 emission. However, range of analysis area is different based on the goal and objective the LCA study. Economic and social aspects less often have been considered in LCA studies in the context of built environment, except for LCC studies which have mostly focused on economic aspects of built environment. For example some studies applied LCC to analyze energy-saving or net zero energy strategies in building, e.g. (Hong et al. 2011; Marszal and Heiselberg 2011; UygunoÄŸlu and KeçebaÅŸ 2011).

In addition, LCA studies have been more frequently conducted for analyzing buildings and building related products, rather than urban infrastructural systems. On the other hand, LCA studies for urban infrastructural systems often consider only one or two environmental factors (e.g. embodied energy and carbon). Table 2-12summarizes some published LCAs applied for sustainability appraisal of built environment within the last 12 years. According to this table, LCA studies in the context of built environment have been grown tremendously from year 2009.

Table 2-12 LCA studies in the context of built environment over the last 12 years

Reference	*Content*	*Built environment product /system*	*Key analysis area**														
			RD	**CED**	**EME**	**EMC**	**GWP**	**AP**	**EP**	**POCP**	**WM**	**ODP**	**HHR**	**EcoR**	**IEnv**	**EcA**	**SoA**
(Jönsson 2000)	Comparing result from LCA with analysis of five selected approaches	The covering material of 1 m^2 of flooring over one year, residential use in Sweden	✓			✓					✓						
(R Ries and Mahdavi 2001)	Implementation of affordance impact assessment method and regional environmental simulation	Alternative floor construction: wood truss vs. Joisted steel framing system in USA				✓											
(Rozycki et al. 2003)	Ecology profile of the German high-speed rail passenger transport system	German high-speed passenger train system	✓	✓		✓											
(Althaus and Kellenberger 2005)	Investigating inventorying infrastructure in ecoinvent database	Manufacturing and disposal of building materials in Switzerland		✓													
(Norman et al. 2006)	Comparing high and low residential density using economic input-output life-cycle assessment (EIO-LCA) model	Two case studies from the City of Toronto (Canada): low-density suburban development vs. High-density urban core development			✓	✓											
(Flower and Sanjayan 2007)	Estimating CO2 emissions for concrete in environmentally sustainable design	Two coarse aggregates quarries, one fine aggregates quarry, six concrete batching plants, and a case study of a building in Australia					✓										
(W. Yang and Kohler 2008)	Simulation and evolution of the building and infrastructure	Chinese building and infrastructure stocks (urban/rural)	✓		✓	✓											
(Friedrich	Investigating environmental burdens	Water supply and sanitation in Thekwini Municipality (Durban),				✓											

et al. 2009)	due to provision of potable water and sanitation	South Africa															
(Vares and Häkkinen 2009)	LCA tool development for system optimization and environmental reporting	Cement manufacturing in Finland			✓						✓						
(Zavrl et al. 2009)	Multicriterial sustainabili ty assessment of building	6-storey residential building built in the early 90s in Ljubljana, Slovenia	✓												✓	✓	✓
(Oliver-Solà et al. 2009)	Estimating overall impact of district heating and natural gas infrastructures	District heating for neighborhood system, building system, and dwelling system in Catalonia (Spain)	✓				✓	✓	✓	✓		✓	✓				
(Meester et al. 2009)	Exergetic LCA for resource consumption evaluation in the built environment	65 optimized Belgian family dwelling types with low energy input		✓													
(Blengini 2009)	LCA of buildings demolition and recycling	Demolition of residential building in Turin, Italy	✓				✓	✓	✓	✓		✓					
(Kellenberger and Althaus 2009)	Simplified LCA of different building components	Building material and component used in Switzerland (wood, steel and concrete structure)	✓	✓													
(E Benetto et al. 2009)	LCA of ecological sanitation system for small-scale wastewater treatment	sanitation system for office building in Beckerich, Luxembourg					✓	✓	✓				✓	✓			
(O. Ortiz, Bonnet, et al. 2009)	Sustainability based on life cycle management (LCM)	residential dwellings in Catalonia, Spain	✓				✓	✓				✓	✓	✓			
(Lee et al. 2009)	Presents foundations for development of a LCA Program for building (SUSB-LCA)	Building in South Korea			✓	✓											
(S. a. Jones and C.	LCA for assessing sustainability of	Rural water and sanitation infrastructure systems, example of arsenic treatment approaches in	✓											✓		✓	✓

Silva 2009)	infrastructure systems	Bangladesh													
(Zheng et al. 2009)	LCA, AHP, and extenics theory for building energy conservation assessment	A new mixed-using commercial building in Beijing, China (6 floors over ground and 1 floor underground)		✓											
(Bribián et al. 2009)	Simplified LCA as a complement for building certification	A single-family house in the municipality of Zaragoza (Aragon, Spain)		✓	✓	✓									
(O. Ortiz, Castells, et al. 2010)	Operational energy in the life cycle of residential dwellings	residential dwellings in Spain and Colombia		✓			✓	✓							
(Verbeeck and Hens 2010)	Presenting overall building inventory model	Reference dwelling in Belgium		✓	✓	✓									
(G Assefa and Glaumann 2010)	Comparing the environmental efficiency of building properties using the EcoEffect tool	Random sample of residential buildings in Sweden and, an energy pilot project without a conventional heating system (Lindås)		✓									✓		✓
(Blengini and Carlo 2010)	LCA of a low energy buildings comparing to conventional building	low energy single family in Northern Italy, Morozzo, in Piedmont	✓	✓			✓	✓	✓	✓		✓			
(O. Ortiz, Pasqualino, et al. 2010)	Environmental impact of construction phase, comparative LCA for different combinations of real construction scenarios for external and internal walls	typical block of flats with composite walls located in Barcelona, Spain					✓	✓					✓		
(Gracia et al. 2010)	LCA of phase change materials (PCM) in experimental buildings	3 monitored cubicles built in Puigverd de Lleida, Spain	✓										✓	✓	
(Blom et al. 2010)	Environmental impact of various maintenance scenarios for the façade components	Maintenance and replacement of external doors and windows in a Dutch reference dwelling	✓				✓	✓	✓	✓		✓	✓	✓	
(Guardigli et al. 2011)	Comparative LCA of green buildings	Reinforced Concrete and innovative wood structures in the		✓											

		European context															
(Broun and Menzies 2011)	Life cycle energy and environmental analysis of partition wall systems	3 types of partition wall systems in the UK: brick from clay; hollow block from concrete; and traditional timber frame		✓	✓	✓											
(Monahan and Powell 2011)	Comparative LCA of buildings with different construction methods and alternative materials	Low energy house constructed with offsite panellised modular timber frame system with two traditional alternative scenarios in Norfolk UK			✓	✓											
(Bolin and S. Smith 2011)	Comparative LCA of building structural framing	borate-treated lumber framing and galvanized steel framing (USA)	✓				✓	✓	✓	✓				✓			
(Bahareh Reza et al. 2011)	AHP-based LCA to compare different flooring system	block joisted flooring systems – concrete, clay, and expanded polystyrene (EPS) blocks – in the city of Tehran, Iran	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
(Tarantini et al. 2011)	LCA approach for Green Public Procurement of building materials and elements	double opening wood window manufactured in Italy and mounted on a residential building in Bologna, North of Italy					✓	✓	✓	✓		✓					
(Bribián 2011)	Comparative LCA of building material	Common building products and material in Europe	✓	✓			✓										
(Cellura et al. 2011)	Sensitivity analysis to quantify uncertainty in LCA	Typical roof tiles employed in restoring old buildings of the Mediterranean area (Sicilian tiles)	✓				✓	✓	✓	✓		✓					
(Ottelé et al. 2011)	Comparative LCA for green façades and living wall systems	Conventional built up European bare brick wall and different types of green façades bare wall in The Netherlands	✓				✓	✓	✓	✓		✓	✓	✓			
(Oliver-Solà et al. 2011)	Presenting GWP-Chart as a LCA method that combines urban planning tools with environmental data	Urban infrastructure (concrete sidewalks with three urban fabrics)					✓										
(Angrill et al. 2011)	LCA for urban planning and water management	rainwater harvesting infrastructures in Mediterranean climate (Barcelona, Spain)	✓				✓	✓	✓	✓		✓	✓				

(Y.-Y. Jing, Bai, and J.-J. Wang 2012)	Multi-objective optimization design and LCA	Building cooling heating and power (BCHP) system for a commercial office building in Beijing, China		✓			✓	✓	✓	✓		✓		
(Iyer-Raniga and J. Wong 2012)	Combining life cycle modeling with building energy efficiency simulation software	8 residential heritage buildings in Victoria, Australia	✓				✓		✓	✓				
(Brattebø and Reenaas 2012)	Comparing CO2 and NOX emissions from heating system and waste-to-energy technologies	Mass-burn waste incineration for urban district heating system in Trondheim, Norway					✓							
(Y.-Y. Jing, Bai, J.-J. Wang, et al. 2012)	LCA of different operation strategies	A novel solar building cooling heating and power (BCHP) system		✓			✓	✓					✓	
(Menoufi et al. 2012)	LCA of experimental cubicles with highlight on the manufacturing	7 experimental cubicles located in Puigverd de Lleida (Spain)	✓				✓	✓	✓			✓	✓	✓
(Slagstad and Brattebø 2012)	LCA for planning a new urban settlement and different infrastructure solutions	5 different scenarios for the waste management system of a new greenfield settlement in Trondheim, Norway					✓	✓	✓	✓		✓	✓	✓
(L. X. Zhang et al. 2012)	Hybrid LCA for a systematic account of carbon emission abatement	family-size biogas utilization system in the rural areas of China					✓							
(Cucchiella and D'Adamo 2012)	LCA for estimation of the energetic and environmental impacts	Roof-mounted building-integrated photovoltaic systems located in Italy			✓		✓							
(Sharma et al. 2012)	comprehensive LCA to estimate energy consumption and GHG emissions	Three-storey educational building in Northern India			✓		✓							
(N. A. Utama et	Comparative LCA for 2 commonly used building	traditional clay versus modern concrete houses in a tropical regime	✓				✓	✓	✓	✓			✓	

al. 2012)	envelope materials	(Indonesia)		
(Stazi et al. 2012)	LCA for optimization of sustainable building envelopes	Trombe wall in a solar residential building prototype in Ancona (central Italy)	✓	✓
(Baptista et al. 2012)	LCA for energy consumption and emissions scenarios for road transportation	Portuguese road transportation sector (light-duty and heavy-duty vehicles)	✓	✓

* RD: Resource Depletion, CED: Cumulative Energy Demand, EME: Embodied Energy, EMC: Embodied Carbon, GWP: Global Warming Potential, EP: Eutrophication Potential, POCP: Photochemical Ozone Creation Potential, WM: Waste Management, ODP: Ozone Depletion Potential, HHR: Human Health Risk, EcoR: Ecological Risk (ecotoxicity), IEnv. : Indoor environment, EcA: Economical Aspects, SoA: Social Aspects

2.5 Promise and problems of existing sustainability appraisal tools

Attempts to improve social, economic, and environmental criteria have turned the attention to the built environment as being one of the most active enterprises. It has been widely accepted that the potential impacts of the built environment and its related activities need to be determined in order to make policy decisions and plan asset management strategies. Several sustainability appraisal tools are under continuous development to apply in the context of built environment. A comprehensive review was conducted in this chapter to understand theoretical concept behind different sustainability assessment tools and their analysis methods, as well as their advantageous and weakness.

Rating systems (see also Appendix A) provide general guidelines to encourage sustainable building practices. Rating systems applied various scoring/weighting approaches in order to rank different building strategies. The performance indicators proposed by rating systems provide only a qualitative measurement of the built environment condition by associating some sustainability recommendations to a subjective rating scale. These subjective/qualitative sustainability ratings do not provide any reliable quantitative information on the long-term sustainability of the assets to maintain their optimum performance and with minimum environmental impacts and socio-economic costs withstand the variable conditions thorough their life span.

For example several rating systems provide guidelines to encourage fenestration designing in order to increase use of daylight and reduce electric lighting and saving energy (Appendix A). But they do not provide a comparative quantitative framework to assess the consequence of such an alternation (e.g. energy loss, required maintenances, indoor environment quantity, additional short-term and long-term costs, etc.). In addition, use of daylight may not be an optimal choice for some region with rainy climate. As a result, although rating systems advocate environmental friendly practices these practices may not necessarily led to the most sustainable alternative for all built environment systems. The use of such subjective and qualitative approaches for assessing sustainability performance of assets can be totally inadequate specifically for safety- and health- critical assets (e.g. highway bridges and water mains).

The other group of sustainability appraisal tools that were studied in this chapter are ESA and LCA-based tools that provide a set of quantitative values of flows of energy, materials/ substances, and/or money. Among those tools, LCA-based tools found to be more comprehensive than other methods as they can be applied for various built environment systems with different level of complexity, in different region, and based on different scenarios. Often, LCA-based tools employ some weighting aggregation techniques (multi-criteria decision tools) to offer a single sustainability index. One of the most common frameworks, AHP-based LCA, investigated in a paper by author (see Appendix B). However, weighting aggregation techniques are usually subjective, and ignore fundamental differences in essence and usefulness of various energy and resources based on factors such as ecological services, biodiversity, carbon sequestration, and hydrological functions.

On the other hand, as it has been argued in some studies, LCA alone cannot addresses all of the aspects of sustainable development[9] (e.g., Zhang et al. 2010c; Zhang et al. 2010d). Zhang et al. (2010c) asseverate that, links between LCA and deterioration of natural capital are mostly missing because of LCA's *user-side perspective* and human-dominated boundary. LCA measure the material and energy flows from the point where they enter the economy and ignore the ecological process that are needed for making the natural resources available (Zhang et al. 2010c). Furthermore, some of the important sustainability goals are neglected, as LCA ignores the role of ecosystem services in dissipating the emissions and absorbing their impacts (Zhang et al. 2010c). In other words, conventional LCA neglects biological capacity required to support resource consumption and waste absorption. In addition, aggregating cumulative effects of varying environmental and socio-economic impacts are the major challenges faced by sustainability appraisal tools including conventional LCA.

Emergy synthesis on the other hand overcomes many of these shortcomings by converting different environmental and socio-economic aspects to a single energy value. Emergy synthesis found to be the most holistic ESA tool that can be provide an evaluation framework and provide links between TBL objectives of sustainability. Emergy synthesis encompass wider boundary and a *donor-side perspective*, considering the role of free services received

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[9] It must be noted that the key aspects of the sustainable development are to "*safeguard the Earth's capacity to support life in all its diversity, respect the limits of the planet's natural resources and ensure a high level of protection and improvement of the quality of the environment, prevent and reduce environmental pollution, and promote sustainable consumption and production to break the link between economic growth and environmental degradation"* (EU SD 2006).

from the environment, contributions from human resources and economy, as well as the role of ecosystem in dissipating waste and emissions (Hau and Bakshi 2004). However, review of literature indicates that emergy synthesis has rarely been applied as a systematic decision-making tool to assess a micro-level built environment (e.g. building, bridge, road, etc.). In addition it was never been applied as a decision support tool for asset management or as a holistic sustainability appraisal tool to imply TBL sustainability principles for long-term policy decision through the service life of the built environment systems. In addition, emergy synthesis has some inherent limitations such as inaccuracy and vagueness of UEV data, and difficult practicability.

Chapter 3 Emergy-based Life Cycle Assessment (Em-LCA)[10]

3.1 Asset management and built environment challenges

Buildings and their supporting infrastructures (road, bridges, water and waste water system, etc.) are critical assets that are facing consistent challenges of rapid urbanization, transit plan changes, and development of new material and structural types. On the other hand, construction of new built environment besides rehabilitation of existing assets and their related operation & maintenance (O&M) activities are economically very expensive, and associated with numerous environment impacts (e.g., non-renewable resource depletion, greenhouse gas emissions, high energy consumption, waste generation, etc.). In addition, the built environment systems are subjected to pressures like aging, obsolescence and deterioration during their service lives, increasing demand, and random extreme events such as floods and earthquakes. Moreover they are also subjected to dead loads, live loads (e.g., traffic and accidental loads), corrosion-effects, and environmental loads during their service lives.

The consequences of these pressures expose deficiencies in the condition of assets, reduction in their capacity and the levels of service over time. As a result, these assets become overstressed with time and may fail before the end of their design lives (see Figure 3-1). Accordingly, they need constant O&M and rehabilitation which in turn cause exponential increase in the costs besides additional environmental impacts with time.

[10] A version of this chapter published by Clean Technologies and Environmental Policy (Reza et al. 2013a)

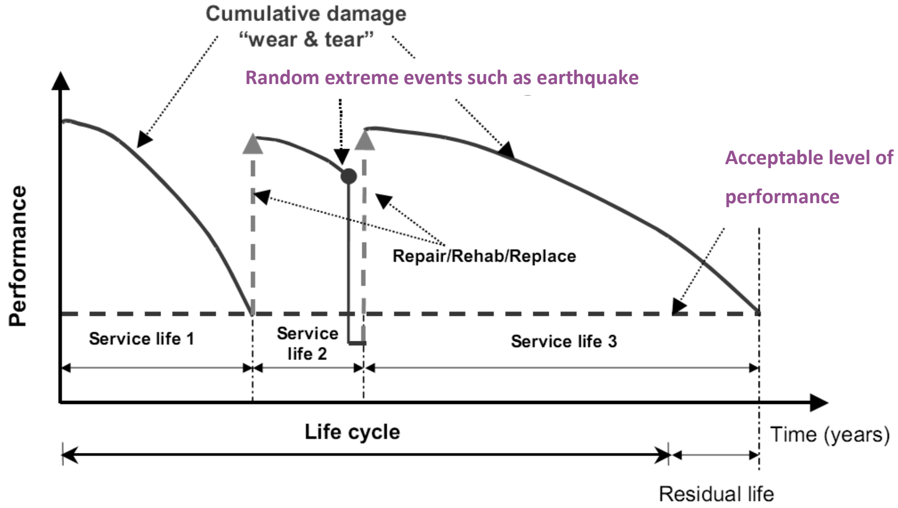

Figure 3-1 Life cycle performance for an built environment system (addopted from Lounis et al. 2010)

The aging and increased demands on built environment and the construction of new assets present major environmental, technical, and socio-economic challenges to asset owners; more specifically, the great challenge is to assess the current and future monetary costs and environmental impacts of their assets in an objective and quantifiable manner. As a result asset owners rely on traditional *"asset management"* methods. Asset management can be defined as a systematic process to manage, operate, maintain, upgrade, and dispose assets effectively. In fact, the main goal of asset management is to make better decisions about existing and future assets to achieve the optimum service levels while reducing lifetime risks (including financial risks, environmental impacts, public health, and safety risks).

However, the main challenge in better decision-making is an availability of reliable information about short- and long-term socio-economic risks and environmental impacts. Accordingly, to achieve an effective asset management plan, all short- and long-term socio-economic issues and environmental impacts must be addressed holistically through assets' life cycle (Horvath 2009). As a result asset management plans must be assisted by a reliable comprehensive sustainability appraisal tool to provide adequate information to make better decisions for construction, rehabilitation, maintenance, and in some case replacement of existing asset with a new one.

As it was discussed in Chapter 2, several sustainability appraisal tools have been developed around the world. However, review of literature shows that most of these tools remain fundamentally at a trial stage and have not yet been put into practice in order to make decision for asset management. Among those tools, LCC and CBA have been more frequently applied in order to achieve long-term cost optimization. But even those tools have been often used incompletely where the hidden long-term costs of a built environment such as waste, emission, and human health related costs neglected.

There has been much discussion on what is sustainable built environment and how can it be evaluated as a part of long-term asset management plan. The principal attributes of sustainable built environment are: taking a longer term view of effects on future generations, and extending the boundaries of consideration beyond the immediate resources used in providing the assets. A comprehensive review of literature shows that there is an urgent need for innovative techniques to facilitate quantitative assessment of sustainability for informed decision-making at various levels of built environment and asset management (Horvath and Hendrickson 1998; Keoleian et al. 2005; Ugwu et al. 2006; Zhang et al. 2010a). Graham (2003) explained that, performing a holistic and system-based sustainability appraisal of built environment can provide improved understanding to make informed decisions for asset management.

Ideally, an effective sustainability appraisal tool should provide comprehensive basis to support decision-making for asset management by addressing the environmental and socio-economic issues over the life cycle of a built environment system (Chew and Das 2007). Missing an important phase in the life cycle of a built environment system may result in suboptimal decisions (Horvath 2009).

Indeed, providing reliable quantitative predictions of the current and future conditions of assets can help to meet new demands within a fiscally responsible and environmentally sustainable framework, while preserving quality of life (FCM 2005). The aim of this chapter is to develop a comprehensive, flexible, and systematic sustainability appraisal framework based on the integration of emergy synthesis and LCA. The motivation for the proposed sustainability appraisal framework stems from the recognition of the fact that traditional asset management paradigms for built environment systems are not adequate. In addition, developing a reliable sustainability assessment tool to assist asset management techniques is critical.

The main propose of developing this framework is to support and facilitate informed decision-making process related to the built environment systems and asset management by identifying and quantifying the attributes of TBL sustainability objectives over the life cycle of a built environment systems. The proposed framework aims to overcome some of the current shortcomings of the existing tools by providing an improved sustainability appraisal framework for asset management that meets certain standard and following advantages as compared to existing tools for built environment and asset management:

1. Comparative *quantitative framework* with minimum subjectivity
2. Comprehensive framework to *cover all life cycle phases* of built environment systems
3. Holistic assessment tool to *cover all TBL sustainability principals* and related performance indicators
4. Realistic quantitative framework to *integrate and aggregate cumulative effects* of varying environmental and socio-economic impacts (TBL sustainability principals) without using subjective weighting/scoring methods
5. Flexible framework to *encompass wider boundaries* beyond the human-dominated boundary
6. *Cradle-to-grave* assessment framework to consider all mass, energy, and money flows to a built environment system during its life cycle
7. *Donor-side perspective* to consider a complete amount of mass, energy, time, money, as well as freely available resources that are invested in a built environment system
8. *Reliable* sustainability appraisal framework to provide precise information and address different sources of uncertainties through analysis. Such framework can be applied to support informed decision-making related to the built environment systems and asset management.

3.2 Emergy synthesis as a valuable complement of LCA

Odum (1996) stated that, universe is organized in a hierarchy of energy transformation. When energy is transformed into something new, work has been accomplished and the process is called production. The environmental production system and the storage of resources (real wealth) were illustrated in Figure 3-2.

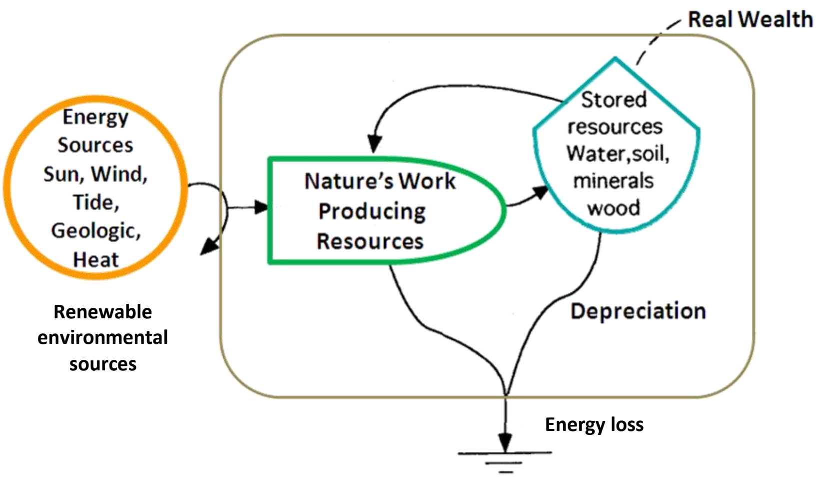

Figure 3-2 Environmental production system diagram (adopted from Odum 1996)

Emergy accounting method is the process of determining the energy (solar energy) that was used up directly or indirectly in biosphere in order to produce a specific product or service. Later emergy synthesis was extended in the time to evaluate the environmental works and services needed for resource formation. This method is based on a holistic framework which estimate the value of non-moneyed and free environmental resources and inputs such as sunlight, wind rain and moneyed recourses such as fossil fuel and material, and indirect environmental support embodied in human labor, services, and commodities in a unified unit (usually solar energy) that was previously used to generate a resource, service or product (Brown and Herendeen 1996).

Recently, a few researches has been initiated by emergy and LCA practitioners, in the direction of integrating and combining emergy synthesis with LCA and to meet the challenges of sustainability (e.g. Zhang et al. 2010c; Zhang et al. 2010d; Brown et al. 2012; Ingwesen 2011; Raugei et al. 2012; Rugani and Panasiuk 2012). Ingwersen (2011) has suggested emergy as a useful metric for LCA, summing life cycle energy inputs (upstream impacts) that directly or indirectly drive all biosphere process. In that research, gold mining was studied, and emergy was applied as an upstream impact indicator to aggregate gold mining emergy and to calculate gold UEV (Ingwersen 2011). In that research the downstream effects were calculated by conventional LCA and were not converted to emergy values.

Brown et al. (2012) discussed the pivotal roles of consistent boundaries and input classification in emergy synthesis and LCA. They carried out a case study on comparative analysis of thermal and PV electricity to compare the environmental support per unit of energy output (UEV) of two electricity production systems. In this research the effects of emissions and wastes on natural environment (ecological quality and human health) were not considered.

It is necessary to mention that none of the studies on integrating emergy and LCA provide a standard systemic framework neither for sustainability assessment of built environment system nor for integrating LCA and emergy. In addition, the mentioned researches have barley considered a complete range of the life cycle upstream and downstream impacts (on ecology and human health) besides the socio-economic consequences.

In a more recent work, Raugei et al. (2012) argued the added value of LCA by linking with emergy synthesis. They primarily discussed the basic theories and conceptual model of emergy synthesis and LCA. They pointed out two fundamental differences:

i. Analysis perspectives; emergy implies an inherently holistic *donor-side* perspective, while LCA has a pragmatic and utilitarian *user-side* perspective.
ii. System boundaries; emergy boundary can be as wide as natural ecosystem boundary while LCA implies human-dominated boundary

Finally, they concluded that emergy can be adopted as a valuable complement to conventional LCA.

Therefore, emergy synthesis can be a creditable addition to LCA for sustainability assessment studies as it can provide a donor-side perspective to consider the role of ecosystem services for making the natural resources available and dissipating the emissions and absorbing their impacts. It is necessary to mention that donor-side perspective is based on the fact that *the more energy, time, and materials that are "invested" in something, the greater its value* (Brown and Ulgiati 1999). Thus, donor-side perspective concept is very similar to the ultimate objective of sustainable development paradigm.

Emergy furthermore can provide a unified measure of the provision of environmental support to produce any natural and human resources including material, energy, or even monetary resources. While these resources consider in an LCA regardless of the type, and an indication of the work of the environment that would be needed to replace what is consumed (Raugei et al. 2012). Therefore, by employing emergy as acomplement of LCA, it would be possible to evaluate the contribution of all environmental, economic, and social burdens that can occur over the life cycle of a system in an energy-based unit and assign an unbiased value to the TBL sustainability criteria.

In this research, to meet the challenges of measuring long-term sustainability of built environment, Emergy-based Life cycle Assessment (Em-LCA) is proposed. Em-LCA aims to offer a more accurate quantitative and comprehensive technique than existing LCA tools in the context of built environment. It should be stressed that emergy concept has been applied as a valuable complement, rather than an alternative to existing LCA.

Em-LCA benefits from LCA's capabilities including standard LCI databases, LCIA techniques such as classification, characterization, and midpoint aggregation that yield impact categories such as resource use, energy consumption, and air/water/land emission. On the other hand, Em-LCA employs emergy synthesis as upstream and downstream (endpoint) impact estimator and provides a comprehensive framework to evaluate the life cycle streams and their associated TBL impacts within a broader perspective and using the same quantitative framework.

Furthermore, Em-LCA is capable to offer original information related to reciprocity of a particular built environment such as an infrastructure system and its surrounded natural environment. As a result, it can use as a valuable environmental assessment tool for informed decision-making related to asset management and to address long-term sustainability strategies. Figure 3-3 shows a Schematic of Em-LCA framework for a built environment system. A step-by-step Em-LCA methodology and its application for assessing sustainability of built environment system presented in following sections.

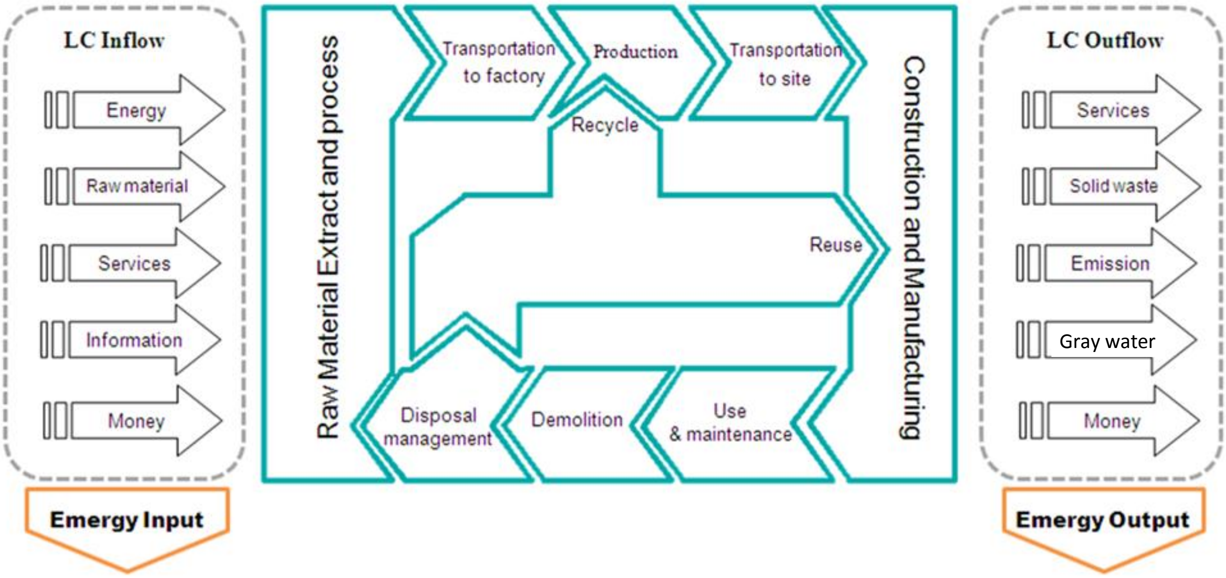

Figure 3-3 Proposed Em-LCA methodology for a built environment system

3.3 Step 1: Identifying Em-LCA scope and developing system diagram boundary

It was assumed that the ultimate goal of Em-LCA framework is to perform a comparative sustainability assessment for different built environment system alternatives and to provide reliable information to support decision-making for asset management strategies. The general methodology for the proposed Em-LCA in this study is a *top-down* systems approach. The first step is describing examined built environment systems by identifying the goal and scope of analysis, establishing the boundaries for analysis, and constructing system diagram. At the first step of Em-LCA, the purpose of decision-making process and the type of information is needed to inform decision makers, project stockholders, or asset owners must be identified clearly. In fact, Em-LCA can be used to inform industry, asset owners, government, consumers, and other built environment and asset stockholders on the tradeoffs of alternative processes, products, and materials that are related to a built environment system.

Primarily, the Em-LCA can evaluate environmental and associated socio-economic impacts of a built environment system over its life cycle (cradle to grave). While, the secondary objective of conducting Em-LCA should be identified according to the decision makers need and type of built environment system under studied. For example if the under studied system is a road or bridge project, decision makers must decide whether they want to consider the effects of fuel consumption and associated emission by vehicles that used that road/bridge through its service life. They must also clearly identify the boundary of analysis, i.e. cradle-to-grave (from material extraction to demolition and disposal), cradle to stage (e.g. from material extraction to construction), or stage-to stage (e.g. construction and maintenance).

Furthermore, accuracy and type of information, details of inflow and outflow to the examined system, and impacts categories is required quantify to inform decision makers must be identified based on the goal of study.

In general, in this research, the Em-LCA technique is developed to consider three major impact categories based on emergy algebra[11]:

i. Recourses inputs or upstream impacts including renewable and non-renewable resources.
ii. Waste and emission or downstream impacts.
iii. Associated socio-economic impacts including monetary costs and purchased labor and services.

After identifying the scope of analysis, a system diagram as a means of organizing thinking and interactions between constituents and pathways of exchange, resource flows, and downstream outflows need to be established. A system diagram is an overview of the scope and boundaries of analysis. System diagram is drawn to put the understudied built environment system in perspective, to organize data-gathering efforts, and to combine information about the examined system from various sources. In order to diagram the examined built environment system, all driving energies and interactions, as well as out flows and feedbacks from the system must be included. The system diagram of built environment in addition must be included both the economy and environment interaction of the system.

Based on the major goal of developing Em-LCA in this research, the inflows and outflows of the examined built environment are simulated as energy pathways in the energy system diagram to visualize the flows and their interaction. The examined built environment system can be assumed as a thermodynamic engine which consumes resources to produce specific

[11] Emergy algebra help to avoid double counting and redundancy by distinguishing emergy value of natural resources and ecological services and emergy value in labor and socio-economic services

services, produce emission to air, water and land, and maintain its performance as a building/infrastructure system and sustain with regard to variable condition such as climate change and earthquake, over its life cycle. Accordingly, a sustainable built environment system is the one that can maintain its performance with low level of resource consumption, and sustain with minimum emission impacts over its life cycle.

Figure 3-4 provides a typical energy system diagram of a built environment system (refer to Figure 2-4 to understand the meaning of energy systems language symbols). The energy system diagram in Figure 3-4 is based on broadest system boundary for built environment system (urban scale). Indeed, analysis system boundary can be shrunk in order to study a micro-scale project (e.g., 1 km of a road system or 1 m^2 of a dwelling system). In addition, some of the units in this figure can be eliminated based on analysis scope and the type of the examined built environment. For example agriculture production unit and tourist transaction unit might be ignored in order to study a residential building.

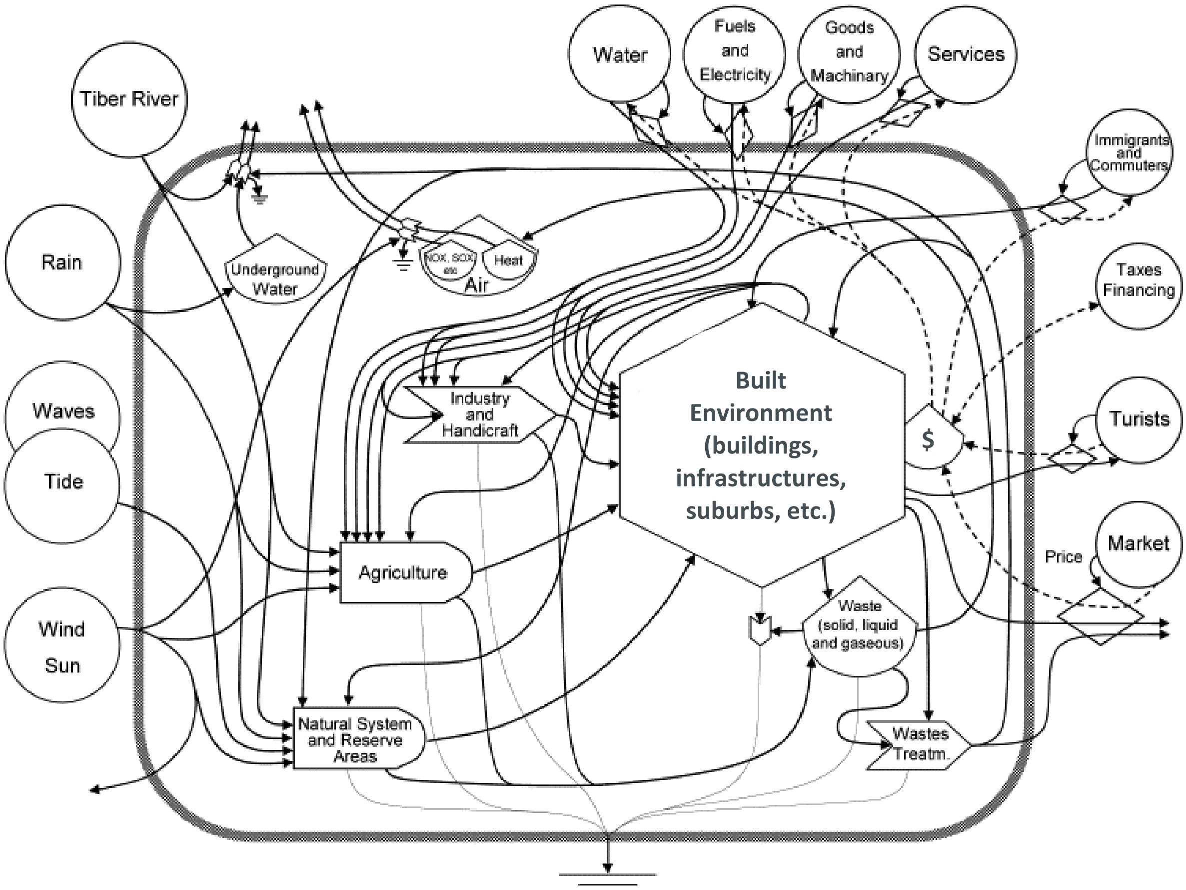

Figure 3-4 Generic energy system diagram of built environment (adopted from Ascione et al. 2009)

The energy system diagram of a built environment system can be then used as a guide to establish a data inventory for built environment life cycle. It's necessary to mention that, each pathway (inflow/outflow) that crosses the system boundary need to be evaluated in the next Em-LCA steps.

3.4 Step 2: Inventory analysis and developing emergy evaluation table

The second step of Em-LCA is to compile life cycle inventory data and to develop emergy synthesis tables directly from the diagrams. In this step, the value of each pathway that crosses the system boundary and the inflows/outflows through each unit process are quantified. Inventory analysis requires collecting data for all process units and life cycle phases, and their associated energy and mass flows, as well as data on emissions and discharges into the receiving waters, soil, and air (Reza et AB20011). Figure 3-5 shows upstream and downstream environmental burdens of a typical built environment system over its lifetime (each upstream/downstream environmental impacts might be associated with socio-economic impacts).

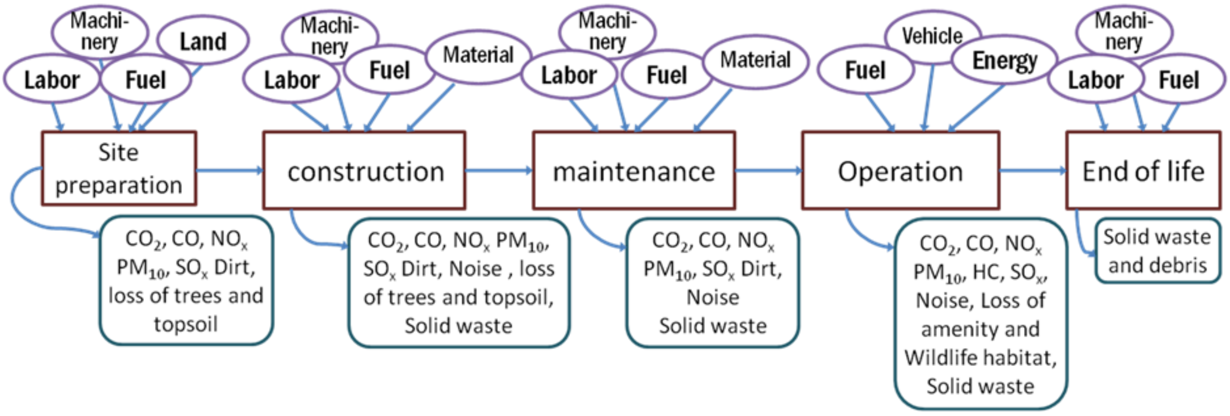

Figure 3-5 Life cycle upstream and downstream environmental burdens of a typical built environment

Inventory analysis of built environment systems are carried out by accounting for the flows of energy, water, materials, land, information, and money that support the system and their associated wastes and emissions on an annual basis at several scales of analysis. As it was discussed in Section 2.4.2, inventory analysis of a complex system like a built environment system can be very complex and encompasses tracking numerous of discrete unit processes as well as dozens of related substances to quantify mass, energy, emission, information and money flows through the extraction of raw resources, various primary and secondary production processes, transportation, demolition, etc. On the other hand, inventory data that can be varied based on geographical, temporal, and technological differences.

As a result, a standard local life cycle inventory database can be applied in order to facilitate inventory analysis and avoid duplication in data compilation. In this research Athena libraries will be used as a Canadian database to obtain background data for built environment system[12]. The obtained inventory data must be classified as upstream, downstream, or socio-economic impacts (3 classes that described in Section 3.3). Then the absolute values of resource use, energy consumption and emission to the air, water, and land of each class will be summarized in three separated emergy evaluation tables (column 1-5 of Table 2-8 must be completed in this step).

3.5 Step 3: Data analysis and impact assessment

Recourses inputs to the examined built environment system life cycle can be quantified as energy resources for geo-biosphere work and services needed for resources formation. While waste and emission impacts can be considered as energy resources (environmental support or feedbacks) are needed to replace the natural or human capital loss (Liu et al. 2011). Data analysis and impact assessment for three classes of impacts (i.e. upstream, downstream, and socio-economic impacts) is described in following sections.

3.5.1 Quantifying resources usage or upstream impacts

Resource inputs to a typical built environment system can be classified in 5 different categories:

i. Non-renewable minerals (Nm) such as limestone and iron ore
ii. Non-renewable petroleum (Np) such as gasoline and oil
iii. Non-petroleum fuel (Nf) include fuel from sources other than crude oil such as natural gas

[12] A local, comprehensive, and reliable inventory database must be used according to the region of the understudy built environment system.

iv. Local slowly-renewable natural resources (Sr) such as soil organic matter, animals, wood, and water use
v. Indigenous renewable energy (R) such as hydroelectricity, solar energy, wind energy.

In this step all inventory data related to resource use that were listed in evaluation table needs to be classified based on 5 categories mentioned above. Then Unit Emergy Values (UEVs) for each inventory item must be extracted from emergy database and adopted based on selected global biosphere emergy baseline[13] before listing in emergy evaluation table. Eventually, using UEV of each input flow, all resource inputs in the inventory can be converted into emergy values.

3.5.2 Quantifying emissions and wastes or downstream impacts

Emission of pollutants and waste discharge into the biosphere and their physical and chemical interactions with other biosphere components can lead to a large number of impacts in the ecosystem self-organization ability (Ulgiati et al. 1995). The consequences of airborne and waterborne emissions and solid waste generation can be quantified based on two main potential effects that can harm ecosystem, people, and economy:

i. The natural and human capital losses cause by emissions or preliminary damage (e.g., Bakshi, 2000; 2002)
ii. The ecological services needed to dilute emission (e.g., Ulgiati et al. 1995; Ulgiati and Brown 2002)
iii. Emissions can cause ecological losses through acidification, eutrophication, ecotoxicity that may resulted in loss of species and fish mortality. In addition, emissions can lead to some socio-economic losses, such as human health effects and land occupation (Zhang et al. 2010b).

[13] Global biosphere emergy baseline is the total emergy driving the biogeosphere. So far a few different global biosphere emergy baselines have been suggested by emergy practitioners. In this research the sum of solar, tidal, and deep heat sources consider to be equal to the value of 15.83E24 sej/yr as suggested by Odum (2000).

Bakshi (2000) described that quantifying the ecological impacts in terms of emergy loss requires knowledge about ecosystem self-organization as well as loss of ecosystem components. In this research, the approach of Eco-indicator 99 LCIA database has been used to evaluate the preliminary damage due to natural and human capital losses. According to the Eco-indicator 99, ecological impacts or natural capital losses can be addressed by *Potentially Disappeared Fraction* (PDF) of species in the affected ecosystem[14] (Bakshi, 2002), while the human capital losses can be expressed as *Disability Adjusted Life Years* (DALYs) per unit emission. Then the emission impacts on ecosystem quality and human health represented by PDF and DALY can be converted to a corresponding emergy loss (EL) as proposed by Liu et al. (2011). Emergy loss in support of local ecological resources can be measured as Equation (3):

$$EL_{\mathrm{EQ}} = \sum m_{\mathrm{i}} \times PDF(\%)_{\mathrm{i}} \times E_{\mathrm{bio}} \qquad \textbf{(3)}$$

where, EL_{EQ} represents emergy equivalent of loss of regional natural resources due to given emission, m_i is the amount of ith chemical released, PDF(%) represents the potentially disappeared fraction, calculated as PDF$\times$ m^2 $\times$ yr $\times$ kg^{-1} , and E_{bio} is the unit of annual emergy allocated to regional natural capital (this value has been calculated for different regions and nations and reported in National Environmental Accounting Database (NEAD)[15]).

In the same way, emergy loss in support of human resources (considering all their complexity such as education, culture, quality of life, etc.) can be calculated using Equation (4) as proposed by Liu et al. (2011):

[14] The PDF expressed the percentage of the species that are exposed to a specific emission (Posthuma et al. 2001).

[15] NEAD can be find in the following web page: http://sahel.ees.ufl.edu/frame_database_resources_test.php?search_type

$$EL_{HH} = \sum m_i \times DALY_i \times E_P \quad \textbf{(4)}$$

where, EL_{HH} represents emergy equivalent of loss of human resources due to given emission m_i , DALY represents the disability adjusted life years per unit emission (yr × g^{-1}) , and E_P is the total annual emergy per population (can be extracted from National Environmental Accounting Database (NEAD) for different nations).

In addition damage associated by solid waste generation can be quantified based on land occupation for landfill and disposal using Equation (5):

$$EL_{\mathrm{SW}} = \sum m_{\mathrm{i}} \times L_{\mathrm{OC}} \times E_{\mathrm{L}} \quad \textbf{(5)}$$

where, EL_{SW} represents emergy loss due to discharge of solid waste on land, m_i is given solid waste total mass (tone), L_{OC} represent land occupation factor (ha per tons of waste) , and E_L is the emergy value of land restoration per area (sej/ha) assuming 50-years recovery time. Approximately 2.85E+4 tones industrial solid waste occupy 1 ha land , and average emergy value due to land erosion and replacement can be measured using the UEV of 1.05E+15 seJ/ha as reported by Zhang et al. (2010b).

The second approach to quantify emission impacts is through emergy synthesis that measures ecological services (feedback) required to prevent or fix reversible damages occurred and charged to a process (Ulgiati et al. 1995; Ulgiati and Brown 2002). Emission adverse effects can be rendered based on ecosystem services needed to absorb, dilute or degrade undesired by-products generated by a process to an acceptable state or concentration level (Zhang et al. 2010b). Ecological services for diluting airborne/waterborne pollutants can be calculated based on required mass of dilution air/water using Equation (6):

$$M = d \times (\mathrm{m/c}) \quad \textbf{(6)}$$

where, d represents air/water density , m is the amount of given emission from the process and c is acceptable concentration according to regulations. Then the energy value of required ecological services (feedback) disposing airborne emission can be determined by calculating kinetic energy of the required to dilute airborne pollution, using the average value of wind speed in the area (e.g., 2 m/s for the study area). Finally, the emergy value of the required ecological service for air dilution (ES_{air}) can be determined multiplying achieved wind kinetic energy by wind solar transformity (2.52E+3 seJ/j).

Ecological services for diluting waterborne emission can be derived with the same concept. The amount of energy required to dilute water pollutant can be achieved by calculating average surface runoff energy in the area (Zhang et al. 2010b). To calculate required runoff energy the average altitude difference of the region must be estimated for the understudy area. Finally, the emergy value of the required ecological service for water dilution (ES_{water}) can be determined multiplying achieved surface runoff energy by runoff solar transformity (3.05E+4 seJ/j).

3.5.3 Evaluating monetary resources and purchased labor and services

Every process consists of investing emergy (F) from the economic system due to different activities such as extract and refine the nonrenewable resource (N), manufacture and produce goods, and provide labor and services for construction, rehabilitation, and maintenance. Ulgiati and Brown (2012) stated that, monetary costs of a process are strictly related to the human working times in resource processing and consuming. If we trace back far enough through the web of energy and material flows it can be revealed that, all the money invested to a process is used in order to purchase labors and services (indirect labors) (Ulgiati and Brown 2012). As a result if we consider resource use or emission impacts by means of their monetary values, we seriously underestimating the emergy of these flows by considering the cost has been paid for labor and services, and ignoring materials, energy, and ecological flows. On the other hand, the whole life cycle cost can be determined by means of monetary cost of labors and services along a project/process life cycle.

Most often, labor and services aren't accounted for in final impact assessment thorough LCA process. However, in the proposed Em-LCA framework, labor and services can be accounted for based on level of training and education and related emergy required to support them (Odum 1996). The emergy value of direct labor (as foreground input) can be measured based on the monetary costs of labor considering the national/regional economy where the product or process is located (Ulgiati and Brown 2012). Similarly, services (background, indirect labors) associated with material and energy inputs to a built environment system can be determined by their monetary cost. Ulgiati and Brown (2012) emphasized that it is not necessary to assessed the monetary value for each input item in the supply chain, and services can be accounted for from the price of final inputs to the foreground.

In order to evaluate emergy value of labor and services, their associated monetary cost must be multiplied by Emergy Money Ratio (EMR) or emergy/GDP. Emergy value for direct labors and local services (e.g. design and tendering, and ownership cost) and labor can be accounted for based on local currency (local EMR). While, emergy value for other services (e.g. material and energy costs for construction, maintenance, rehabilitation and operation related services) associated with national flows of material and energy inputs has can be determined based on national currency (national EMR). National EMRs for different regions have been reported in NEAD database.

It's necessary to mention that, based on this research scope, labor and services will be considered for entire built environment life cycle, including prior activities to operation phase such as design, tendering and construction process, future expenditures after operation such as maintenance and rehabilitation services, as well as transportation specific cost such as, gas price, automobile price, insurance, and taxes.

3.6 Step 4: Flow summary and calculation of indices

In this step of the proposed Em-LCA, the emergy of different items through the examined built environment system life cycle can be combined and aggregated to obtain different emergy-based indicators that can be used to compare different built environment strategies or alternatives.

Several emergy-based indices can be calculated from the flows of emergy supporting processes and products. In general emergy based indices can be used to provide perspective to compare different processes and products. So far, different emergy indices have been calculated by emergy practitioner and each of them has a specific sustainability meaning (Dezhi et al. 2011). However, most of those indicators have been calculated for macro level studies (national, regional, or industrial level) and not for small projects (e.g. see Brown and Ulgiati 2010; Brown, Ulgiati 1997; Huang and Hsu 2003; Ulgiati et al. 1995; Zhang et al. 2011). Some of the most common emergy indices and their related calculations are provided in Figure 3-6.

Despite a few of studies that suggest considering the effects of downstream impacts in emergy-based indices (e.g. Brown and Ulgiati 2002; Zhang et al. 2010b; Zhang et al. 2011), often emergy-based indicators have been calculated for upstream impacts, neglecting the importance of end point indicators. In this study, the common emergy indicators have been modified to consider the contribution of both upstream and downstream impacts for a built environment system. Table 3-1 summarized emergy-based impact indicators that have been suggested to assess and compare different built environment strategies or alternatives.

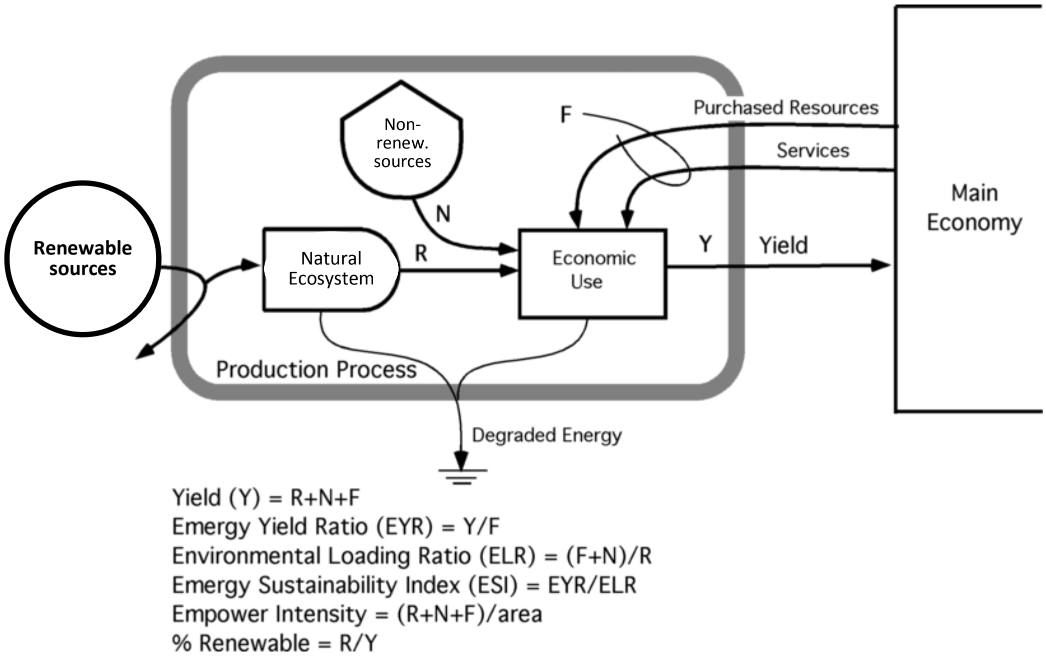

Figure 3-6 Emergy based indices (adopted from Browna and Ulgiati 1997)

Table 3-1 Emergy-based impact indicators for built environment

Indicator	*Description*	*Unit*
N_m	Non-renewable minerals	seJ
S_r	Slowly-renewable natural resources	seJ
N_f	Non-petroleum fuel	seJ
N_p	Non-renewable petroleum fuel	seJ
R	Renewable energy	seJ
EL_{HH}	Emergy equivalent of human health loss (emission discharge to air and water)	seJ
EL_{EQ}	Emergy equivalent of ecological loss (emission discharge to air and water)	seJ
EL_{SW}	Emergy loss due to solid waste discharge on land	seJ
Es_{air}	Ecological services for dispersal of air pollutants	seJ
Es_{water}	Ecological services for dispersal of water pollutants	seJ
F_S	Emergy equivalent of purchased services	seJ
F_L	Emergy equivalent of labor	seJ
N	Non-renewable Emergy inputs: $N_m + N_f + N_p + S_r$	seJ
F	Emergy Feedback(from economy and ecology): $F_l + F_s + Es_{air} + Es_{water}$	seJ
EL	Emergy equivalent of loss: $EL_{HH} + EL_{EQ} + EL_{SW}$	seJ
Y	Yield Emergy: N + R + F	seJ
EYR	Emergy yield ratio: Y/F	-
ELR	Environmental loading ratio: (N + F + EL) / R	-
ESI	Emergy Sustainability Index: EYR/ELR	-
E_c	Emergy per capita: (Y+EL)/people	seJ/person
E_P	Empower: (Y +EL) /Lifetime	seJ/yr
E_D	Emergy Density: Y/area or Y/length (for linear built environment e.g. road)	seJ/m2 or seJ/km

3.7 Step 5: Investigating result reliability and validity (accuracy)

In the final step, reliability and validity of the Em-LCA results are investigated. The aim of this step is to verify the extent to which the final conclusion or measurement is well-founded and corresponds accurately. Accordingly, initially a sensitivity analysis to find the pathways those contribute more significantly in the final results and yield emergy (Y) must be carried out. Sensitivity analysis can be done assuming a variation of the emergy value by ±10%, ±20%,…, ±50%, and assessing to what extent such a variation affected the final results. It is necessary to mention that, sensitivity analysis can be conducted based on variation of two parameters: related unit emergy value (UEV) and quantity of that pathway which can be variable based on different geographical, temporal, and technical scenarios. In addition, a sensitivity analysis regarding to the lifetime of the under study system can be carried out similarly.

If the results of sensitivity analysis verified that variation (e.g. ±50% variation) of different pathways and the lifetime of the under study system cannot change the main conclusions of the Em-LCA study and alter the ultimate comparative analysis results, Em-LCA process will be finalized and the most sustainable alternative can be selected. Otherwise it is needed to characterize and propagate the effects of different sources of uncertainties incorporated in Em-LCA process. Accordingly, uncertainty modeling must be carried out in order to perform realistic Em-LCA and achieve reliable output results. In this research *fuzzy-based uncertainty modeling* and *scenario analysis* has been proposed in conjunction with Em-LCA to evaluate the reliability of the analysis results. Characterization of uncertainties in emergy synthesis and Em-LCA will be discussed in detail in Chapter 6. Step by step Em-LCA framework has been summarized in a flowchart indicated in Figure 3-7.

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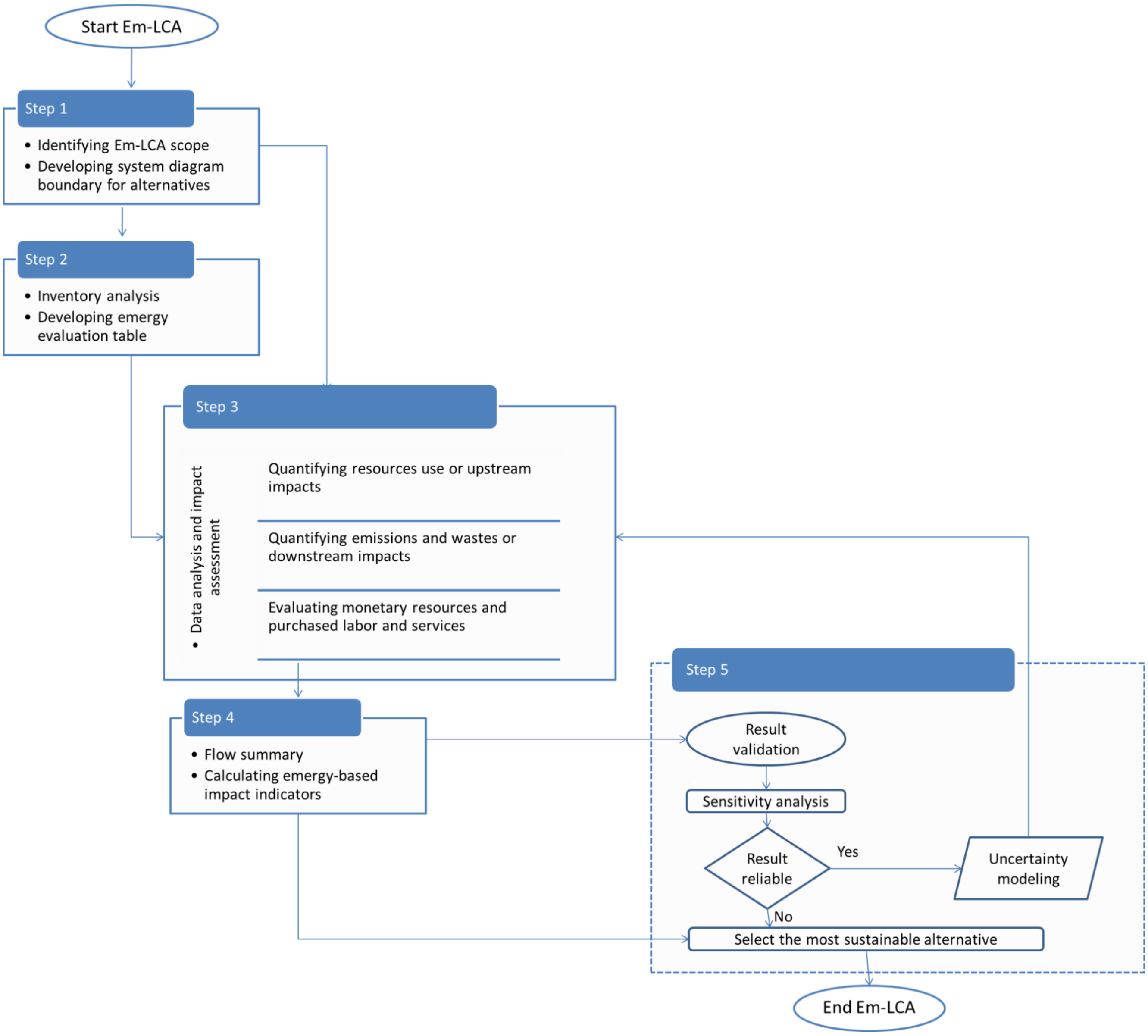


Figure 3-7 Em-LCA flowchart

Chapter 4 Em-LCA Framework for Sustainability Appraisal of Building Systems[16]

4.1 Overview

In general, the built environment systems include places and spaces created or modified by people including buildings (such as residential and commercial) and their supporting infrastructures and utilities (such as bridges, roads, water supply, wastewater systems, and transit systems), as well as other built structures and modifications to the natural environment (Brandon and Bentivegna 1997).

In this research the under studied built environment systems are classified into two broad categories, *linear infrastructure systems* and *building systems*. Linear built environment, also known as continuous assets, includes civil infrastructure systems such as urban arterial road, railway lines, bridges, airports, and utility easements (e.g., power lines, pipelines) those their length plays a critical role in their construction and maintenance (e.g. constructing 1 km of a 2-lane road), while the second group, building systems include different types of buildings that usually measured by area (e.g., building 1 m^2 of a 2-storey commercial building).

In order to examine the application of the proposed Em-LCA framework for assessing the sustainability of built environment and asset management plans two groups of studies have been developed. In the first study that is presented in this chapter, Em-LCA framework has been applied to evaluate the sustainability of building systems. Two different residential buildings (i.e. multi-unit residential and single-family house) have been selected and analyzed based on different scenarios in four Canadian providences (i.e. BC, Ontario, Alberta, and Quebec). In the second study, Em-LCA framework has been used to assess the sustainability of linear civil infrastructure systems that will be presented in next chapter.

[16] A version of this chapter prepared as a journal paper (Reza et al. 2013b)

4.2 Em-LCA framework for comparing multi-unit versus single-family residential buildings in Canada

According to the report by (PWGS Canada 2000) a significant portion of annual resource consumption by building and construction industry in Canada is due to applying traditional building development for different building practices: designing and selecting types of development (e.g. house, townhouse, condominium, etc.), building materials and structure, heating/cooling systems, and planning renovation and construction practices.

On the other hand, apart from structural suitability, building designers and asset managers mostly consider the basic requirements of the public owners or private occupants of the buildings where the main criteria for selecting building strategies are "*costs*" and long term environmental and socio-economic impacts are ignored. This research aims to investigate and compare short- and long- term environmental and socio-economic impacts of two different types of residential buildings in Canada.

4.2.1 Em-LCA scope and system diagram boundary

As it was described in the third chapter the first step of Em-LCA is goal definition and scoping where the process is described as a system diagram and the boundaries of analysis are established. The major goal of this study is to evaluate the environmental impacts (upstream impacts or resource use, and downstream impacts including natural and human loss, and ecological services to remove waste and emission) and associated socio-economic costs of two types of residential buildings (i.e. multi-unit condo and single-family house) over their life cycle (cradle to grave). This research ultimately aims to quantitatively investigate the metabolism (inflow-outflow) of each building system and compare the total environmental and socio-economic burdens of each building systems in term of emergy per unit area.

In this case study, Em-LCA framework considers main impact categories:

(1) recourses inputs or upstream impacts including renewable and non-renewable resources; (2) waste and emission or downstream impacts; and (3) associated socio-economic impacts including monetary costs and purchased labor and services. These three impact categories used to compare residential building practices in Vancouver, BC. Then the analysis will be repeated considering the first impact category for three other provinces in Canada (Ontario,

Alberta, and Quebec) where three populous large cities of Toronto, Calgary, and Montreal are located.

A typical 200 square meters single-family house was designed based on BC building code (under part 9) and Vancouver seismic load. A 2-level wood-frame structural system has been selected based on common practices for single family houses in BC and Canada. In addition a typical 4000 square meters multi-unit condominium residential was designed based on BC building code (under part 4) and Vancouver seismic load. A 7-storey plus one underground parking concrete-frame structural system has been chosen according to the common practices for multi-unit residential buildings in BC and Canada. The building has been designed to serve as a rental multi-unit residential encompasses 6 two-bedroom suites at each level (the total 42 unites). Both buildings have then been redesigned based on design requirements and seismic load of cities of Toronto, Calgary, and Montreal.

The operational energy of single-family house have been assigned based on average household energy use in different provinces of Canada reported by Statistics Canada (2007). The main source of energy of single-family house has been considered to be natural gas. In addition, the service life operational energy intensity of multi-unit residential buildings have been assigned based on average energy use for condominium in different provinces of Canada reported by (Liu 2007). The main source of energy of multi-unit residential has been considered to be electricity.

The period of 60 years life-span for the general Canadian building has been considered for all building assemblies. The functional unit of emergy per 1 square meter of building design, construction, operation and maintenance has been chosen for all the comparative analysis in the next steps. The system diagram of the examined buildings and the boundary of analysis have been shown in Figure 4-1 to visualize the mass and energy flows and their interaction. Later the differences between building types that are located in different cities will be analyzed by quantifying the pathways through the system diagram.

4.2.2 Inventory analysis

In this step, the inputs and outputs through different life cycle stages of buildings must be compiled. The life cycle inventory (LCI) analysis requires collecting data for all process units and their associated energy and mass flows, as well as the data on emissions and discharges into the receiving waters, soil, and air. In previous Em-LCA step, the system boundaries were established, while in this step the quantity of system inflows and outflows (pathways that crossed the system boundary) are accounted. Accordingly the bill of material (BOM) of each building system was provided. Table 4-1 and Table 4-2 indicate the BOM of single-family house and multi-residential building in Vancouver, BC.

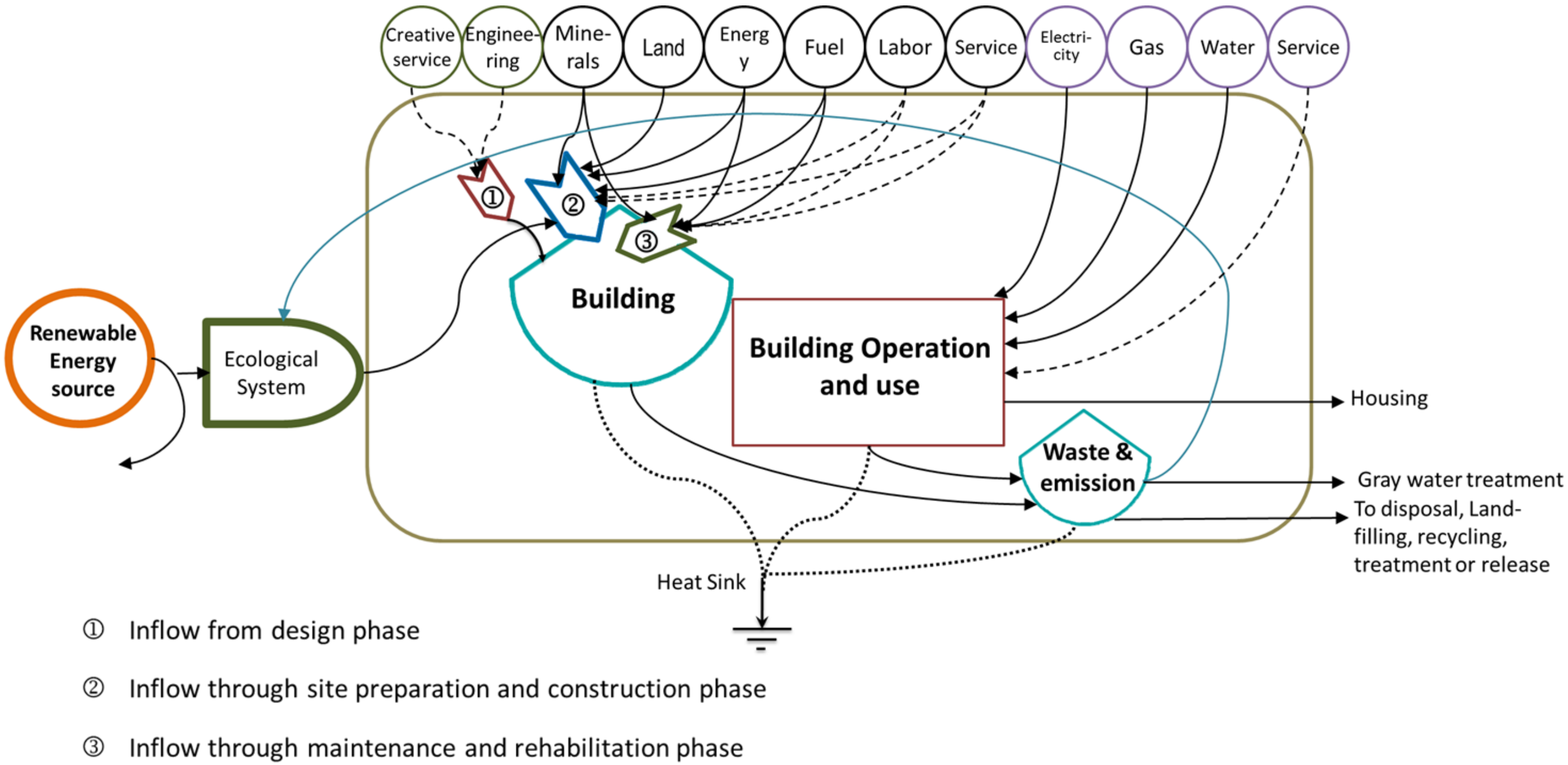


Figure 4-1 Energy system diagram of building[17]

[17] Dash lines represent pathways associated with monetary costs while point lines represent degraded energy pathways.

Later by applying Athena Canadian inventory database and assigning relevant operational energy to each building profile, the data inventory of each building has been compiled and summarized into the emergy evaluation table. Figure 4-2 compares life cycle energy (MJ /m^2) of multi-unit residential and single-family house by building assembly while Figure 4-3 compares energy consumption (MJ /m^2) of multi-unit residential and single-family house by building life cycle stages (both figures indicates data related to case studies in Vancouver, BC). From this figures it can realize that, based on the absolute value of building LCA, multi-residential building is more energy demanding especially in service life or operation phase. The absolute values of resource use, energy consumption and emission to the air, water and land will be used later for the impact assessment step.

Table 4-1 Bill of material report for typical single-family residential in BC

Material	*Quantity*	*Unit*
#15 Organic Felt	530.4549	m^2
1/2" Regular Gypsum Board	974.4204	m^2
5/8" Regular Gypsum Board	228.3303	m^2
6 mil Polyethylene	573.3610	m^2
Aluminum	0.9535	Tonnes
Batt. Fiberglass	4725.2731	m^2 (25mm)
Cold Rolled Sheet	0.9929	Tonnes
Concrete 20 MPa (flyash av)	49.7196	m^3
EPDM membrane (black, 60 mil)	223.9296	kg
Galvanized Sheet	0.2063	Tonnes
Joint Compound	1.2004	Tonnes
Large Dimension Softwood Lumber, kiln-dried	6.3607	m^3
Low E Tin Argon Filled Glazing	165.4599	m^2
Metric Modular (Modular) Brick	256.4363	m^2
Mortar	6.7362	m^3
Nails	0.3679	Tonnes
Organic Felt shingles 25yr	488.5769	m^2
Paper Tape	0.0138	Tonnes
PVC	1197.8257	kg
Rebar, Rod, Light Sections	1.6778	Tonnes
Screws Nuts & Bolts	0.0856	Tonnes
Small Dimension Softwood Lumber, kiln-dried	12.8069	m^3
Softwood Plywood	890.9060	m^2 (9mm)
Water Based Latex Paint	906.8422	L
Welded Wire Mesh / Ladder Wire	0.1213	Tonnes
Wide Flange Sections	1.8786	Tonnes

Table 4-2 Bill of material report for typical multi-unit residential in BC (7-storey condo)

Material	*Quantity*	*Unit*
1/2" Regular Gypsum Board	470.8000	m^2
5/8" Regular Gypsum Board	704.8800	m^2
Aluminum	34.3954	Tonnes
Ballast (aggregate stone)	142366.3043	kg
Batt. Fiberglass	7182.8192	m^2 (25mm)
Concrete 20 MPa (flyash av)	180.6732	m^3
Concrete 30 MPa (flyash 25%)	1040.9091	m^3
Concrete 30 MPa (flyash av)	1921.9318	m^3
EPDM membrane (black, 60 mil)	1651.3817	kg
Extruded Polystyrene	3583.6763	m2 (25mm)
Galvanized Sheet	7.5265	Tonnes
Galvanized Studs	4.0241	Tonnes
Glazing Panel	110.0253	Tonnes
Joint Compound	1.1734	Tonnes
Nails	0.0952	Tonnes
Paper Tape	0.0135	Tonnes
Polyester felt	0.8259	Tonnes
Polyethylene Filter Fabric	0.1764	Tonnes
Polyiso Foam Board (unfaced)	1325.4797	m^2 (25mm)
PVC Membrane 48 mil	5203.5291	kg
Rebar, Rod, Light Sections	264.8485	Tonnes
Screws Nuts & Bolts	1.2485	Tonnes
Water Based Latex Paint	22333.6454	L
Welded Wire Mesh / Ladder Wire	0.7835	Tonnes

4.2.3 Data analysis and impact assessment

In this step, the inflows and outflows of the buildings life cycle are converted to their emergy value[18]. Recourses inputs (upstream impacts) to the buildings life cycle are quantified as energy resources for geo-biosphere work and services needed for resources formation as it was discussed in section 3.5.1. Emergy equivalent of resources use or upstream impacts for the single-family house in Vancouver, BC have been summarized in Table 4-3. Emergy equivalent of resources use or upstream impacts for the multi-residential building in Vancouver, BC has been noted in Table 4-4.

[18] All the analysis has been done using Microsoft Excel spreadsheets.

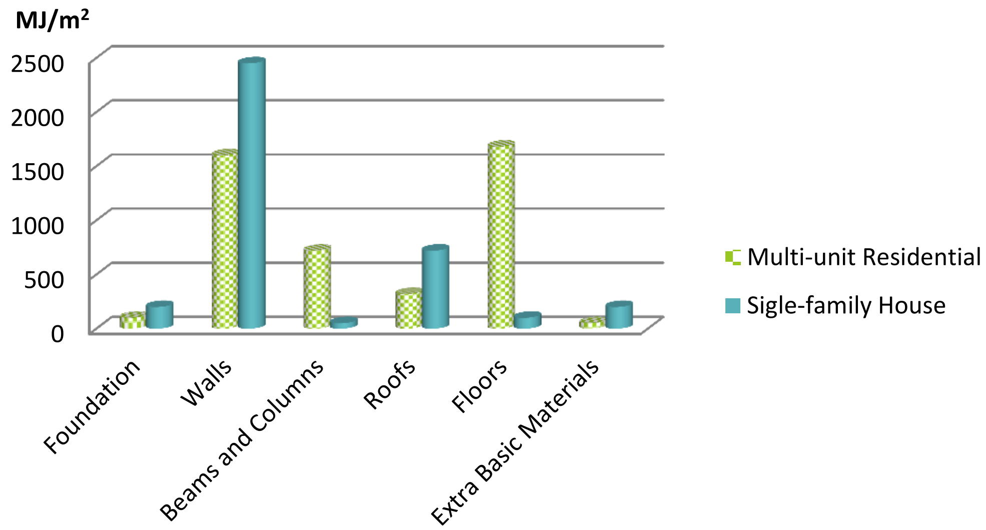
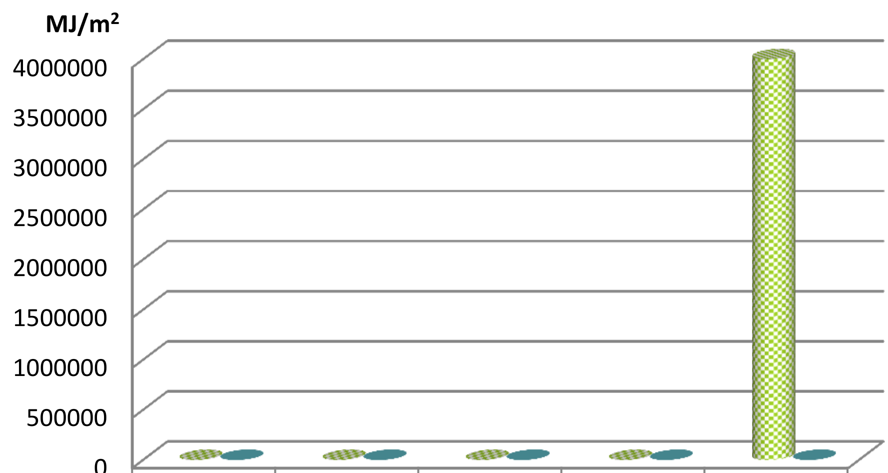


Figure 4-2 Life cycle energy (MJ /m²) of multi-unit and single-family residential by building assembly (in Vancouver, BC)



	Manufacturing	Construction	Maintenance	End-of-Life	Annual Operational Energy
Multi-unit Residential	60	60	60	25	4000000
Sigle-family House	50	50	50	20	80

Figure 4-3 Energy consumption (MJ /m²) of multi-unit and single-family residential by building life cycle stages (in Vancouver, BC)

Table 4-3 Emergy equivalent of resources use or upstream impacts (Single-family house in Vancouver, BC)

Resources (Unit)	*Type*	*UEV (seJ/unit)*	*Manufacturing*	*Construction*	*Maintenance*	*Operating Energy*		*End - Of - Life*	*Total*	*Emergy (seJ)*	*Emergy Density (seJ/m^2)*
						Annual	Total				
Limestone (kg)	N_m	1.69E+12	1.8E+04	-	3.8E+03	-	-	-	2.2E+04	3.7E+16	1.9E+14
Clay & Shale (kg)	N_m	4.10E+12	3.4E+04	-	6.4E+00	-	-	-	3.4E+04	1.4E+17	7.0E+14
Iron Ore (kg)	N_m	4.43E+12	1.0E+03	-	8.0E+02	-	-	-	1.8E+03	8.0E+15	4.0E+13
Sand (kg)	N_m	1.69E+12	3.3E+03	-	1.9E+03	-	-	-	5.3E+03	8.9E+15	4.5E+13
Ash (kg)	N_m	2.35E+13	1.3E+02	-	-	-	-	-	1.3E+02	3.1E+15	1.5E+13
Gypsum (Natural) (kg)	N_m	1.69E+12	3.7E+03	-	-	-	-	-	3.7E+03	6.2E+15	3.1E+13
Gypsum (Synthetic) (kg)	N_m	2.35E+13	5.3E+03	-	-	-	-	-	5.3E+03	1.2E+17	6.2E+14
Semi-Cementitious Material (kg)	N_m	3.70E+12	1.1E+03	-	-	-	-	-	1.1E+03	4.1E+15	2.0E+13
Coarse Aggregate (kg)	N_m	1.69E+12	5.0E+04	-	-	-	-	-	5.0E+04	8.5E+16	4.2E+14
Fine Aggregate (kg)	N_m	1.69E+12	5.1E+04	-	-	-	-	-	5.1E+04	8.7E+16	4.3E+14
Water (L)	N_r	2.10E+09	1.1E+05	-	4.8E+04	-	-	-	1.6E+05	3.4E+14	1.7E+12
Obsolete Scrap Steel (kg)	N_m	7.80E+12	2.7E+03	-	2.9E+02	-	-	-	3.0E+03	2.3E+16	1.2E+14
Prompt Scrap Steel as feedstock(kg)	N_m	7.80E+12	1.7E+03	-	1.7E+02	-	-	-	1.9E+03	1.5E+16	7.3E+13
Wood Fiber (kg)	N_r	1.40E+12	1.6E+04	-	-	-	-	-	1.6E+04	2.2E+16	1.1E+14
Metallurgical Coal as feedstock (kg)	N_p	1.69E+12	1.8E+02	-	2.8E+02	-	-	-	4.5E+02	7.7E+14	3.8E+12
Natural Gas as feedstock (MJ)	N_f	8.05E+10	1.2E+04	-	2.8E+04	-	-	-	4.1E+04	3.3E+15	1.6E+13
Crude Oil as feedstock (MJ)	N_p	9.27E+10	2.9E+04	-	6.3E+04	-	-	-	9.2E+04	8.5E+15	4.3E+13

Hydro (MJ)	R	2.67E+11	4.0E+04	2.1E+03	4.3E+04	1.1E+01	6.3E+02	1.2E+01	8.6E+04	2.3E+16	1.1E+14
Coal (MJ)	N_p	6.71E+10	5.7E+04	5.3E+02	2.6E+04	1.5E+02	9.2E+03	1.7E+02	9.2E+04	6.2E+15	3.1E+13
Diesel (MJ)	N_p	1.21E+11	3.7E+04	6.8E+04	1.4E+04	5.4E+02	3.2E+04	2.6E+04	1.8E+05	2.2E+16	1.1E+14
Gasoline (MJ)	N_p	1.11E+11	1.7E+02	-	4.1E+01	-	-	-	2.1E+02	2.4E+13	1.2E+11
Heavy Fuel Oil (MJ)	N_p	1.11E+11	1.7E+04	1.5E+03	1.2E+04	6.8E+01	4.1E+03	5.8E+02	3.5E+04	3.9E+15	1.9E+13
LPG (MJ)	N_p	8.05E+10	4.2E+03	6.9E+01	1.2E+02	3.2E+01	1.9E+03	2.6E+01	6.4E+03	5.1E+14	2.6E+12
Natural Gas (MJ)	N_f	8.05E+10	2.7E+05	3.1E+03	6.1E+04	8.7E+04	5.2E+06	1.1E+03	5.6E+06	4.5E+17	2.2E+15
Nuclear (MJ)	N_f	2.00E+11	3.4E+05	1.3E+02	1.1E+06	3.9E+01	2.3E+03	4.5E+01	1.4E+06	2.9E+17	1.5E+15

Table 4-4 Emergy equivalent of resources use or upstream impacts (Multi-residential building in Vancouver, BC)

Resources (Unit)	*Type*	*UEV (seJ/unit)*	*Manufacturing*	*Construction*	*Maintenance*	*Operating Energy*		*End - Of - Life*	*Total*	*Emergy (seJ)*	*Emergy density (seJ/m2)*
						Annual	**Total**				
Limestone (kg)	N_m	1.69E+12	1.2E+06	-	2.4E+04	-	-	-	1.2E+06	2.0E+18	5.0E+14
Clay & Shale (kg)	N_m	4.10E+12	3.0E+05	-	2.9E+01	-	-	-	3.0E+05	1.2E+18	6.2E+15
Iron Ore (kg)	N_m	4.43E+12	3.8E+04	-	3.6E+01	-	-	-	3.8E+04	1.7E+17	8.5E+14
Sand (kg)	N_m	1.69E+12	1.3E+05	-	5.0E+04	-	-	-	1.8E+05	3.0E+17	1.5E+15
Ash (kg)	N_m	2.35E+13	9.4E+03	-	-	-	-	-	9.4E+03	2.2E+17	1.1E+15
Gypsum (Natural) (kg)	N_m	1.69E+12	4.0E+03	-	-	-	-	-	4.0E+03	6.8E+15	3.4E+13
Gypsum (Synthetic) (kg)	N_m	2.35E+13	5.6E+03	-	-	-	-	-	5.6E+03	1.3E+17	6.6E+14
Semi-Cementitious Material (kg)	N_m	3.70E+12	1.6E+05	-	-	-	-	-	1.6E+05	5.8E+17	2.9E+15
Coarse Aggregate (kg)	N_m	1.69E+12	3.5E+06	-	8.9E+04	-	-	-	3.5E+06	6.0E+18	3.0E+16
Fine Aggregate (kg)	N_m	1.69E+12	2.3E+06	-	-	-	-	-	2.3E+06	3.9E+18	1.9E+16
Water (L)	N_r	2.10E+09	3.2E+06	-	2.2E+05	-	-	-	3.5E+06	7.3E+15	3.6E+13
Obsolete Scrap Steel (kg)	N_m	7.80E+12	1.7E+05	-	-	-	-	-	1.7E+05	1.3E+18	6.7E+15
Prompt Scrap Steel as feedstock(kg)	N_m	7.80E+12	1.1E+05	-	-	-	-	-	1.1E+05	8.6E+17	4.3E+15
Wood Fiber (kg)	N_r	1.40E+12	4-4962489	-	8.0E+01	-	-	-	1.2E+02	1.7E+14	8.4E+11
Metallurgical Coal as feedstock (kg)	N_p	1.69E+12	3.9E+03	-	-	-	-	-	3.9E+03	6.6E+15	3.3E+13
Natural Gas as feedstock (MJ)	N_f	8.05E+10	2.7E+03	-	7.9E+03	-	-	-	1.1E+04	8.5E+14	4.3E+12
Crude Oil as feedstock (MJ)	N_p	9.27E+10	4.4E+03	-	7.6E+03	-	-	-	1.2E+04	1.1E+15	5.6E+12
Hydro (MJ)	R	2.67E+11	2.9E+06	3.3E+02	2.4E+05	1.9E+06	1.2E+08	4.7E+02	1.2E+08	3.2E+19	1.6E+17
Coal (MJ)	N_p	6.71E+10	2.4E+06	4.8E+03	9.6E+04	7.1E+04	4.2E+06	6.9E+03	6.7E+06	4.5E+17	2.3E+15
Diesel (MJ)	N_p	1.21E+11	9.5E+05	1.1E+06	5.3E+05	4.5E+04	2.7E+06	1.0E+06	6.3E+06	7.6E+17	3.8E+15
Gasoline (MJ)	N_p	1.11E+11	2.2E+01	-	-	-	-	-	2.2E+01	2.5E+12	1.2E+10
Heavy Fuel Oil (MJ)	N_p	1.11E+11	1.1E+06	1.6E+04	3.9E+04	3.6E+03	2.2E+05	2.3E+04	1.4E+06	1.5E+17	7.6E+14

LPG (MJ)	N_p	8.05E+10	9.3E+03	7.2E+02	4.1E+02	1.5E+03	9.1E+04	1.0E+03	1.0E+05	8.3E+15	4.1E+13
Natural Gas (MJ)	N_f	8.05E+10	5.9E+06	3.0E+04	3.5E+05	4.0E+06	2.4E+08	4.2E+04	2.4E+08	2.0E+19	9.9E+16
Nuclear (MJ)	N_f	2.00E+11	5.1E+07	1.3E+03	1.4E+04	1.3E+04	7.6E+05	1.8E+03	5.2E+07	1.0E+19	5.2E+16

Figure 4-4 compares upstream impacts of different resource categories (resource used categories explained in 3.5.1) of the multi-unit residential and single-family house in Vancouver, BC. According to this figure multi-unit residential building is more recourse intensive based on non-renewable mineral (Nm) consumption non-petroleum fuel consumption (Nf and Np) and renewable resource use (R), while single-family house is slightly more resource intensive according to the slowly-renewable natural resources (Sr). All in all, the cumulative upstream impact, yield emergy per unit area (Y), of the multi-unit residential is ~3 times greater than the single-family house in Vancouver, BC.

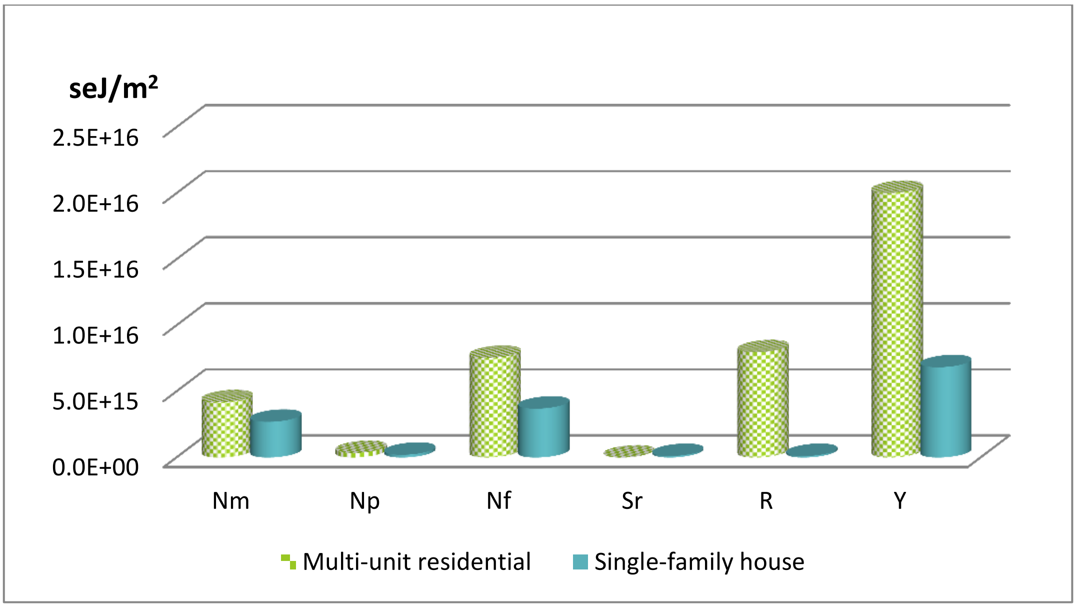


Figure 4-4 Upstream impacts of multi-unit residential and single-family house (Vancouver, BC)

In addition, the impacts of waste and emission (downstream impacts) are quantified as energy resources (environmental support or feedbacks) are needed to replace the natural or human capital loss as it was discussed in 3.5.2. Emergy equivalent of air and water emissions downstream impacts, emergy loss (loss of human health EL_{HH} and ecosystem quality EL_{EQ}) and air and water ecological services (ES_{air} and ES_{water}) for the single-family in Vancouver, BC have been summarized in Table 4-5 and Table 4-6. In addition, emergy equivalent of air and water emissions downstream impacts for the multi-unit residential building in Vancouver, BC have been summarized in Table 4-7 and Table 4-8. Moreover, emergy equivalent of ecological loss due to solid waste discharge on land for the single-family house and multi-unit residential building in Vancouver, BC have been summarized in Table 4-9 and Table 4-10.

Table 4-5 Emergy equivalent of air emissions downstream impacts (Single-family house in Vancouver, BC)

Airborne Pollution	*Damage Category HH*	*DALY /g*	*Damage Category EQ*	*PDF %*	*Manufacturing*	*Construction*	*Maintenance*	*Operating Energy*		*Total Effect*	*Emergy Loss (seJ)*		*Ecological Services (seJ)*
								Annual	**Total**		**EL_{HH}**	**EL_{EQ}**	**Es_{air}**
Carbon dioxide, biogenic g	Climate change	2.10E-10	–	–	2.2E+03	0.0E+00	2.7E+00	–	–	2.2E+03	7.9E+10	–	2.2E+07
Carbon dioxide, fossil g	Climate change	2.10E-10	–	–	3.3E+04	5.4E+03	1.2E+04	4.5E+03	2.7E+05	3.2E+05	1.2E+13	–	1.5E+10
Nitrogen oxides g	Respiratory disorders	8.87E-08	Acidification	5.71E+00	9.9E+04	3.7E+04	4.1E+04	3.4E+02	2.0E+04	2.0E+05	3.1E+15	6.4E+14	1.2E+14
Sulfur dioxide g	Respiratory disorders	5.46E-08	Acidification	1.04E+00	1.8E+05	2.0E+02	9.1E+04	4.0E+04	2.4E+06	2.7E+06	2.5E+16	1.5E+15	3.2E+15
Sulfur oxides g	Respiratory disorders	5.46E-08	Acidification	1.04E+00	2.5E+04	5.5E+03	2.1E+04	7.3E+01	4.4E+03	5.8E+04	5.4E+14	3.3E+13	6.9E+13
Particulates, > 2.5 um, and < 10um g	Respiratory disorders	3.75E-07	–	–	1.5E+04	6.4E+02	1.4E+03	2.8E+02	1.7E+04	3.5E+04	2.3E+15	–	1.3E+13
Particulates, < 2.5 um g	Respiratory disorders	3.75E-07	–	–	1.3E+05	3.8E+02	1.1E+05	1.4E+01	8.2E+02	2.4E+05	1.6E+16	–	9.0E+13
Methane g	Respiratory disorders	1.28E-11	–	–	8.6E+04	9.4E+01	2.8E+04	2.0E+04	1.2E+06	1.3E+06	3.0E+12	–	5.7E+11
Methane g	Climate change	4.40E-09	–	–	8.6E+04	9.4E+01	2.8E+04	2.0E+04	1.2E+06	1.3E+06	1.0E+15	–	–

Table 4-6 Emergy equivalent of water emissions downstream impacts (Single-family house in Vancouver, BC)

Waterborne Pollution	***Damage Category Human Health***	***DALY/g***	***Damage Category Ecosystem Quality***	***PDF %***	***Manufacturing***	***Construction***	***Maintenance***	***Operating Energy***		***Total Effect***	***Emergy Loss (seJ)***		***Ecological Services (seJ)***
								Annual	Total		EL_{HH}	EL_{EQ}	Es_{water}
Arsenic, ion (mg)	Carcinogenic impacts	6.57E-05	Ecotoxic	1.14E+01	6.7E+03	1.6E+03	2.8E+03	1.6E+03	9.8E+04	1.1E+05	5.5E+06	6.9E+11	6.5E+12
Cadmium, ion (mg)	Carcinogenic impacts	7.12E-05	Ecotoxic	4.80E+02	1.2E+03	2.3E+02	7.1E+02	2.4E+02	1.4E+04	1.6E+04	2.0E+14	4.3E+12	4.9E+13
Cyanide (mg)	Carcinogenic impacts	4.60E-08	–	–	3.4E+05	4.1E-01	3.6E+05	5.3E-01	3.2E+01	7.0E+05	5.6E+12	–	4.2E+14
Lead (mg)	–	–	Ecotoxic	7.39E+00	1.7E+05	3.4E+03	8.8E+04	2.3E+03	1.4E+05	4.1E+05	–	1.7E+12	1.2E+14
Mercury (μg)	–	–	Ecotoxic	1.97E+02	1.7E+04	5.6E+03	8.9E+03	1.5E+03	8.9E+04	1.2E+05	–	1.3E+13	7.3E+15
Oils, unspecified (mg)	Carcinogenic impacts	4.16E-08	–	–	1.0E+07	1.3E+05	1.1E+07	1.4E+05	8.5E+06	3.0E+07	2.2E+14	–	1.8E+15

Table 4-7 Emergy equivalent of air emissions downstream impacts (Multi-unit residential building in Vancouver, BC)

Airborne Pollution	*Damage Category HH*	*DALY /g*	*Damage Category EQ*	*PDF %*	*Manufacturing*	*Construction*	*Maintenance*	*Operating Energy*		*Total Effect*	*Emergy Loss (seJ)*		*Ecological Services (seJ)*
								Annual	**Total**		**EL_{HH}**	**EL_{EQ}**	**Es_{air}**
Carbon dioxide, biogenic g	Climate change	2.10E-10	–	–	6.4E+04	0.0E+00	1.0E+05	0.0E+00	0.0E+00	1.7E+05	6.1E+12	–	1.7E+09
Carbon dioxide, fossil g	Climate change	2.10E-10	–	–	1.3E+09	7.9E+07	1.4E+08	2.1E+08	1.3E+10	1.4E+10	5.1E+17	–	6.8E+14
Nitrogen oxides g	Respiratory disorders	8.87E-08	Acidification	5.71E+00	5.8E+06	6.2E+05	9.2E+05	2.9E+04	1.8E+06	9.2E+06	1.4E+17	2.9E+16	5.5E+15
Sulfur dioxide g	Respiratory disorders	5.46E-08	Acidification	1.04E+00	5.9E+06	0.0E+00	2.4E+05	1.9E+06	1.1E+08	1.2E+08	1.1E+18	6.8E+16	1.4E+17
Sulfur oxides g	Respiratory disorders	5.46E-08	Acidification	1.04E+00	8.0E+05	7.4E+04	4.3E+05	4.6E+03	2.8E+05	1.7E+06	1.6E+16	9.5E+14	2.0E+15
Particulates, > 2.5 um, and < 10um g	Respiratory disorders	3.75E-07	–	–	1.7E+05	9.1E+03	1.5E+04	1.3E+04	7.7E+05	1.0E+06	6.5E+16	–	3.8E+14
Particulates, < 2.5 um g	Respiratory disorders	3.75E-07	–	–	5.5E+06	3.9E+03	2.6E+06	5.1E+03	3.0E+05	8.4E+06	5.4E+17	–	3.1E+15
Methane g	Respiratory disorders	1.28E-11	–	–	1.9E+06	1.7E+03	1.8E+05	9.3E+05	5.6E+07	5.8E+07	1.3E+14	–	2.5E+13
Methane g	Climate change	4.40E-09	–	–	1.9E+06	1.7E+03	1.8E+05	9.3E+05	5.6E+07	5.8E+07	4.4E+16	–	–

Table 4-8 Emergy equivalent of water emissions downstream impacts (Multi-unit residential building in Vancouver, BC)

Waterborne Pollution	*Damage Category Human Health*	*DALY/g*	*Damage Category Ecosystem Quality*	*PDF %*	*Manufacturing*	*Construction*	*Maintenance*	*Operating Energy*		*Total Effect*	*Emergy Loss (seJ)*		*Ecological Services (seJ)*
								Annual	Total		EL_{HH}	EL_{EQ}	Es_{water}
Arsenic, ion mg	Carcinogenic impacts	6.57E-05	Ecotoxic	1.14E+01	3.8E+05	1.7E+04	6.6E+05	7.4E+04	4.5E+06	5.5E+06	5.5E+06	3.5E+13	3.3E+14
Cadmium, ion mg	Carcinogenic impacts	7.12E-05	Ecotoxic	4.80E+02	1.6E+05	2.5E+03	4.2E+05	1.1E+04	6.5E+05	1.2E+06	1.5E+16	3.3E+14	3.7E+15
Cyanide mg	Carcinogenic impacts	4.60E-08	–	–	7.3E+06	4.4E+00	1.3E+05	2.4E+01	1.5E+03	7.4E+06	5.9E+13	–	4.5E+15
Lead mg	–	–	Ecotoxic	7.39E+00	8.1E+06	3.6E+04	3.4E+05	1.1E+05	6.5E+06	1.5E+07	–	6.1E+13	4.5E+15
Mercury µg	–	–	Ecotoxic	1.97E+02	6.3E+05	5.9E+04	9.8E+05	6.9E+04	4.1E+06	5.9E+06	–	6.4E+14	3.5E+17
Oils, unspecified mg	Carcinogenic impacts	4.16E-08	–	–	2.6E+08	1.4E+06	2.9E+06	6.5E+06	3.9E+08	6.6E+08	4.7E+15	–	3.9E+16

Table 4-9 Emergy equivalent of ecological loss due to solid waste discharge on land (Single-family house in Vancouver, BC)

Solid waste	***Manufacturing***	***Construction***	***Maintenance***	***Operating Energy***		***End-of-Life***	***Total Effects***	***Land Occupation***	***Emergy Loss EL_{SW} (seJ)***	***EL_{SW} Density(seJ/m^2)***
				Annual	**Total**					
Bark/Wood Waste kg	1.2E+02	6.7E+02	1.1E+02	-	-	-	9.1E+02	3.2E-08	3.3E+07	1.7E+05
Concrete Solid Waste kg	2.6E+03	-	-	-	-	-	2.6E+03	9.1E-08	9.6E+07	4.8E+05
Blast Furnace Slag kg	4.0E+02	-	1.3E+02	-	-	-	5.3E+02	1.9E-08	1.9E+07	9.7E+04
Blast Furnace Dust kg	3.0E+02	-	1.6E+01	-	-	-	3.2E+02	1.1E-08	1.2E+07	5.9E+04
Steel Waste kg	1.3E+01	-	6.2E+00	-	-	-	1.9E+01	6.7E-10	7.0E+05	3.5E+03
Other Solid Waste kg	2.0E+03	5.1E+01	2.1E+03	4.6E+01	2.8E+03	1.9E+01	6.9E+03	2.4E-07	2.5E+08	1.3E+06

Table 4-10 Emergy equivalent of ecological loss due to solid waste discharge on land (Multi-unit residential building in Vancouver, BC)

Solid waste	***Manufacturing***	***Construction***	***Maintenance***	***Operating Energy***		***End-of-Life***	***Total Effects***	***Land Occupation***	***Emergy Loss EL_{SW} (seJ)***	***EL_{SW} Density(seJ/m^2)***
				Annual	**Total**					
Bark/Wood Waste kg	8.9E-06	5.6E+04	5.6E+04	-	-	-	1.1E+05	4.0E-06	4.2E+09	1.0E+06
Concrete Solid Waste kg	1.5E+05	1.1E+05	1.1E+05	-	-	-	3.6E+05	1.3E-05	1.3E+10	3.4E+06
Blast Furnace Slag kg	2.4E+04	-	-	-	-	-	2.4E+04	8.4E-07	8.8E+08	2.2E+05
Blast Furnace Dust kg	2.2E+04	-	-	-	-	-	2.2E+04	7.6E-07	7.9E+08	2.0E+05
Steel Waste kg	2.9E+02	4.2E+02	4.2E+02	-	-	-	1.1E+03	4.0E-08	4.2E+07	1.0E+04
Other Solid Waste kg	1.0E+05	5.4E+02	8.1E+03	2.9E+03	1.7E+05	7.6E+02	2.9E+05	1.0E-05	1.1E+10	2.6E+06

Figure 4-5 compares different downstream impact categories (explained in 3.5.2) of the single-family house and multi-unit residential building in Vancouver, BC. According to this figure, the multi-unit residential building causes more natural and human capital losses due to emission to air and water and discharge of solid waste on land (preliminary damage) and simultaneously need more ecological services (ES_{air} and ES_{water}) to dilute emissions.

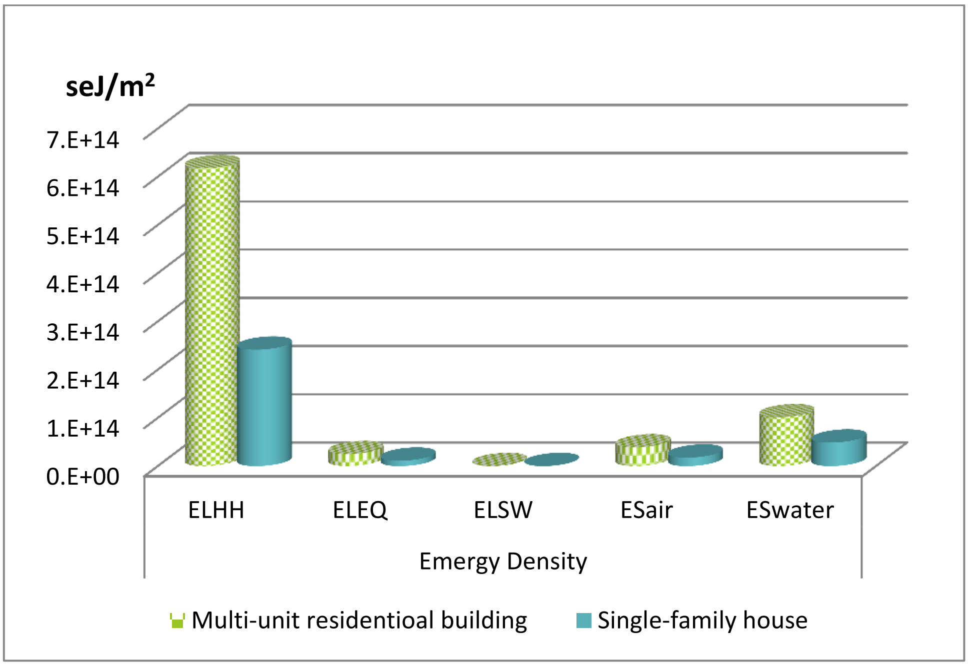


Figure 4-5 Downstream impacts of multi-unit residential and single-family house (Vancouver, BC)

Moreover, life cycle monetary costs were calculated based on average cost of labors and services in Canada. The impacts of life cycle costs (socio-economic impacts) are considered as emergy investment (F) from the economic system due to different activities such as extract and refine the nonrenewable resource, manufacture and produce goods, and provide labor and services for construction, rehabilitation, and maintenance. Emergy value for local services (i.e. design and tendering, and ownership cost) and labor has been accounted for based on local currency (BC Emergy/GDP is 2.67E+12 sej/CAD$ (Hossaini and Kasun Hewage 2013). While, emergy value for other services (i.e. construction, maintenance, rehabilitation and operation related services) associated with national flows of material and energy inputs has been determined based on national currency (Canada Emergy/GDP is 4.22E+12 sej/CAD (Hossaini and Kasun Hewage 2013)).

The associated life cycle costs of the single-family house (based on average cost in Vancouver, BC) have been converted to the emergy values as it was explained in 3.5.3 and summarized in Table 4-11. Moreover, the associated life cycle costs of the multi-unit residential building (based on average cost of rental complexes in Vancouver, BC) have been converted to the emergy values in Table 4-12. Figure 4-6 compares emergy investment from the economic system to purchase labors (F_L) and services (F_S) of the single-family house and multi-unit residential building in Vancouver, BC. In addition Figure 4-7compares the life cycle costs of the two buildings. According to these figures the emergy costs per unit area associated through the life cycle of multi-unit residential building is ~2 times greater than the single-family house. Moreover, the ownership cost per unit area is the highest life cycle cost that for the rental suites costs about ~2 times more than the single-family house in a 60 years' time period.

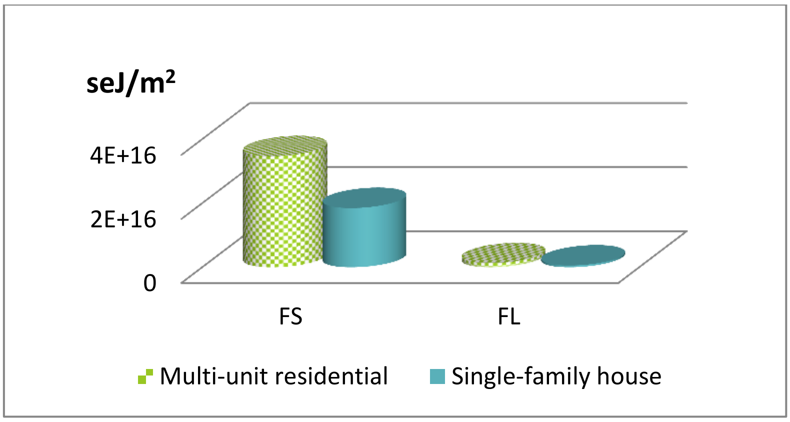


Figure 4-6 Life cycle costs of multi-unit residential and single-family house (Vancouver, BC)

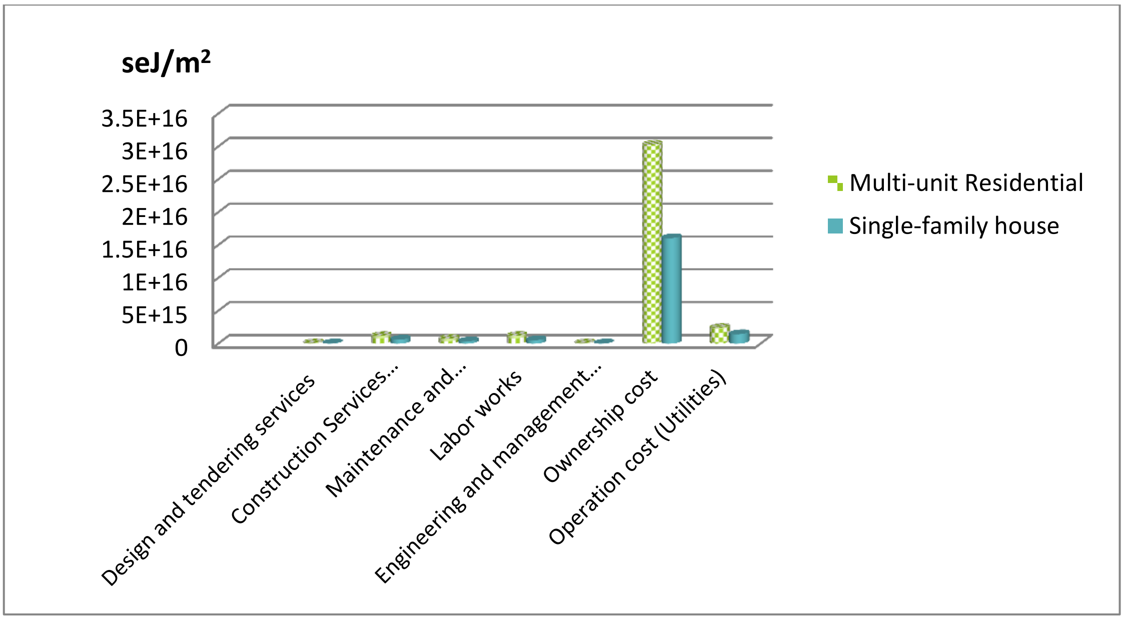


Figure 4-7 Life cycle costs of multi-unit residential and single-family house (Vancouver, BC)

Table 4-11 Emergy evaluation of single-family house life cycle costs (Vancouver, BC)

Purchased Input	*Type*	*UEV (sej/unit)*	*Design*	*Construction*	*Maintenance*	*Operating*		*Total*	*Emergy (sej)*	*Emergy density (seJ/m^2)*
						Annual	**Total**			
Design and tendering services	F_s	2.67E+12	3251.7	-	-	-	-	3.3E+03	8.7E+15	4.3E+13
Construction Services (Material and Equipment)	F_s	4.22E+12	-	29011.2	-	-	-	2.9E+04	1.2E+17	6.1E+14
Maintenance and rehabilitating services	F_s	4.22E+12	-	-	16328.2	-	-	1.6E+04	6.9E+16	3.4E+14
Labor works	F_L	2.67E+12	-	25184.1	14174.2	-	-	3.9E+04	1.1E+17	5.3E+14
Engineering and management works	F_L	2.67E+12	-	1625.9	915.1	-	-	2.5E+03	6.8E+15	3.4E+13
Ownership cost	F_s	2.67E+12	-	-	-	20048.3	1202897.0	1.2E+06	3.2E+18	1.6E+16
Operation cost (Utilities)	F_s	2.67E+12	-	-	-	180-	10800-	1.1E+05	2.9E+17	1.4E+15

Table 4-12 Emergy evaluation of multi-unit residential life cycle costs (in Vancouver, BC)

Purchased Input	***Type***	***UEV (seJ/CAD)***	***Design***	***Construction***	***Maintenance***	***Operating***		***Total***	***Emergy (sej)***	***Emergy density (seJ/m²)***
						Annual	**Total**			
Design and tendering services	F_s	2.67E+12	131510.0	0.0	0.0	0.0	0.0	1.3E+05	3.5E+17	8.8E+13
Construction Services (Material and Equipment)	F_s	4.22E+12	0.0	1102318.4	0.0	0.0	0.0	1.1E+06	4.7E+18	1.2E+15
Maintenance and rehabilitating services	F_s	4.22E+12	0.0	0.0	698157.3	0.0	0.0	7.0E+05	2.9E+18	7.4E+14
Labor works	F_L	2.67E+12	0.0	1089515.1	690048.2	0.0	0.0	1.8E+06	4.8E+18	1.2E+15
Engineering and management works	F_L	2.67E+12	0.0	65755.0	41646.2	0.0	0.0	1.1E+05	2.9E+17	7.2E+13
Ownership cost	F_s	2.67E+12	0.0	0.0	0.0	756000.0	45360000.0	4.5E+07	1.2E+20	3.0E+16
Operation cost (Utilities)	F_s	2.67E+12	0.0	0.0	0.0	60480.0	3628800.0	3.6E+06	9.7E+18	2.4E+15

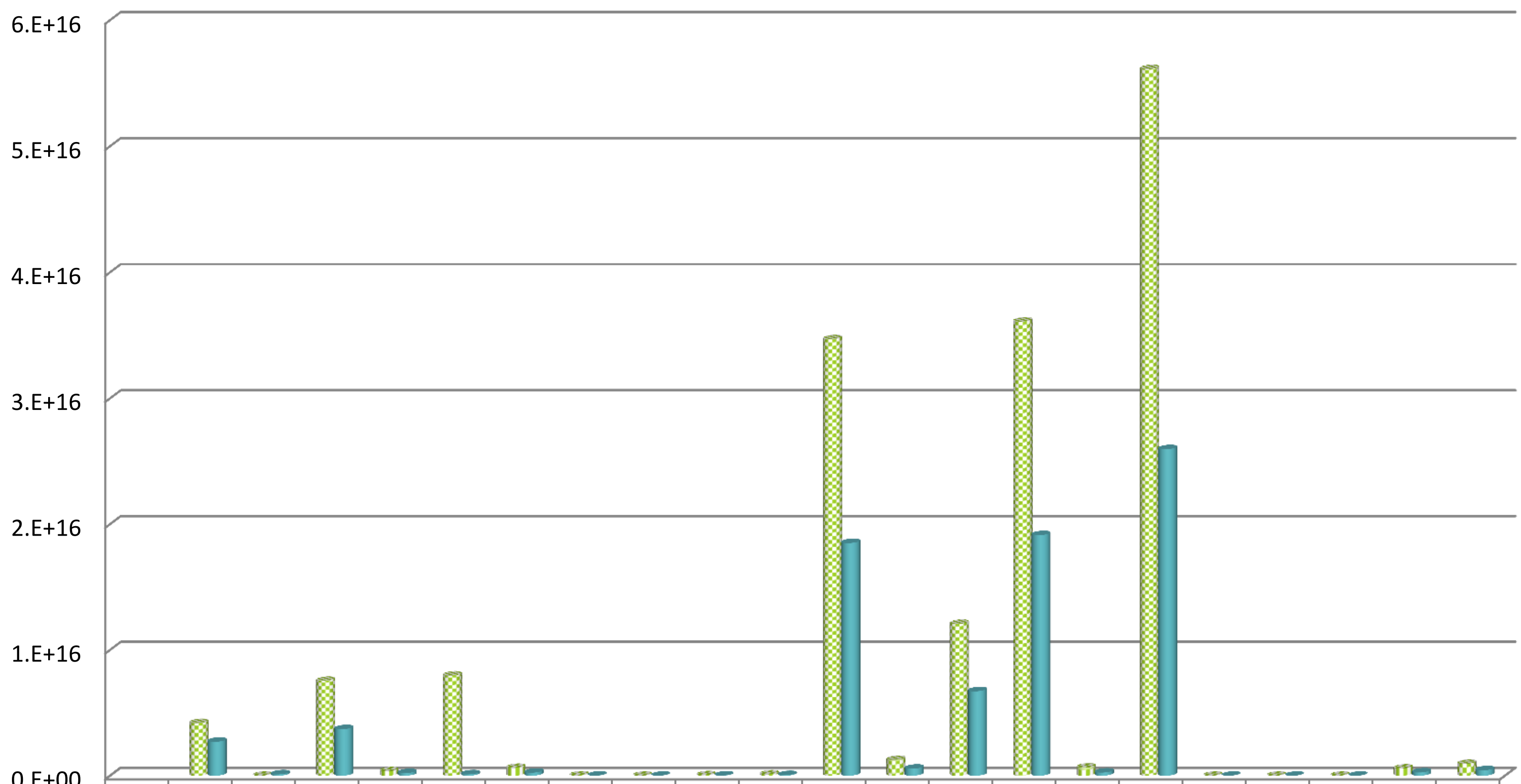
4.2.4 Flow summary and calculation of indices

In the final step, the emergy of different items of buildings life cycle have been combined and aggregated to obtain different emergy-based indicators to compare the two types of building assemblies. Table 4-13 summarized emergy-based indicators of multi-unit residential building and single-family house in Vancouver, BC. In addition Figure 4-8 compares emergy-based indicators of the two buildings.

According to Table 4-13 and Figure 4-8, multi-unit residential building cause more significant upstream and downstream impacts through its life cycle. The yield emergy (total life cycle emergy) per unit area of multi-unit residential building is ~3 times greater than the single-family house. In addition, emergy yield ratio (EYR), which indicates total emergy released per unit of emergy invested, for multi-unit residential building is ~10% greater than the single-family house.

However, the environmental loading ratio (ELR), which indicates total emergy loss plus nonrenewable and invested emergy released per unit of local renewable resource, for the single-family house is significantly greater than ELR for multi-unit residential building. On the other hand, according to the emergy sustainability index (ESI) that indicates emergy yield per unit of environmental loading, the multi-unit residential building shows higher sustainability level than the single-family house in Vancouver, BC.

This is because the main source of energy in the multi-unit residential building in Vancouver is hydroelectricity which is a renewable source of energy. So the operation of multi-unit residential building is highly dependent on local renewable energy sources. Whereas, the main source of energy in the single-family house in Vancouver is natural gas which is a non-renewable source of energy. As a result, while the multi-unit residential building consumes significantly higher service life energy and cause greater emission impact, it consumes energy in a more sustainable manner (use more renewable sources) as compare to the single-family house. In other word, single-family house can be more sustainable option, considering all emergy indices, if the source of service life energy replace by hydroelectricity.



	Nm	Sr	Nf	Np	R	ELHH	ELEQ	ELSW	Esair	Eswater	FS	FL	N	F	EL	Y	EYR	ELR	ESI	Ec	EP
Multi-unit residential	4.2E+15	1.9E+12	7.5E+15	3.5E+14	8.0E+15	6.2E+14	2.5E+13	1.9E+03	3.9E+13	1.0E+14	3.5E+16	1.3E+15	1.2E+16	3.6E+16	6.4E+14	5.6E+16	1.6E+00	6.1E+00	2.5E-01	5.7E+14	9.5E+14
Single-family house	2.7E+15	1.1E+14	3.7E+15	2.1E+14	1.1E+14	2.4E+14	1.1E+13	1.0E+04	1.8E+13	4.9E+13	1.9E+16	5.6E+14	6.7E+15	1.9E+16	2.5E+14	2.6E+16	1.4E+00	2.3E+02	6.0E-03	2.6E+14	4.4E+14

Figure 4-8 Emergy-based indicators of multi-unit residential building and single family house in Vancouver (BC)

Table 4-13 Emergy-based indicators of multi-unit residential building and single family house in Vancouver, BC

Indicator	*Description*	*Unit*	*Multi-unit residential*	*Single-family house*
Nm	Non-renewable minerals	seJ/m^2	4.2E+15	2.7E+15
Sr	Slowly-renewable natural resources	seJ/m^2	1.9E+12	1.1E+14
Nf	Non-petroleum fuel	seJ/m^2	7.5E+15	3.7E+15
Np	Non-renewable petroleum fuel	seJ/m^2	3.5E+14	2.1E+14
R	Renewable energy	seJ/m^2	8.0E+15	1.1E+14
EL_{HH}	Emergy equivalent of human health loss	seJ/m^2	6.2E+14	2.4E+14
EL_{EQ}	Emergy equivalent of ecological loss	seJ/m^2	2.5E+13	1.1E+13
EL_{SW}	Emergy loss due to solid waste discharge on land	seJ/m^2	1.9E+03	1.0E+04
ESair	Ecological services for dispersal of air pollutants	seJ/m^2	3.9E+13	1.8E+13
ES_{water}	Ecological services for dispersal of water pollutants	seJ/m^2	1.0E+14	4.9E+13
F_S	Emergy equivalent of purchased services	seJ/m^2	3.5E+16	1.9E+16
F_L	Emergy equivalent of labor	seJ/m^2	1.3E+15	5.6E+14
N	Non-renewable Emergy inputs: $N_m + N_f + N_p + S_r$	seJ/m^2	1.2E+16	6.7E+15
F	Emergy Feedback(from economy and ecology): $F_l + F_s + Es_{air} + Es_{water}$	seJ/m^2	3.6E+16	1.9E+16
EL	Emergy equivalent of loss: $EL_{HH} + EL_{EQ} + EL_{SW}$	seJ/m^2	6.4E+14	2.5E+14
Y	Yield Emergy: N + R + F	seJ/m^2	5.6E+16	2.6E+16
EYR	Emergy yield ratio: Y/F_l+F_S	-	1.6E+00	1.4E+00
ELR	Environmental loading ratio: (N + F + EL) / R	-	6.1E+00	2.3E+02
ESI	Emergy Sustainability Index (EYR/ELR)	-	2.5E-01	6.0E-03
E_c	Emergy per capita (Y+EL)/people	seJ/person	5.7E+14	2.6E+14
E_P	Empower intensity: (Y +EL) /Lifespan	seJ/m^2/yr	9.5E+14	4.4E+14

4.2.5 Investigating result validity for other Canadian provinces

In order to investigate the validity of Em-LCA result in other Canadian provinces, steps 1-4 of Em-LCA framework have been repeated for the two types of building in other large and populous cities in other provinces in Canada, i.e. Toronto (ON), Calgary (AB), and Montreal (QC). From the previous analysis it was realized that, the first categories of impacts (upstream impacts) are dominant (e.g. compare "N" and "EL" in Figure 4-8). Hence, only upstream impacts have been considered for the second run of Em-LCA.

Emergy equivalent of resources use or upstream impacts for single-family house in different provinces of Canada has been summarized in Table 4-14. The results of upstream impacts have been combined and aggregated to obtain emergy-based indicators to compare the cumulative effects of single-family house in different provinces of Canada (Figure 4-9). According to this figure, while the amount of mineral resource (N_m) use for a single-family house in 4 provinces is slightly similar, a single-family house in BC consumes more mineral resources as compared to other provinces as a result of higher seismic risk in Vancouver, BC. On the other hand a single-family house in AB consumes more fuel resources (N_p and N_F) and less renewable resources (R). Consequently, a single-family house in AB cause greater ELR that shows life cycle energy consumption in AB is less sustainable as compared to the other provinces (Figure 4-10).

Emergy equivalent of upstream impacts for multi-unit residential building in different provinces of Canada has been summarized in Table 4-15. The results of upstream impacts have been aggregated to calculate emergy-based indicators to compare the cumulative effects of multi-unit residential building in different provinces of Canada. Figure 4-11 indicates that the amount of mineral resource (N_m) use for multi-unit residential buildings in 4 provinces is slightly the same. However, multi-unit residential building in BC consumes more mineral resources as compared to other provinces as a result of higher seismic risk in Vancouver, BC. On the other hand, a multi-unit residential building in AB consumes more petroleum fuel resources (N_p) and less renewable resources (R). Moreover, a multi-unit residential building in ON consumes significantly higher non-petroleum fuel (N_F). Consequently, while the yield emergy (Y) of a multi-unit residential building in ON is higher than other provinces, a multi-unit residential building in AB causes greater ELR. It shows that life cycle energy consumption in AB is less sustainable as compared to the other provinces (Figure 4-13).

Table 4-14 Emergy equivalent of resources use or upstream impacts for single-family house in different provinces of Canada

Resources (Unit)	***Type***	***UEV (seJ/unit)***	*Resource Input (Unit)*				*Emergy (seJ)*			
			BC	ON	AB	QC	**BC**	**ON**	**AB**	**QC**
Limestone (kg)	N_m	1.69E+12	2.2E+04	2.3E+04	2.4E+04	2.2E+04	3.7E+16	3.9E+16	4.0E+16	3.7E+16
Clay & Shale (kg)	N_m	4.10E+12	3.4E+04	3.1E+04	3.0E+04	3.2E+04	1.4E+17	1.3E+17	1.2E+17	1.3E+17
Iron Ore (kg)	N_m	4.43E+12	1.8E+03	1.8E+03	1.8E+03	1.5E+03	8.0E+15	8.1E+15	8.1E+15	6.6E+15
Sand (kg)	N_m	1.69E+12	5.3E+03	4.6E+03	4.4E+03	5.4E+03	8.9E+15	7.8E+15	7.4E+15	9.1E+15
Ash (kg)	N_m	2.35E+13	1.3E+02	3.4E+02	8.0E-01	8.0E-01	3.1E+15	7.9E+15	1.9E+13	1.9E+13
Gypsum (Natural) (kg)	N_m	1.69E+12	3.7E+03	3.7E+03	3.7E+03	3.7E+03	6.2E+15	6.2E+15	6.2E+15	6.2E+15
Gypsum (Synthetic) (kg)	N_m	2.35E+13	5.3E+03	5.3E+03	5.3E+03	5.3E+03	1.2E+17	1.2E+17	1.2E+17	1.2E+17
Semi-Cementitious Material (kg)	N_m	3.70E+12	1.1E+03	1.1E+03	1.1E+03	1.1E+03	4.0E+15	4.0E+15	4.0E+15	4.0E+15
Coarse Aggregate (kg)	N_m	1.69E+12	5.0E+04	5.0E+04	5.0E+04	5.0E+04	8.5E+16	8.5E+16	8.5E+16	8.5E+16
Fine Aggregate (kg)	N_m	1.69E+12	5.1E+04	5.1E+04	5.1E+04	5.1E+04	8.7E+16	8.7E+16	8.7E+16	8.7E+16
Water (L)	N_r	2.10E+09	1.6E+05	1.6E+05	1.6E+05	1.6E+05	3.3E+14	3.3E+14	3.3E+14	3.3E+14
Obsolete Scrap Steel (kg)	N_m	7.80E+12	3.0E+03	2.7E+03	2.7E+03	2.7E+03	2.3E+16	2.1E+16	2.1E+16	2.1E+16
Prompt Scrap Steel as feedstock(kg)	N_m	7.80E+12	1.9E+03	1.7E+03	1.7E+03	1.7E+03	1.5E+16	1.3E+16	1.3E+16	1.3E+16
Wood Fiber (kg)	N_r	1.40E+12	1.6E+04	1.5E+04	1.5E+04	1.5E+04	2.2E+16	2.1E+16	2.1E+16	2.1E+16
Metallurgical Coal as feedstock (kg)	N_p	1.69E+12	4.5E+02	4.5E+02	4.5E+02	4.5E+02	7.7E+14	7.7E+14	7.7E+14	7.7E+14
Natural Gas as feedstock (MJ)	N_f	8.05E+10	4.1E+04	4.1E+04	4.1E+04	4.1E+04	3.3E+15	3.3E+15	3.3E+15	3.3E+15
Crude Oil as feedstock (MJ)	N_p	9.27E+10	9.2E+04	9.2E+04	9.2E+04	9.2E+04	8.5E+15	8.5E+15	8.5E+15	8.5E+15
Hydro (MJ)	R	2.67E+11	8.6E+04	5.7E+04	4.6E+04	9.3E+04	2.3E+16	1.5E+16	1.2E+16	2.5E+16
Coal (MJ)	N_p	6.71E+10	9.2E+04	1.1E+05	1.9E+05	7.3E+04	6.2E+15	7.1E+15	1.3E+16	4.9E+15
Diesel (MJ)	N_p	1.21E+11	1.8E+05	1.3E+05	1.6E+05	1.4E+05	2.2E+16	1.6E+16	2.0E+16	1.7E+16
Gasoline (MJ)	N_p	1.11E+11	2.1E+02	2.1E+02	2.1E+02	2.1E+02	2.4E+13	2.4E+13	2.4E+13	2.4E+13
Heavy Fuel Oil (MJ)	N_p	1.11E+11	3.5E+04	4.0E+04	3.0E+04	5.5E+04	3.9E+15	4.4E+15	3.3E+15	6.1E+15
LPG (MJ)	N_p	8.05E+10	6.4E+03	6.6E+03	7.2E+03	6.6E+03	5.1E+14	5.3E+14	5.8E+14	5.3E+14
Natural Gas (MJ)	N_f	8.05E+10	5.6E+06	6.3E+06	7.8E+06	6.3E+06	4.5E+17	5.1E+17	6.3E+17	5.1E+17
Nuclear (MJ)	N_f	2.00E+11	1.4E+06	1.5E+06	1.4E+06	1.4E+06	2.9E+17	3.0E+17	2.9E+17	2.9E+17

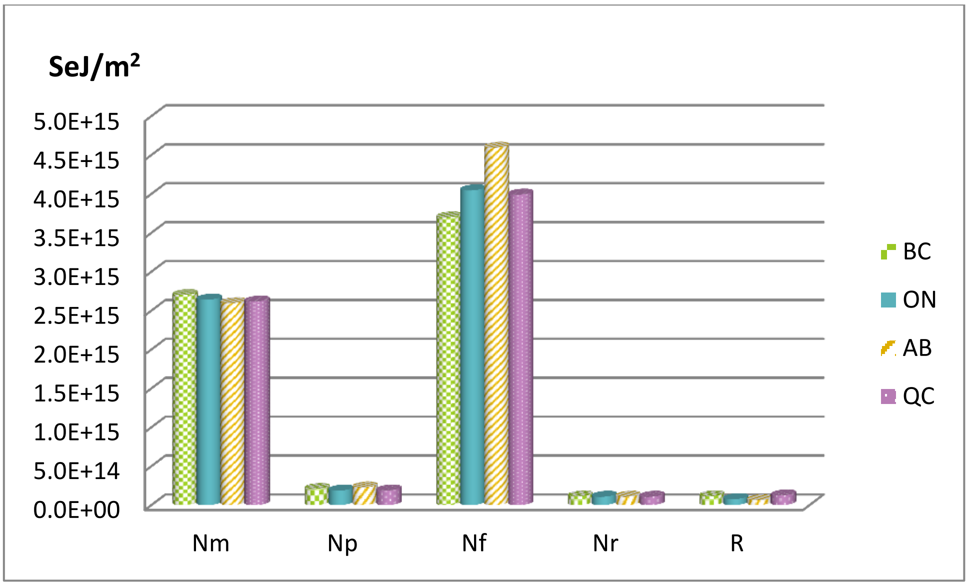


Figure 4-9 Upstream impacts for single-family house in different provinces of Canada

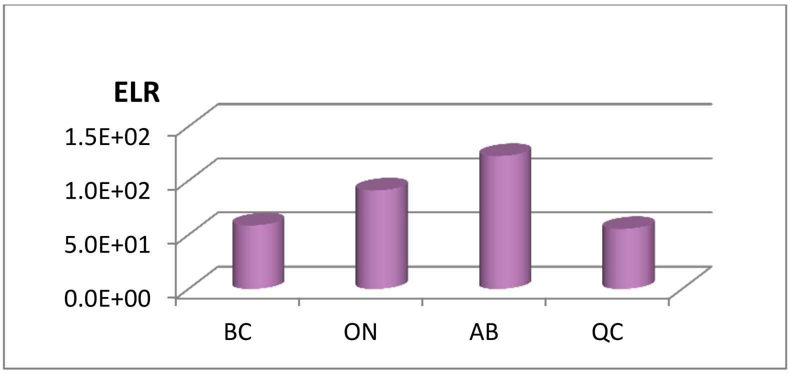


Figure 4-10 Environmental Loading Ratio (ELR) for single-family house in different provinces of Canada

Emergy equivalent of upstream impacts for multi-unit residential building in different provinces of Canada has been summarized in Table 4-15. The results of upstream impacts have been aggregated to calculate emergy-based indicators to compare the cumulative effects of multi-unit residential building in different provinces of Canada. Figure 4-11 indicates that the amount of mineral resource (N_m) use for multi-unit residential buildings in 4 provinces is slightly the same. However, multi-unit residential building in BC consumes more mineral resources as compared to other provinces as a result of higher seismic risk in Vancouver, BC. On the other hand, a multi-unit residential building in AB consumes more petroleum fuel resources (N_p) and less renewable resources (R). Moreover, a multi-unit residential building in ON consumes significantly higher non-petroleum fuel (N_F). Consequently, while the yield emergy (Y) of a multi-unit residential building in ON is higher than other provinces (see

Figure 4-12) a multi-unit residential building in AB cause greater ELR that shows life cycle energy consumption in AB is less sustainable as compared to the other provinces (see Figure 4-13).

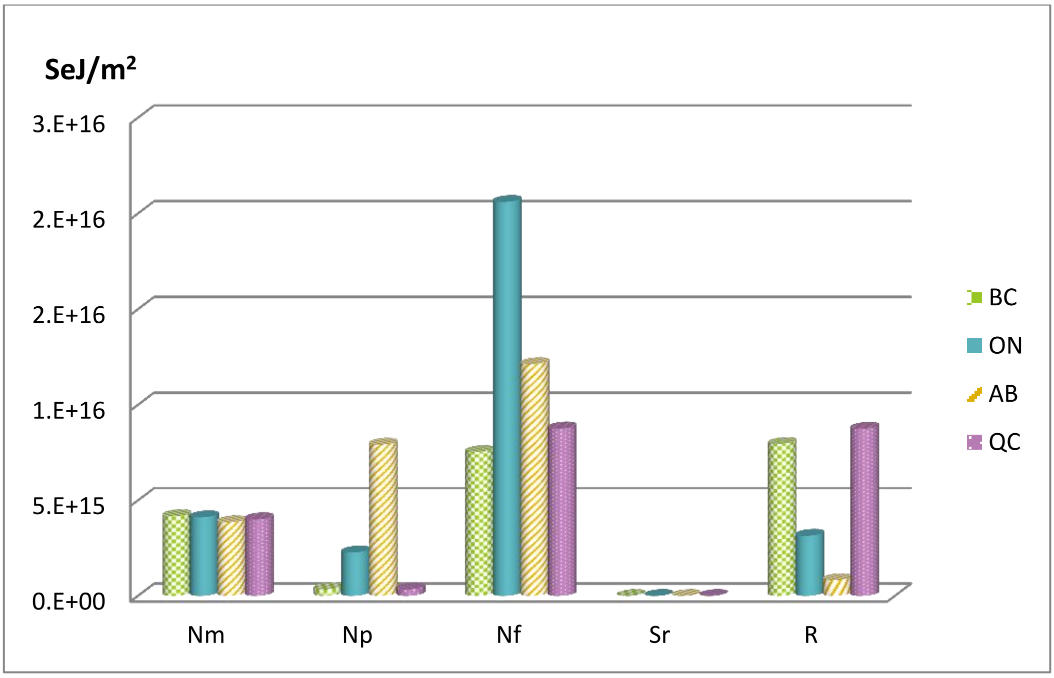


Figure 4-11 Upstream impacts for multi-unit residential in different provinces of Canada

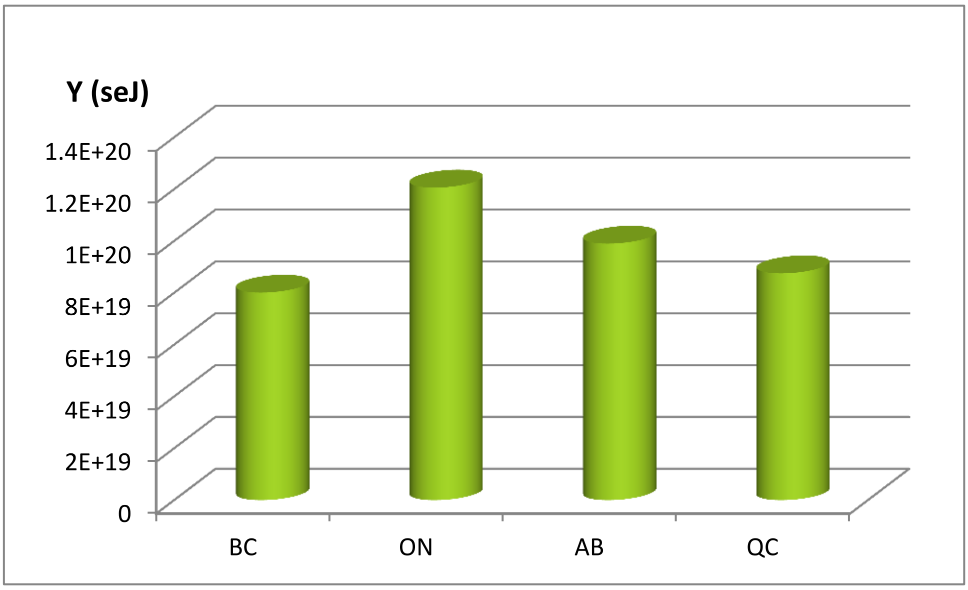


Figure 4-12 Yield emergy (Y) for multi-unit residential in different provinces of Canada

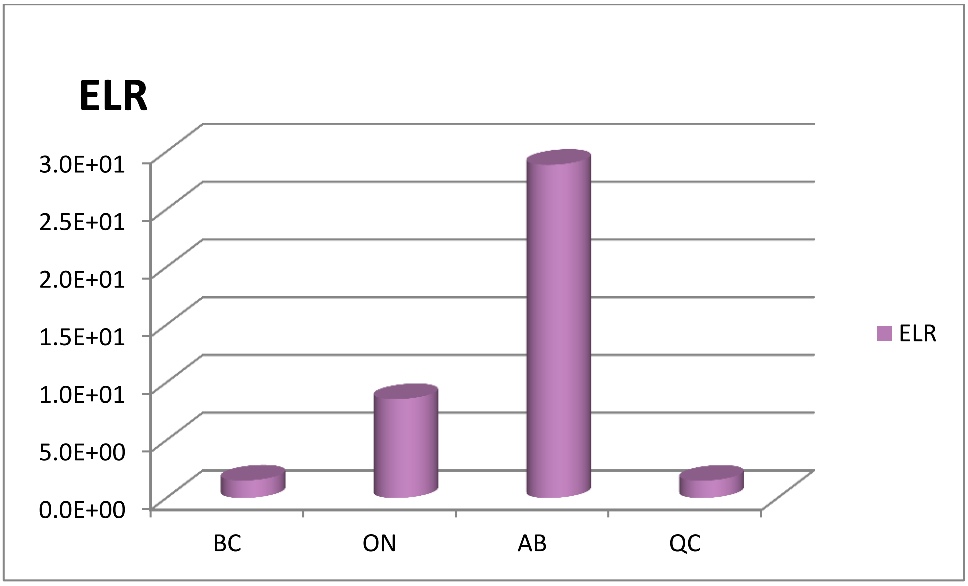


Figure 4-13 Environmental Loading Ratio for multi-unit residential in different provinces of Canada

In addition emergy-based indicators for two types of building have been compared in different Canadian provinces as it was shown in Figure 4-14 to Figure 4-20. Results shows that life cycle resource use or upstream impacts caused by different building types in 3 other Canadian provinces (AB, ON, and QC) follow the same pattern as for BC.

Table 4-15 Emergy equivalent of resources use or upstream impacts for multi-unit residential in different provinces of Canada

Resources (Unit)	*Type*	*UEV (seJ/unit)*	*Resource Input (Unit)*				*Emergy (seJ)*			
			BC	ON	AL	QC	BC	ON	AL	QC
Limestone (kg)	N_m	1.69E+12	1181175.2	1442802.7	1330154.8	1316073.8	2.0E+18	2.4E+18	2.2E+18	2.2E+18
Clay & Shale (kg)	N_m	4.10E+12	300974.6	56904.0	22170.9	174245.7	1.2E+18	2.3E+17	9.1E+16	7.1E+17
Iron Ore (kg)	N_m	4.43E+12	38380.5	46570.9	46570.9	18408.9	1.7E+17	2.1E+17	2.1E+17	8.2E+16
Sand (kg)	N_m	1.69E+12	179155.0	132218.4	113443.7	197929.7	3.0E+17	2.2E+17	1.9E+17	3.3E+17
Ash (kg)	N_m	2.35E+13	9388.2	28162.8	0.8	0.8	2.2E+17	6.6E+17	1.9E+13	1.9E+13
Gypsum (Natural) (kg)	N_m	1.69E+12	3997.0	3997.0	3997.0	3997.0	6.8E+15	6.8E+15	6.8E+15	6.8E+15
Gypsum (Synthetic) (kg)	N_m	2.35E+13	5636.1	5636.1	5636.1	5636.1	1.3E+17	1.3E+17	1.3E+17	1.3E+17
Semi-Cementitious Material (kg)	N_m	3.70E+12	157236.5	157236.5	157236.5	157236.5	5.8E+17	5.8E+17	5.8E+17	5.8E+17
Coarse Aggregate (kg)	N_m	1.69E+12	3546773.2	3546773.2	3546773.2	3546773.2	6.0E+18	6.0E+18	6.0E+18	6.0E+18
Fine Aggregate (kg)	N_m	1.69E+12	2299007.5	2299007.5	2299007.5	2299007.5	3.9E+18	3.9E+18	3.9E+18	3.9E+18
Water (L)	N_r	2.10E+09	3465676.7	3334983.3	3334983.3	3334983.3	7.3E+15	7.0E+15	7.0E+15	7.0E+15
Obsolete Scrap Steel (kg)	N_m	7.80E+12	171644.1	165148.4	165148.4	165148.4	1.3E+18	1.3E+18	1.3E+18	1.3E+18
Prompt Scrap Steel as feedstock(kg)	N_m	7.80E+12	109745.1	105605.0	105605.0	105605.0	8.6E+17	8.2E+17	8.2E+17	8.2E+17
Wood Fiber (kg)	N_r	1.40E+12	120.4	120.4	120.4	120.4	1.7E+14	1.7E+14	1.7E+14	1.7E+14
Metallurgical Coal as feedstock (kg)	N_p	1.69E+12	3914.3	3386.9	3386.9	3386.9	6.6E+15	5.7E+15	5.7E+15	5.7E+15
Natural Gas as feedstock (MJ)	N_f	8.05E+10	10580.8	402310.7	402310.7	402310.7	8.5E+14	3.2E+16	3.2E+16	3.2E+16
Crude Oil as feedstock (MJ)	N_p	9.27E+10	12079.7	505426.1	505426.1	505426.1	1.1E+15	4.7E+16	4.7E+16	4.7E+16
Hydro (MJ)	R	2.67E+11	119246295.9	47210486.2	12416210.5	131118864.7	3.2E+19	1.3E+19	3.3E+18	3.5E+19
Coal (MJ)	N_p	6.71E+10	6728321.3	112838124.4	438831944.0	3174936.6	4.5E+17	7.6E+18	2.9E+19	2.1E+17
Diesel (MJ)	N_p	1.21E+11	6284053.9	10169764.1	15983199.0	6459428.9	7.6E+17	1.2E+18	1.9E+18	7.8E+17
Gasoline (MJ)	N_p	1.11E+11	22.4	19.4	19.4	19.4	2.5E+12	2.2E+12	2.2E+12	2.2E+12
Heavy Fuel Oil (MJ)	N_p	1.11E+11	1374326.9	2173354.1	1898095.1	2991768.3	1.5E+17	2.4E+17	2.1E+17	3.3E+17
LPG (MJ)	N_p	8.05E+10	102918.4	254262.7	567761.1	118608.2	8.3E+15	2.0E+16	4.6E+16	9.5E+15
Natural Gas (MJ)	N_f	8.05E+10	244755148.6	398617480.2	473054623.8	294264474.5	2.0E+19	3.2E+19	3.8E+19	2.4E+19
Nuclear (MJ)	N_f	2.00E+11	52249424.0	251528159.6	52192005.8	56748102.9	1.0E+19	5.0E+19	1.0E+19	1.1E+19

The multi-unit residential buildings consume more non-renewable and renewable resources (N_m, N_f, N_P, R) than single-family houses in 4 provinces. But single-family houses consume more slowly-renewable resources through their life cycle (as they have wood-frame structure). The yield emergy (total life cycle emergy) per unit area of multi-unit residential buildings is ~3 - 4.5 times greater than the single-family houses in different Canadian provinces.

On the other hand, the Environmental Loading Ratio (ELR), which indicates total emergy loss plus nonrenewable and invested emergy released per unit of local renewable resource, for the single-family houses is always greater than ELR for multi-unit residential buildings. ELR for the single-family house in BC is about 40 times greater than multi-unit residential building, while in AB it's about only 4 times more intensive than multi-unit residential building. This is because the electricity in BC is hydro, which is a renewable energy source, while a significant portion of electricity in AB produces from fossil fuel resources such as coal (see Table 4-15).

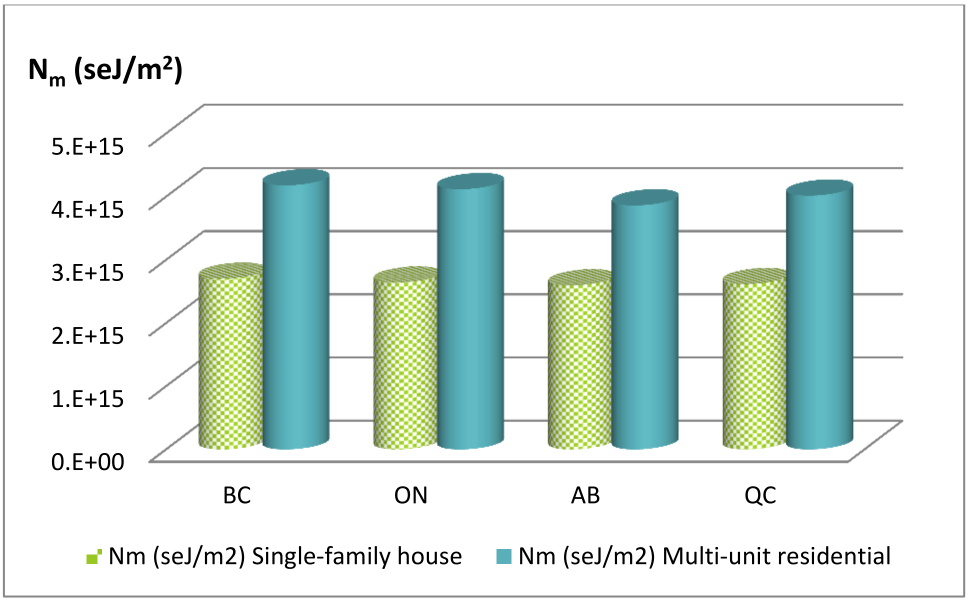


Figure 4-14 Emergy equivalent of non-renewable mineral (Nm) use for single-family houses and multi-unit residential buildings

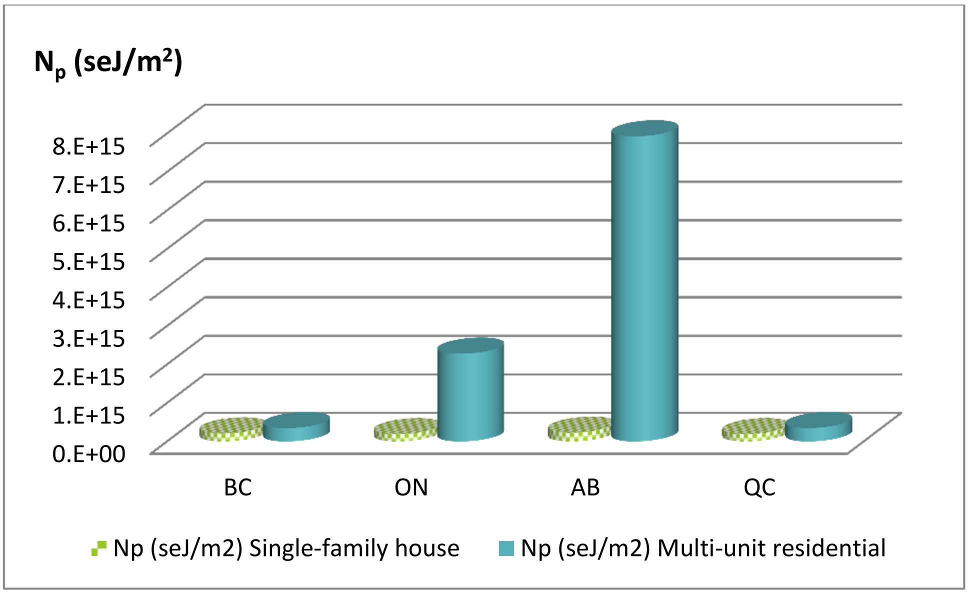


Figure 4-15 Emergy equivalent of non-renewable petroleum (N_p) use for single-family houses and multi-unit residential buildings

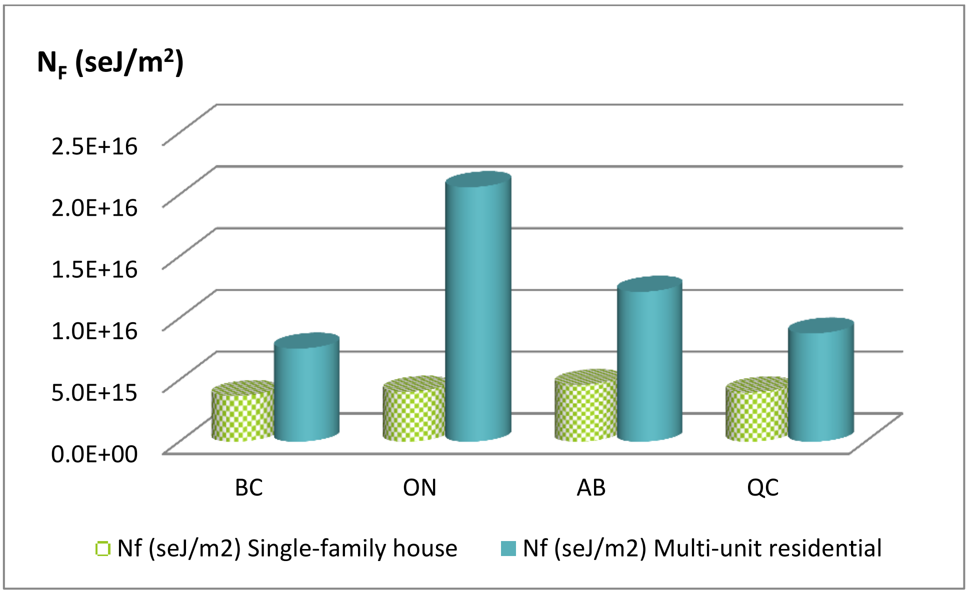


Figure 4-16 Emergy equivalent of non-petroleum fuel (N_F) use for single-family houses and multi-unit residential buildings

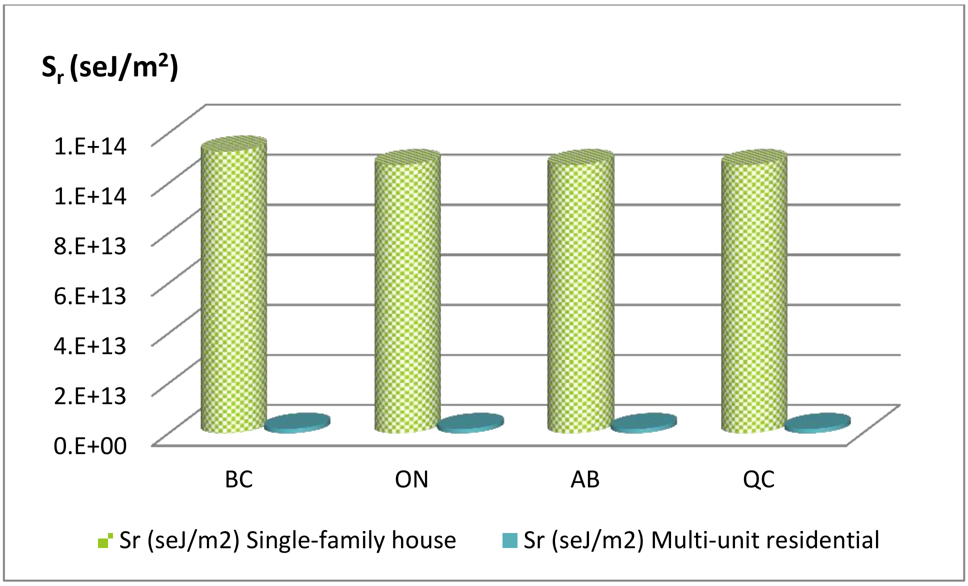


Figure 4-17 Emergy equivalent of slowly-renewable natural resource (S_s) use for single-family houses and multi-unit residential buildings

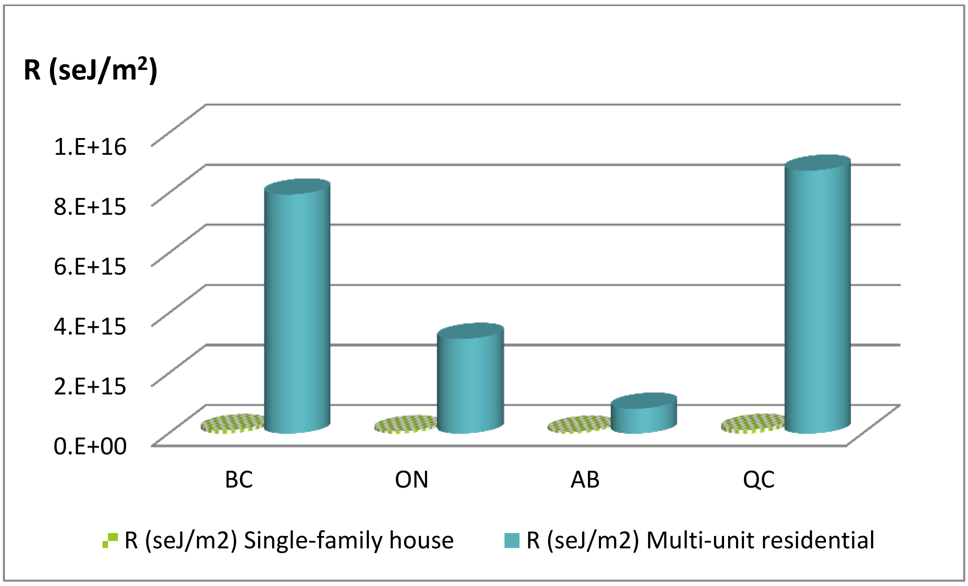


Figure 4-18 Emergy equivalent of renewable natural resource (R) use for single-family houses and multi-unit residential buildings

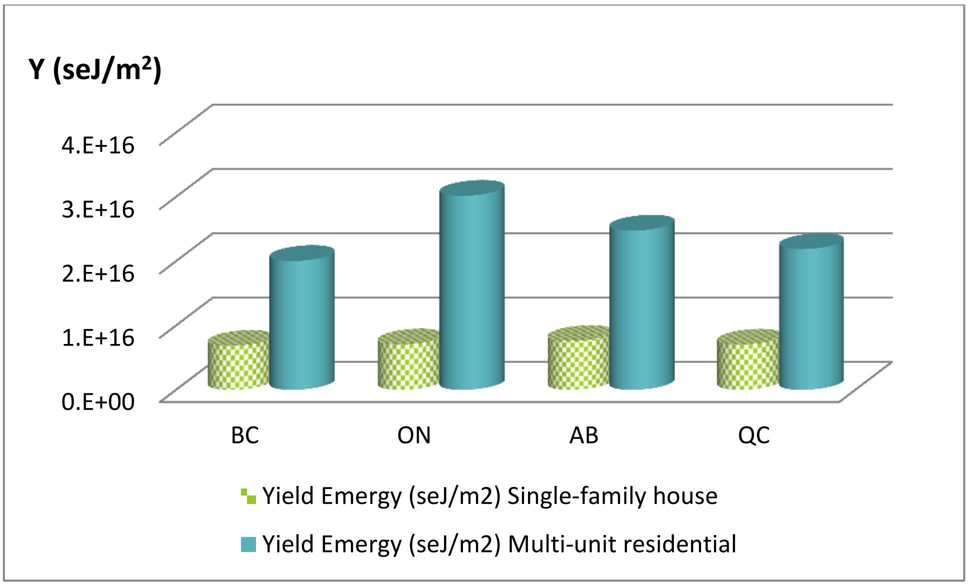


Figure 4-19 Yield emergy (Y) for single-family houses and multi-unit residential buildings

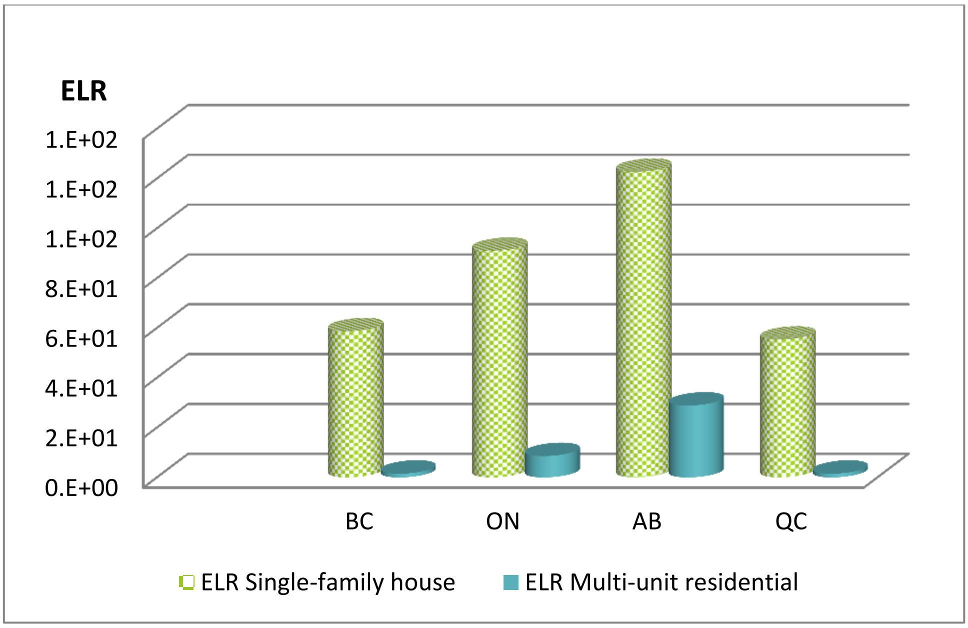


Figure 4-20 Environmental Loading Ratio (ELR) for single-family houses and multi-unit residential buildings

Ultimately, a sensitivity analysis has been conducted for buildings' annual operational energy use as the largest emergy inputs to the building system (refer to Figure 4-3). The sensitivity analysis has been done assuming a variation of the energy input and related UEVs by ±10%, ±20%,…, ±50%, and assessing to what extent such a variation affected the final conclusion (e.g., see Figure 4-21and 4-22). Results of sensitivity analysis in this study verify that the final conclusions are analogous and in all cases multi-unit residential buildings cause greater yield emrgy (seJ/m^2) while bring about a smaller environmental loading ratio (ELR). In other words, multi-unit residential buildings in Canada consume significantly higher life cycle material and energy per unit area (yield emergy) and cause greater associated emission impact. However, they consum energy in a more sustainable manner (use more renewable sources) as compare to the single-family house. As a result, considering all emergy indices, single-family house can be a more sustainable option in Canada if the source of service life energy replace by a local renewable energy resource such as hydroelectricity.

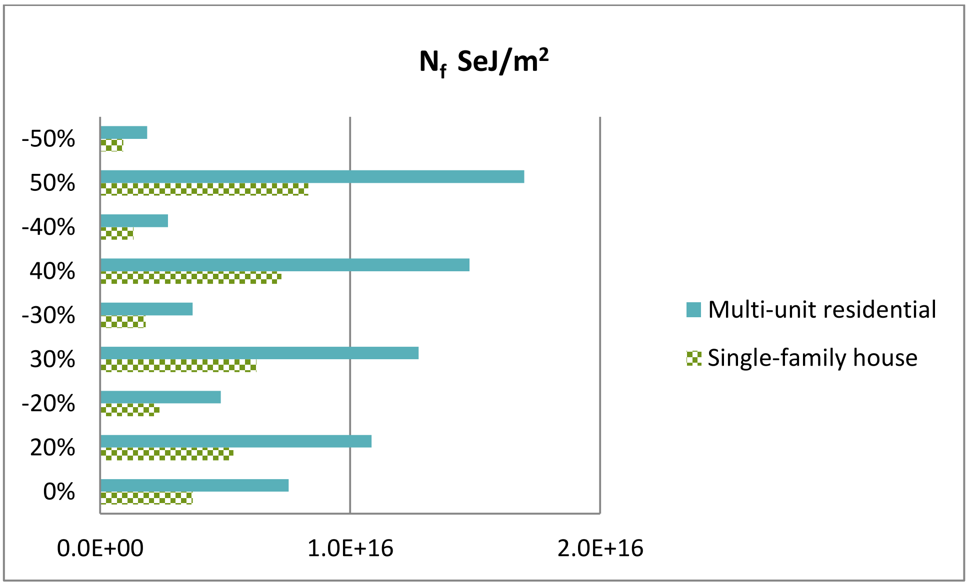


Figure 4-21 Sensitivity analysis (effect of variable annual operational energy on N_f index)

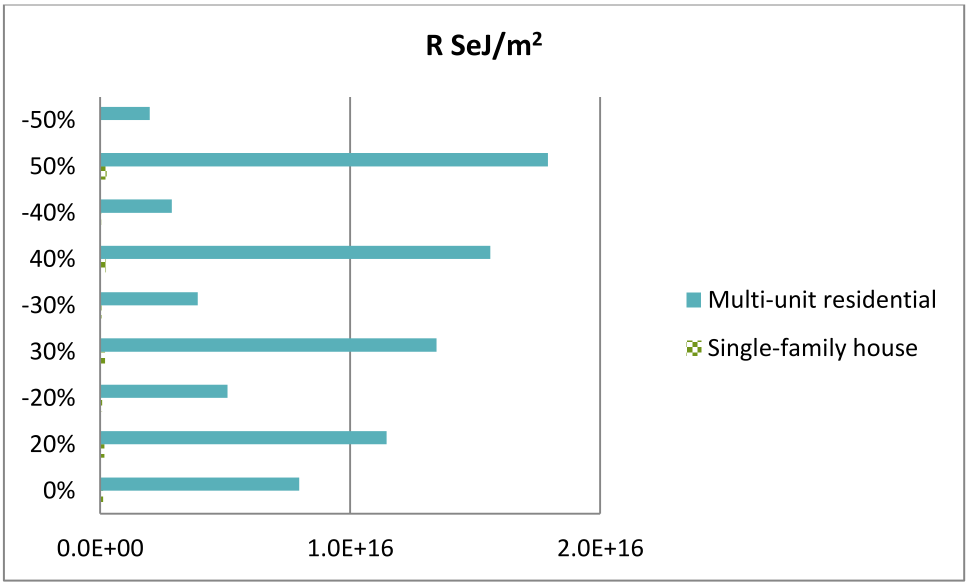


Figure 4-22 Sensitivity analysis (effect of variable annual operational energy on R index)

4.3 Summary

In this chapter the implementation of the proposed Em-LCA framework for building systems has been explored. Em-LCA was applied as a holistic assessment tool in order to document both direct and indirect ecological and human health impacts (environmental impacts) of building system by considering the planet‘s ecological assets (bio-capacity) for resource production and waste/emission assimilation. In addition, one of the most important characteristic of Em-LCA is that, it can develop a link that connects economic and ecological systems and convert all energy, mass, and money flows and their associated environmental and socio-economic impacts to a single energy unit.

Em-LCA provides a comparative quantitative framework for sustainability appraisal of building systems with minimum subjectivity (human judgment). It also provides a set of quantitative sustainability indicators for building systems to aggregate cumulative effects of life cycle environmental and socio-economic impacts and to advocate sustainable use of natural resources. Ultimately, Em-LCA for building systems delivers a quantitative characterization of building metabolism (resource input and emission/waste output) and their associated TBL impacts that can be used to support long-term decision-making related to building industry and asset management. These include, but not limited to, the following decisions:

- Selecting the most sustainable type of building development (multi-uni, single-family, townhouse, condominium, etc.) for different region and based on different scenarios (e.g. service life energy and structural system)
- Selecting the most sustainable building structural system (e.g. wood-frame, concrete-frame, steel-frame, hybrid, etc.) based on the different scenarios (regional resources, transportation, manufacturing, climate, etc.)
- Selecting the most sustainable building material based on the different scenarios (regional resources, transportation, manufacturing, climate, etc.)
- Selecting the most sustainable and high efficiency operation energy system (e.g., natural gas, electricity, geothermal, solar) for building energy supply, storage, co-generation, distribution, and recovery (e.g. sewer heat recovery) based on the different scenarios (regional resources, climate, etc.).

Chapter 5 Em-LCA Framework for Sustainability Appraisal of Road Systems[19]

5.1 Overview

Civil infrastructure systems (CIS) (e.g., roads, bridges, water supply, wastewater, and transit systems) have been developed to respond to the increasing demands of growing population, rapid urbanization, and the needs to establish safe and sustainable urban and inter-urban infrastructure facilities. They provide basic and core services at municipal, regional, provincial, and federal levels and are critical for any country's socio-economic development (Lounis et al. 2010).

In Canada, over 80% of the public infrastructure including 85% of roads and bridges will reach to the 'end of life' or need to be repaired by 2030 (CIC, 2009). The Federal Government recently announced an investment of $12-billion in new civil infrastructure, and $7.8-billion for renovating and rehabilitating existing infrastructure (CEAP-B, 2009). Although the completion of these infrastructure projects will help improve the quality of life for all Canadians, the short- and long-term impacts of civil infrastructure assets and their services on public health & safety and on the environment are also important considerations. Figure 5-1 provides a snapshot of the distribution of infrastructure value in Canada (CIC, 2009).

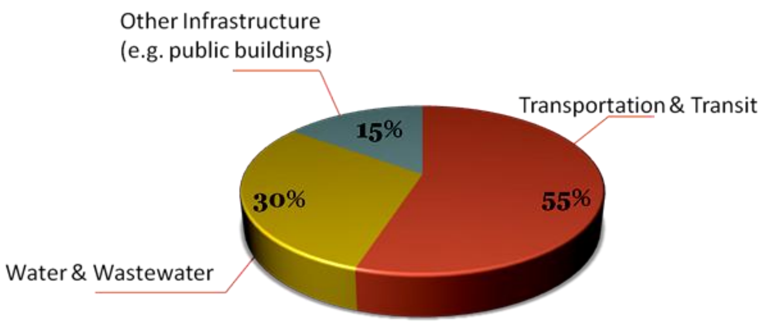


Figure 5-1 Distribution of infrastructure value in Canada

[19] A version of this chapter published by Clean Technologies and Environmental Policy (Reza et al. 2013a)

National Guide to Sustainable Municipal Infrastructure (InfraGuide 2003) has stated that *existing Canadian infrastructure is ageing while demand grows for more and better roads, and improved transportation systems responding both to higher standards of safety, health and environmental protection as well as population growth.* The aging and increased demands on these assets and the construction of new assets present major environmental, technical, and economic challenges to the owners of public infrastructure; more specifically, the great challenge is to assess the current and future conditions of their assets in an objective and quantifiable manner (Reza et al. 2011). Reliable predictions of the current and future conditions of the assets are of utmost importance for the prediction of their life cycle environmental impacts and socio-economic costs over their service lives. Such prediction can provide adequate information to make policy decision for construction and development of new CIS as well as asset rehabilitation and maintenance.

Motivation for this study stems from the recognition of the fact that applying an accurate sustainability appraisal framework over the life cycle of the core public infrastructure systems is critical to develop effective and sustainable asset management plans that will ensure adequate safety, serviceability, functionality, and optimized allocation of limited funds over their life span. In this study, Em-LCA framework has been used to assess the sustainability of linear civil infrastructure systems. Accordingly two different scenarios for a road construction project in interior BC (Canada) have been selected.

5.2 Em-LCA scope and system diagram boundary

A roadway project, located in a small community in the district of Peachland, British Columbia (Canada), has been selected. The project area, District of Peachland and surrounding Okanagan Valley, is widely recognized as an ecologically diverse and sensitive area that is experiencing rapid population growth. In general, the proposed project area has complex topography with many steep slopes and gullies, is comprised of sensitive ecological communities with minimal evidence of disturbance, provides habitat for rare and endangered wildlife, and is considered one of the highest quality deer winter range in the province.

The selected roadway project has been designed to serve as a new dedicated access to a housing project, alleviating traffic and safety concerns with the existing accesses. The housing project encompasses approximately 400 acres that will provide 2310 residential units, plus a commercial node and many amenity features to residents and the community at large.

There were two different design scenarios for this roadway project namely **A** and **B**. Plan **A** is 1,150 meters long, with 2-lane width 8.6 meters through environmentally sensitive areas due to flora and fauna. Plan **B** is a longer road around natural barriers, approximately 2,450 meters in length, and has 8.6 meters pavement width. The construction method for both scenarios is open cut blasting. In addition, the designed plan of Road **A** shows that, it will cross Ada Creek at the lower section where there is an existing culvert. As a result, it needs retaining walls on the slopes which require top-down excavation and shotcrete retaining. To sum up, plan **A** is a shorter road which can cause more soil loss and deforestation during construction phase, while plan **B** is a longer road that may cause more operational energy and emission impact.

The major goal of this study is to evaluate environmental and associated socio-economic impacts of two road scenarios over their life cycle (cradle to grave). The main inflows and outflows of the roadway life cycle that will be considered in this study have been simulated as energy pathways in the roadway energy system diagram to visualize the flows and their interaction (Figure 5-2).

5.3 Inventory analysis

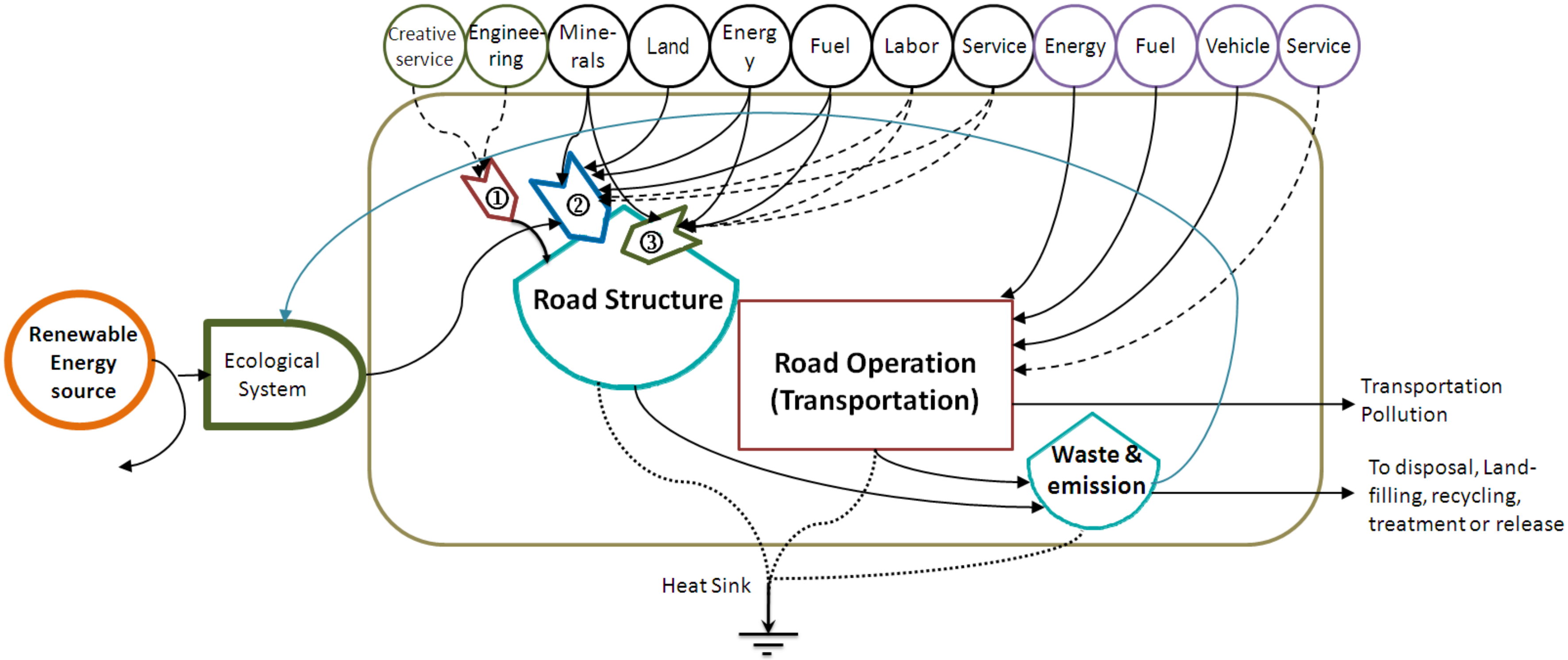
In this step, the inputs and outputs of each life cycle phases and relevant processes of two roadway scenarios are compiled. In this study, Athena Impact Estimator for Highways has been used as a Canadian LCI data base. Then the absolute values of resource use, energy consumption and emission to air, water and land compartment has been used for the impact assessment step. The Athena Impact Estimator provides LCI results for the materials manufacturing, roadway construction and maintenance life cycle stages. It allows custom roadway design and includes a large materials database and the flexibility to specify unique pavements. It is possible to identify use-phase energy loads, if desired, to be included in the final LCI results (Athenasmi 2012). Accordingly, it is possible to provide a complete set of LCI considering all required transportation, material use, rehabilitation and maintenance activities, construction machineries, operational energy and fuel consumption (through roadway use phase), and all other relevant processes and activities over the life cycle a roadway.

Athena Impact Estimator has been run considering the period of 50 years life-span for the general Canadian roadway design, in order to have a same functional unit for each of the design options. In addition, to attain this 50 years design-life for each of the roads' pavement, proper rehabilitation and maintenance was considered. An average distance of 50 km for site to stockpile, plant to site, and equipment depot to site has been considered.

Roadway typical cross section and design details have been shown in Figure 5-3. Minor and routine roadway maintenance includes activities such as joint and crack sealing and patch repairs has been analyzed. In addition, pavement rehabilitation activities have been considered at years 18 and 35 (Weiland 2011). The first pavement rehabilitation (at year 18) expected to implicate removing 40 mm of the existing asphalt and replacing it with one 50 mm lift of asphalt. The second overlay (at year 35) is assumed to involve removing 80 mm of the existing asphalt and replacing it with 100 mm of placed in two lifts. In addition replacing 100 mm concrete for sidewalk have been assumed. All these activities are reported as a total maintenance stage.

All absolute value for manufacturing, construction, maintenance, and operation phases has been measured by Athena LCI. In addition to Athena LCI result for resource use, the amount of loss of soil organic matter and loss of boreal forest biomass has been evaluated based on project information and project environmental analysis report. For soil loss, weight of 1 meter depth of total excavation has been multiplied by 3% of organic substance, 22.6 kilo joule energy content per each gram of soil organic matter. To evaluate loss of boreal forest biomass 80% deforestation per construction area has been considered for Scenario A, while 20% deforestation per construction area has been considered for Scenario B. The average weight of 5.19 kg dray weight boreal forest and 1.1 g dry weight deer has been considered per m^2 of area with the average of 25 kilo joule energy content per each gram of biomass.

The data inventory of each roadway scenario has been compiled and summarized into the emergy evaluation table. The absolute values of resource use, energy consumption and emission to the air, water and land will be used later for the impact assessment step.

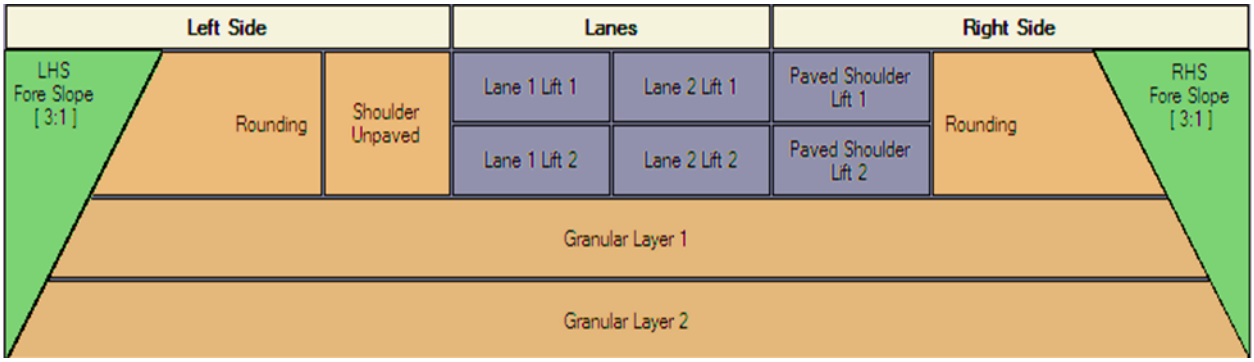


① Inflow from design phase

② Inflow through road sitepreparation and construction phase

③ Inflow through road maintenance and rehabilitation phase

Figure 5-2 Energy system diagram of a paved road life cycle



Element Name	Material	Width [m]	Thickness [mm]
Granular Layer 1	Granular A	12	150
Granular Layer 2	Granular B Type II	12.6	300
Lane 1 Lift 1	Superpave 25.0	4.3	40
Lane 1 Lift 2	Superpave 25.0	4.3	60
Lane 2 Lift 1	Superpave 25.0	4.3	40
Lane 2 Lift 2	Superpave 25.0	4.3	60
Left Side Rounding	Clear Stone 13.2	1.5	100
Left Side Shoulder Unpaved	RAP Aggregate	1.5	100
Right Side Rounding	Clear Stone 13.2	1.5	100
Right Side Shoulder Paved Lift 1	Concrete PC 30 MPa (flyash 25%)	1.5	40
Right Side Shoulder Paved Lift 2	Concrete PC 30 MPa (flyash 25%)	1.5	60

Figure 5-3 Typical roadway cross section designed in Athena

5.4 Data analysis and impact assessment

In this step, the life cycle inflows and outflows of the two roadway scenarios (plan A and B) have been converted to their emergy value. Unit Emergy Values (UEVs) have been extracted from online transformity database (ISAER 2012), and then all input flows in the inventory have been converted into emergy values. All the UEVs in this research have been adopted based on global biosphere Emergy baseline of 15.83×10^{24} sej/yr suggested by Odum (2000).

In this study, the Em-LCA technique considers all three impact categories: (1) recourses inputs or upstream impacts including renewable and non-renewable resources; (2) waste and emission or downstream impacts; and (3) associated socio-economic impacts including monetary costs and purchased labor and services.

Recourses inputs (upstream impacts) to the buildings life cycle are quantified as energy resources for geo-biosphere work and services needed for resources formation as it was discussed in 3.5.1. Emergy equivalent of resources use or upstream impacts for scenario A. have been summarized in Table 5-1. Results indicate that the most intensive upstream impact is due to use of heavy fuel oil and gasoline. On the other hand, despite the fact that scenario A can lead to a huge deforestation thorough its construction path, the associated impact (see emerge value as a result of loss of topsoil, boreal forest and wildlife habitat in Table 5-1) is not as significant as compared to petroleum and non-petroleum energy consumption (see emerge value as a result of N_f and N_p in Table 5-1).

The consequences of airborne and waterborne emissions and solid waste generation that can cause during the life cycle of a roadway have been quantified based on two main potential effects that can harm ecosystem, people, and economy: (1) the natural and human capital losses cause by emissions or preliminary damage and (2) the ecological services needed to dilute air and water emissions as it was explained in 3.5.2.

Table 5-2 and Table 5-3 indicate downstream impact assessment for emission to air and water for the understudied road system (Plan A). Athena LCI provides complete list of chemical and substance by-products released to the air/water. However, in order to reduce the volume of calculations, the result was shown only for air/water pollutants with a noticeable environmental impacts and considerable effects in final results (this was test through a preliminary sensitivity analysis). The result of emergy loss due to solid waste discharge into the land associated by the understudied road system (Plan A) has been summarized in Table 5-4.

Moreover, the life cycle cost has been determined by means of monetary cost of labors and services along the examined roadway life cycle as it was discussed in 3.5.3. Table 5-5 indicates emergy equivalent of labors and services for understudied road system (Plan A). Emergy value for local services (i.e. design and tendering, and vehicle ownership cost) and labor has been accounted for based on local currency (BC Emergy/GDP is 2.67E+12 sej/CAD$ (Hossaini and Kasun Hewage 2013). While, Emergy value for other services (i.e. construction, maintenance, rehabilitation and operation related services) associated with national flows of material and energy inputs has been determined based on national currency (Canada Emergy/GDP is 4.22E+12 sej/CAD$ (Hossaini and Kasun Hewage 2013).

Table 5-1 Emergy equivalent of resources use or upstream impacts (Plan A)

Resources (Unit)	*Type*	*UEV[20] (sej/unit)*	*Manufacturing*	*Construction*	*Maintenance*	*Operating*		*Total*	*Emergy (EseJ)*
						Annual	**Total**		
Limestone (kg)	Nm	1.69E+12	8.4E+04	-	-	-	-	8.4E+04	1.4E-01
Clay & Shale (kg)	Nm	4.10E+12	8.9E+03	-	-	-	-	8.9E+03	3.6E-02
Iron Ore (kg)	Nm	4.43E+12	1.8E+03	-	-	-	-	1.8E+03	7.9E-03
Sand (kg)	Nm	1.69E+12	2.9E+03	-	-	-	-	3.0E+03	5.0E-03
Ash (kg)	Nm	2.35E+13	4.6E-03	-	-	-	-	4.6E-03	1.1E-07
Gypsum (kg)	Nm	1.69E+12	4.7E+03	-	-	-	-	4.7E+03	8.0E-03
Coarse Aggregate (kg)	Nm	1.69E+12	9.2E+05	-	-	-	-	9.2E+05	1.6E+00
Fine Aggregate (kg)	Nm	1.69E+12	2.8E+07	-	-	-	-	2.8E+07	4.7E+01
Water (L)	Sr	2.10E+09	3.3E+05	-	-	-	-	3.3E+05	6.9E-04
Obsolete Scrap Steel (kg)	Nm	7.80E+12	2.6E+04	-	-	-	-	2.7E+04	2.1E-01
Coal (MJ)	Nf	6.71E+10	8.0E+04	5.7E+04	5.3E+02	7.6E+05	3.8E+07	3.8E+07	2.5E+00
Wood Fiber (kg)	Sr	1.40E+12	3.1E-01	-	-	-	-	3.1E-01	4.4E-07
Nuclear MJ	Nf	2.00E+11	4.3E+03	1.5E+04	1.4E+02	2.2E+05	1.1E+07	1.1E+07	2.2E+00
Natural Gas (MJ)	Np	8.05E+10	7.7E+05	3.5E+05	3.2E+03	6.2E+06	3.1E+08	3.1E+08	2.5E+01
Natural Gas as feedstock (m3)	Np	8.05E+10	2.3E+04	-	-	-	-	2.3E+04	1.8E-03
Diesel (MJ)	Np	1.21E+11	5.0E+05	8.6E+06	5.1E+04	3.4E+05	1.7E+07	1.7E+07	2.1E+00
Crude Oil as feedstock (MJ)	Np	9.27E+10	1.3E+07	-	-	-	-	1.3E+07	1.2E+00
Prompt Scrap Steel as feedstock (kg)	Nm	7.80E+12	1.7E+04	-	-	-	-	1.7E+04	1.3E-01
Electricity (MJ)	Nf	3.35E+11	3.0E+05	0.0E+00	0.0E+00	2.5E+07	1.2E+09	1.2E+09	4.2E+02
Hydro (MJ)	R	2.67E+11	3.0E+05	3.9E+03	3.6E+01	2.5E+07	1.2E+09	1.2E+09	3.3E+02
Gasoline (MJ)	Np	1.11E+11	1.5E+04	0.0E+00	0.0E+00	8.4E+08	4.2E+10	4.2E+10	4.7E+03
LPG (MJ)	Np	8.05E+10	2.4E+05	8.6E+03	7.9E+01	5.0E+04	2.5E+06	2.8E+06	2.2E-01

[20] For UEV database see http://emergydatabase.org

Heavy Fuel Oil (MJ)	Np	1.11E+11	6.0E+05	1.9E+05	1.7E+03	1.1E+06	5.3E+07	2.7E+11	3.0E+04
Loss of Topsoil (J)	Sr	1.05E+05	-	2.0E+14	0.0E+00	0.0E+00	0.0E+00	2.0E+14	2.0E+01
Loss of Boreal Forest (J)	Sr	8.27E+03	-	1.9E+12	0.0E+00	0.0E+00	0.0E+00	1.9E+12	1.5E-02
Loss of Wildlife Habitat (Deer) (J)	Sr	7.52E+06	-	4.9E+08	0.0E+00	1.7E+10	8.4E+11	1.7E+10	1.3E-01

Table 5-2 Emergy equivalent of air emissions or downstream impacts (Plan A)

Airborne Pollution	***Damage Category HH***	***DALY /g***	***Damage Category EQ***	***PDF %***	***Manufacturing***	***Construction***	***Maintenance***	***Operating***		***Total Effects***	***Emergy Loss (EseJ)***		***Ecological Services (EseJ)***
								Annual	**Total**		**EL_{HH}**	**EL_{EQ}**	**Es_{air}**
Carbon dioxide, biogenic (g)	Climate change	2.10E-10	–	–	3.3E+05	–	–	0.0E+00	0.0E+00	3.3E+05	1.2E-05	–	3.3E-09
Carbon dioxide, fossil (g)	Climate change	2.10E-10	–	–	1.8E+08	6.9E+08	6.1E+06	3.7E+09	1.8E+11	1.9E+11	6.7E+00	–	8.9E-03
Carbon dioxide, loss of biomass* (g)	Climate change	2.10E-10	–	–	–	1.2E+08	–	–	–	1.2E+08	4.5E-03	–	6.0E-06
Nitrogen oxides (g)	Respiratory disorders	8.87E-08	Acidification	5.71	6.9E+05	4.5E+06	4.1E+04	1.9E+07	9.7E+08	9.8E+08	1.5E+01	3.1E+00	5.9E-01
Sulfur dioxide (g)	Respiratory disorders	5.46E-08	Acidification	1.04	4.2E+05	1.7E+05	–	3.2E+06	1.6E+08	1.6E+08	1.5E+00	9.3E-02	2.0E-01
Sulfur oxides (g)	Respiratory disorders	5.46E-08	Acidification	1.04	7.6E+05	6.3E+05	5.5E+03	3.5E+06	1.8E+08	1.8E+08	1.7E+00	1.0E-01	2.1E-01
Particulates, 2.5 -10um (g)	Respiratory disorders	3.75E-07	–	–	2.2E+04	7.8E+04	7.0E+02	1.2E+05	6.0E+06	6.1E+06	4.0E-01	–	2.3E-03
Particulates, unspecified (g)	Respiratory disorders	3.75E-07	–	–	1.5E+06	5.1E+04	4.3E+02	3.2E+05	1.6E+07	1.8E+07	1.2E+00	–	6.6E-03
Methane (g)	Respiratory disorders	1.28E-11	–	–	1.3E+06	8.4E+05	6.7E+03	6.6E+06	3.3E+08	3.3E+08	7.4E-04	–	1.4E-04
Methane (g)	Climate change	4.40E-09	–	–	1.3E+06	8.4E+05	6.7E+03	6.6E+06	3.3E+08	3.3E+08	2.5E-01	–	–
VOC compounds (g)	Respiratory disorders	6.46E-10			3.3E+04	2.2E+05	2.0E+03	4.4E+06	2.2E+08	2.2E+08	2.4E-02	–	6.6E-02

* CO_2 content is equal to mass of biomass x 0.45 carbon contend per mass of bio mass x 3.67 mass conversion factor for carbon to carbon dioxide (ESA21 2012)

Table 5-3 Emergy equivalent of water emissions or downstream impacts (Plan A)

Waterborne Pollution	*Damage Category HH*	*DALY /g*	*Damage Category EQ*	*PDF%*	*Manufacturing*	*Construction*	*Maintenance*	*Operating*		*Total Effects*	*Emergy Loss (EseJ)*		*Ecological Services(EseJ)*
								Annual	**Total**		**EL_{HH}**	**EL_{EQ}**	**Es_{water}**
Arsenic, ion mg	Carcinogenic impacts	6.57E-05	Ecotoxicity	1.1E+01	3.2E+05	2.1E+05	1.8E+03	1.3E+06	6.3E+07	6.3E+07	7.2E-01	4.0E-04	3.8E-03
Cadmium, ion mg	Carcinogenic impacts	7.12E-05	Ecotoxicity	4.8E+02	5.0E+04	3.1E+04	2.7E+02	1.8E+05	9.2E+06	9.3E+06	1.2E-01	2.5E-03	2.8E-02
Cyanide mg	Carcinogenic impacts	4.60E-08	–	–	2.4E+03	5.4E+01	4.7E-01	3.3E+02	1.7E+04	1.9E+04	1.5E-07	–	1.1E-05
Lead mg	–	–	Ecotoxicity	7.4E+00	1.6E+06	4.4E+05	3.9E+03	2.6E+06	1.3E+08	1.3E+08	–	5.3E-04	3.9E-02
Mercury μg	–	–	Ecotoxicity	2.0E+02	1.4E+06	7.2E+05	6.4E+03	4.2E+06	2.1E+08	2.1E+08	–	2.3E-02	1.3E+01
Oils, unspecified mg	Carcinogenic impacts	4.16E-08	–	–	2.9E+07	1.7E+07	1.5E+05	1.1E+08	5.3E+09	5.3E+09	3.8E-02	–	3.2E-01

Table 5-4 Emergy equivalent of ecological lost due to solid waste discharge (Plan A)

Solid waste	*Manufacturing*	*Construction*	*Maintenance*	*Operating Energy*		*Total Effects*	*Land Occupation*	*Emergy Loss EL_{SW} (seJ)*
				Annual	**Total**			
Blast Furnace Slag (kg)	3.5E+03	-	-	-	-	3.5E+03	1.2E-07	1.3E+08
Blast Furnace Dust (kg)	1.0E+03	-	-	-	-	1.0E+03	3.6E-08	3.8E+07
Other Solid Waste (kg)	1.3E+04	7.2E+03	5.8E+01	4.8E+04	2.4E+06	2.4E+06	8.5E-05	9.0E+10

Labor and services have been considered for entire road life cycle, including prior activities to operation phase such as design, tendering and construction process, future expenditures after operation such as maintenance and rehabilitation services, as well as transportation specific cost such as average gas price, automobile price, insurance, and taxes through 50 years life cycle.

Result shows, the transportation services costs is the most intensive economic impact through the road life cycle. Transportation services only considered for residents assuming 2 vehicles per household (cars and light trucks), and a two roundtrip per vehicle per day. Vehicle ownership costs determined based on annual average cost for a vehicle per km in Canada (40 cent/car/km/yr including insurance, license and registration, depreciation, and car loan). In addition, vehicle operation cost has been calculated based on average fuel consumption and maintenance of residents' vehicle and average Canadian automobile operation cost (12 cent/car/km/yr including fuel, maintenance and tire costs) (CAA 2011). Considering equal and constant total number of vehicle for the understudied roadway, transportation cost would be highly sensitive to length of road for Plan A and B (longer distances bring about more fuel consumption, vehicle deterioration, and associated cost).

5.5 Flow summary and calculation of indices

In the final step, the emergy of different items of road life cycle are combined and aggregated to obtain different emergy-based indicators to compare the two different scenarios. The aggregated result for emergy flows and emergy-based impact indicators have been summarized and indicated for the both road system scenarios has in Table 5-6 and Figure 5-4.

Results from Table 5-6 indicate that non-renewable petroleum fuel is the most intensive emergy flow as a consequence of 50 years operation phase of the road system. Emergy equivalent of human health loss is the most intensive downstream impact which is highly sensitive to NO_x emission during roadway operation phase. From the emergy comparison of the two scenarios, Plan A and B, was found out that, Plan B can be performed with 95% more resource inputs (renewable and non-renewable) and 85% more emission impacts, as compared to Plan A.

Table 5-5 Emergy equivalent of labor and services (Plan A)

Purchased Input	*Type*	*UEV (sej/$)*	*Design*	*Construction*	*Maintenance*	*Operating*		*Total*	*Emergy (EseJ[21])*
						Annual	**Total**		
Design and tendering services	F_s	2.67E+12	3.3E+05	-	-	-	-	3.3E+05	8.8E-01
Construction Services	F_s	4.22E+12	-	2.7E+06	-	-	-	2.7E+06	1.2E+01
Maintenance and rehabilitating services	F_s	4.22E+12	-	-	1.1E+06	-	-	1.1E+06	4.5E+00
Labor works	F_L	2.67E+12	-	1.5E+05	5.9E+04	-	-	2.1E+05	5.6E-01
Engineering and management works	F_L	2.67E+12	-	4.0E+04	1.6E+04	-	-	5.6E+04	1.5E-01
Vehicle Ownership cost	F_s	2.67E+12	-	-	-	1.6E+06	7.8E+07	7.8E+07	2.1E+02
Vehicle operation cost	F_s	4.22E+12	-	-	-	4.7E+05	2.3E+07	2.3E+07	9.8E+01

[21] Exa solar equivalent Joule

Table 5-6 Comparison of Emergy-based indicators for two road system scenarios

Indicator	*Description*	*Unit*	*Scenario*	
			Plan A	Plan B
N_m	Non-renewable minerals	EseJ	4.9E+01	9.8E+01
S_r	Slowly-renewable natural resources	EseJ	2.1E+01	4.1E+01
N_f	Non-petroleum fuel	EseJ	4.2E+02	8.2E+02
N_p	Non-renewable petroleum fuel	EseJ	4.7E+03	9.2E+03
R	Renewable energy	EseJ	3.3E+02	6.4E+02
EL_{HH}	Emergy equivalent of human health loss	EseJ	2.8E+01	5.1E+01
EL_{EQ}	Emergy equivalent of ecological loss	EseJ	3.3E+00	6.3E+00
EL_{SW}	Emergy loss due to solid waste discharge on land	EseJ	9.0E-08	1.8E-07
Es_{air}	Ecological services for dispersal of air pollutants	EseJ	1.1E+00	1.7E+00
Es_{water}	Ecological services for dispersal of water pollutants	EseJ	1.3E+01	2.5E+01
F_S	Emergy equivalent of purchased services	EseJ	3.2E+02	6.2E+02
F_L	Emergy equivalent of labor	EseJ	7.1E-01	9.4E-01
N	Non-renewable Emergy inputs: $N_m + N_f + N_p + S_r$	EseJ	5.2E+03	1.0E+04
F	Emergy Feedback(from economy and ecology): $F_l + F_s + Es_{air} + Es_{water}$	EseJ	3.4E+02	6.5E+02
EL	Emergy equivalent of loss: $EL_{HH} + EL_{EQ} + EL_{SW}$	EseJ	3.1E+01	5.7E+01
Y	Yield Emergy: N + R + F	EseJ	5.9E+03	1.1E+04
EYR	Emergy yield ratio: Y/F		1.7E+01	1.8E+01
ELR	Environmental loading ratio: (N + F + EL) / R		5.5E+03	1.1E+04
E_P	Empower: (Y +EL) /Lifetime	EseJ/yr	1.2E+02	2.3E+02
E_D	Emergy Density: Y/road length	EseJ/km	3.3E-01	3.3E-01

The Emergy Yield Ratio (EYR), which represents the ratio of the investment pushes the process to exploit local resources and the contribution to the economy, is slightly the same for two scenarios. The Environmental Loading Ratio (ELR) for both scenarios is very high as a result of huge non-renewable energy consumption, and it's ~95% higher for Plan B. Emergy density (E_D) is very similar for 1km of both scenarios, which describes, the TBL impacts along a roadway life cycle is highly sensitive to the length of that road system. Although, a longer road system around a natural barrier can save part of ecosystem in construction phase, however it will have much greater impact due to more resource and fuel use and emission release through its life cycle.

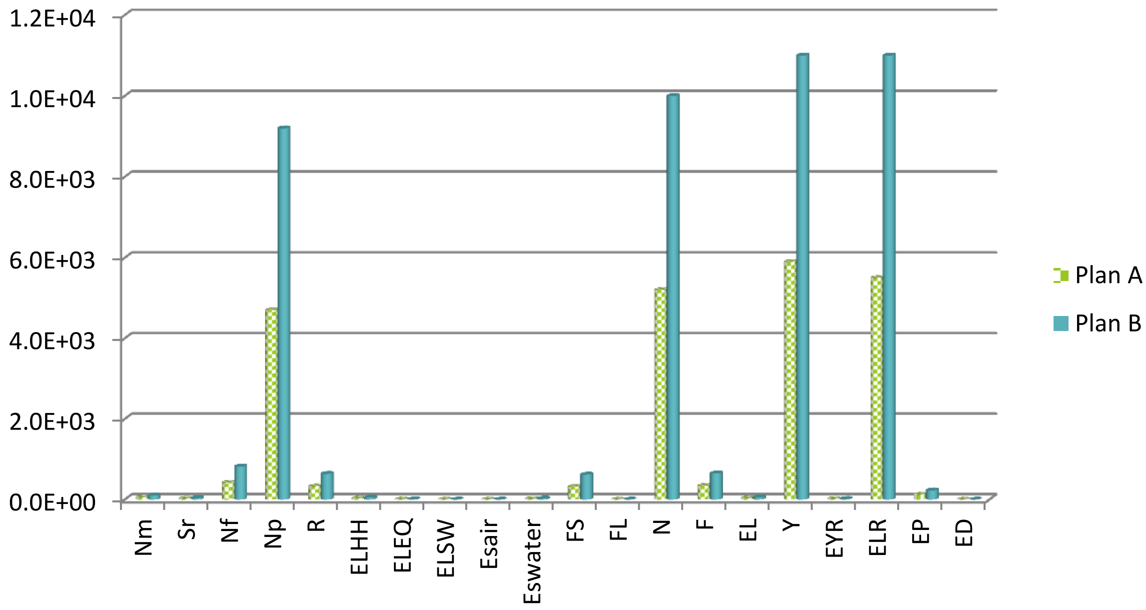


Figure 5-4 Comparison of Emergy-based indicators for two road system scenarios

5.6 Investigating result reliability and validity

In order to investigate the validity of Em-LCA result, a sensitivity analysis on significant pathways must be carried out. In this study the sensitivity analysis has been done for the petroleum fuel consumption as the largest inputs to the road system assuming a variation of the fuel input by ±10%, ±20%,…, ±50%, and assessing to what extent such a variation affected the final results. It is necessary to mention that, sensitivity analysis for fuel consumption has been conducted based on variation of two parameters: related unit emergy value (UEV) and quantity of fuel consumption which could be variable due to variability of traffic load. Results of that analysis verified that this did not change the main conclusions of the study.

This study and the results of the analysis are in regarded with a conventional Canadian roadway system. Indeed, the final result of this study can be sensitive to the estimated lifetimes of machinery and roadway, as well as traffic inputs to the roadway life cycle that can significantly affect the yield emergy for the operation phase. A sensitivity analysis regarding to the roadway lifetime indicates that if the lifetime of a road system increases to 70 years the emergy equivalent of resource inputs to the O&M phase will increase to ~40%. In addition, a 50% increase in the traffic input can bring equal increase in the emergy equivalent of resource inputs to the O&M phase which implies that this phase is significantly sensitive to the traffic load. Ultimately, the results of sensitivity analysis in this study verify that the final conclusion is reliable and validate and variation of significant inputs and road system lifetime cannot alternate the result of Em-LCA for both road system options.

5.7 Summary

Construction and operation of CIS can lead to various environmental and socio-economic impacts. In general, to construct CIS, forests have been cleared, rivers and the air have been fouled, and mountains have been leveled. To conduct an effective infrastructure asset management, all these issues must be addressed holistically in order to ascertain the short- and long-term (life cycle) TBL impacts of CIS.

In this chapter the implementation of the proposed Em-LCA framework for the CIS, paved road system, has been explored. The proposed framework is used to analyze upstream/downstream environmental impacts (ecological and human health impacts) and socio-economic impacts over the life cycle of two paved road scenarios.

One of the more significant findings to emerge from this study is that, Em-LCA as a holistic evaluation framework not only estimates a broad range of life cycle environmental impact (including the effects of deforestation, habitat loss, ecological services, ecological loss, and human health effects) but also considers socio-economic burdens.

Em-LCA for road system delivers a quantitative characterization of a road system metabolism (resource input, emission/waste output) and their associated TBL impacts that can be used to support long-term decision-making related to infrastructure industry and asset management. Interestingly, considering a broad range of TBL impacts the result of this study shows that, unlike the traditional tendency that recommend roadway patterns with less deforestation (comparing to shorter routes with more deforestation) during design and construction, those roadway patterns can bring about more long-term environmental impacts.

The results of this study confirm the idea that Em-LCA provides valuable information regarding to life cycle of a CIS that can be applied to facilitate policy decisions for resource allocation and capital investment. By applying emergy synthesis as a life cycle impact estimator for a CIS it's be possible to quantify the sustainability performance indices associated with the upstream and downstream life cycle impacts. In addition, different CIS or asset management scenarios (i.e. road pattern options in this study) can be compared based on those indices such as emergy per length and EYR and ELR.

The findings of this study have a number of important implications for future CIS practices and decision-making. The outcomes of this paper provide a basis for future evaluation of civil infrastructures and road systems. Em-LCA can be assisted as a way to augment and enhance the service life and thus provide the most sustainable and technically applicable engineering solution. The information provides using Em-LCA can be used ultimately for effective and much greater sustainability solutions for infrastructure asset management.

By applying this method, different scenarios for CIS (such as different pavement options, construction methods) can be compared considering the emergy-based indices. In order to adapt Em-LCA approach for any other CIS, an appropriate life cycle inventory database (e.g. Athena was used as a Canadian database for a road system in BC, Canada), as well as a set of related UEVs are required.

Furthermore, the result of Em-LCA can be applied to different CIS and at the larger scale, giving a measure of TBL impacts in a whole urban setting. The integrated results of Em-LCA will help to support policy decisions (such as replacement versus rehabilitation/retrofit, constructing tunnel versus build a bridge or build a long road around a natural barrier) at the design level of CIS and for asset management.

Chapter 6 Characterization of Uncertainties in Em-LCA

6.1 Overview

In this research emergy synthesis has been used to quantify environmental resources and services, as well as money, and human services that are used up directly or indirectly during the life cycle of built environment systems. Emergy synthesis has an extensive and ambitious scope (Ingwersen 2010) that can cover diverse environmental and socio-economic aspects of a complex environmental system such as built environment. To implement emergy synthesis as part of LCA, the built environment system must be considered as networks of energy flows, then the emergy value of all system steams is determined (Hau and Bakshi 2004).

However, major controversy surrounded emergy synthesis is the lack of studies for characterizing and documenting the uncertainties involved in the emergy evaluation process. Uncertainty can arise due to analysis of numerous components and flows in a complex environmental system. The embedded uncertainty in emergy parameters and model, besides the lack of knowledge about the degree of certainty of the resulting output, may undermine the reliability of emergy analysis' results.

It's necessary to mention that, uncertainty and variability are not restricted to emergy evaluation process and is unavoidable component of any other environmental assessment tools (these tools discussed in Chapter 2) that deal with complex environmental systems. Benetto et al. (2008) stated that the application of environmental assessment tools involves significant uncertainties concerning data, models and practitioner's choices. This issue often makes a problem less tangible and undermines decision-making. Accordingly, a reliable uncertainty modeling needs to be an integral part of any environmental accounting tools including, Em-LCA technique.

In order to perform realistic Em-LCA and achieve reliable output result, it is needed to characterize and propagate different sources of uncertainties incorporated in emergy evaluation process. This chapter aims to explore the utility of fuzzy-based methods in emergy synthesis, UEVs, and Em-LCA.

Uncertainty characterization has not been reported well in emergy synthesis. Recently, the need for uncertainty modeling in emergy accounting has been stressed and a few researches have been initiated by emergy practitioners (Bastianoni et al. 2009; Ingwersen 2010; Li et al. 2011). They proposed different methods to propagate uncertainties in the emergy analysis. In a recent publication, probability theory and Monte Carlo Simulations have been used to estimate total uncertainty of calculating unit emergy values (Ingwersen 2010). Further, Li et al. (2011) used two analytical methods (Variance propagation and Taylor series methods) to estimate uncertainty of emergy table-form calculations.

However, as it will be discussed more in following section, emergy synthesis data, model, and parameters are fuzzier in nature due to lack of trustworthiness, and imprecision in measurements, as compared to the stochasticity and randomness. In other worlds, the type of uncertainty in emergy synthesis is "*epistemic uncertainty*"[22] due to variability of system behavior and performance. Complexity of the environmental system leads emergy accounting method to build mathematical models of the examined system in a hierarchical form (i.e. energy system diagram). But mathematical models often neglect certain effects. In addition, there are always certain limitations in measuring a quantity (e.g. amount of an energy pathway in system diagram) sufficiently accurately. Moreover, sometime a particular data is deliberately hidden. Recently, numerous efforts have been made to gain better knowledge of the system, process or mechanism in order to evaluate epistemic uncertainty (Urbina et al. 2011) and methods such as fuzzy logic and evidence theory are suggested to handle epistemic type of uncertainty (e.g. see Curcurù et al. 2012; Hanss and Turrin 2010).

Gonza and Gonza (2002) used fuzzy logic to incorporate uncertainty modeling for environmental assessment tools. They argued that using fuzzy logic as compare to other uncertainty modeling techniques facilitate the assessment as it doesn't need profound environmental knowledge and exceptionally accurate data to carry out environmental

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[22] The term of epistemic uncertainty represents systematic type of uncertainty which used in uncertainty terminology in contrast with aleatoric uncertainty. Aleatoric uncertainty represents statistical type of uncertainty due to experimental data or behavior and often this type of uncertainty must be propagated using stochastic methods such as Monte Carlo.

assessment technique such as LCA. Therefore, they conclude that incorporating fuzzy logic in LCA makes this method more appropriate to small and medium sized enterprises. Tan et al. (2002) applied fuzzy data sets as a tool for handling imprecision of life cycle inventory data and pointed out that fuzzy-based methods are more appropriate than stochastic modeling (for epistemic uncertainty). They discussed that imprecision in life cycle inventory data is caused by ambiguity and cannot be described in probabilistic terms. Tan et al. (2004) further argued that limited inventory data is another issue of using probabilistic approaches and restricted uncertainty modeling to perform goodness-of-fit tests to obtain the probability distributions. Accordingly, probabilistic approaches requires more computation time while fuzzy-based methods offers the advantage of computational efficiency.

Consequently in this research, fuzzy-based methods (Zadeh 1965) have been explored to estimate and propagate different sources of uncertainties embedded in the emergy analysis process. The main reason to select fuzzy-based methods for emergy analysis is measurement efficiency and simplicity based on fuzzy logic, as compared to analytical propagation methods that require complex mathematical expressions. One of the specific characteristics of fuzzy-based methods is that it can be implemented with a limited data to handle epistemic type of uncertainty, in terms degree of membership. In addition, by applying fuzzy logic as compared to the traditional binary logic, it is possible to establish a relationship between system input variables and output variables to propagate uncertainty without making approximation for assigning probability distribution.

6.2 Sources of uncertainty in emergy synthesis

This section aims to identify and characterize different sources of uncertainty in emergy synthesis and unit emergy values (UEVs). Ingwersen (2010) stated that, there is a fundamental difference in the way UEVs are calculated, i.e. the *formula-type* and the *table-form* UEVs model. In order to characterize uncertainty, it is necessary to distinguish each UEV type characteristics and its related evaluation process in emergy analysis.

The type of UEVs used in emergy analysis process of a product can be selected based on analysis system boundary. If the system boundary of analysis expanded far enough to trace back and elicit the inventory of all basic pathways to a product, formula-type UEV can be used in emergy analysis of the system. Environmental accounting techniques such as LCA can be applied in order to achieve inventory of primary pathways to a product. Formula-type

UEVs are multiple parameter models that often used to estimate the emergy value of creation of primary environmental resource or main sector flows in biosphere (wind, water, and earth), raw materials, and other biophysical flows and storages such as fossil fuels, and minerals (Ingwersen 2010). Formula type UEVs is a function of positive values, such as total solar emergy supporting the system (e.g. web of the geobiosphere), and global average data (e.g. flux of global sedimentary cycle) that are multiplied/divided to generate the UEVs. Formula-type UEVs of mineral, petroleum, groundwater, and labor have been discussed by Ingwersen (2010).

On the other hand, if the system boundary of a product is limited to the secondary pathways or the bill of energy and material (products of human activities), table-form UEVs are applied. Table-form model is constituted of the sum products of amount of each energy pathway or input that contributes in the total emergy output of a system multiply by its associated UEV. According to emergy equations (Equation (2)) table-form UEV or solar transformity of a product can be determined from Equation (7):

$$\boldsymbol{Tr} = \boldsymbol{f}(\boldsymbol{E}_1, \boldsymbol{E}_2, \dots, \boldsymbol{E}_n, \boldsymbol{Tr}_1, \boldsymbol{Tr}_2, \dots, \boldsymbol{Tr}_n, \boldsymbol{E}) = \frac{\sum_{i=1}^{n} \boldsymbol{Ei} \times \boldsymbol{Tri}}{\boldsymbol{E}} \tag{7}$$

where E_1, E_2, …, E_n represent the energy or material input quantities of a system, Tr_1, Tr_2, …, Tr_n indicate their corresponding UEVs, while E and Tr, respectively, represent the energy or material output quantity of the system and its corresponding UEV (Li et al. 2011). Usually applying table-form UEVs is more common approach in evaluating human made products (e.g. manufactured products). For example to apply emergy analysis for a concrete-frame building, concrete or cement UEVs (table-form) can be applied. However, by applying inventory analysis (LCI) and achieving the list of raw material and energy, formula-type UEVs related to biophysical flows and storages such as limestone, crude oil or fine aggregate can be used. Once UEVs (formula-type or table-form) of all energy pathways to a product were determined, the total yield emergy value of a product, U, can be derived from Equation (2), considering the energy/material input quantities (E_i) of each energy/material pathway and its corresponding UEV (Tr_i).

In general, three main sources of uncertainty can be identified according to the classification scheme defined by the US EPA: *data*, *model* including parameters and structure, and *scenario* uncertainty (Lloyd and Robert Ries 2007).

Data uncertainties are due to data input used in the model such as the data from different literature or inventory items which are used to calculate emergy value. According to emergy Equation (2) to determine the uncertainty of yield emergy value (U), the uncertainty due to lack of trustworthiness and precision of data used for E_i, Tr_i parameters must be appropriately taken into consideration. The uncertainty of UEVs (Tr_i) can be arisen due to lack of trustworthiness and precision of UEVs that have been calculated (formula-type or table-form) for each energy pathway in different literature, or based on conflicting global baseline, imprecision average global data used for formula-type UEVs, and in some case using inappropriate UEVs for different pathways into production system (e.g. using the specific emergy of cast in place concrete for precast concrete). While the uncertainty of E_i can be arisen due to calculating the amount of different inventory items (may also cause by different human judgment e.g. calculating bill of material) that contribute in a production process (variability of LCI result)[23].

Model uncertainties are due to the selection of an appropriate model or oversimplifying energy system diagram model of the understudied system and ignoring some significant pathways in energy system diagram. This consist uncertainties as a result of number, type, and interaction between different input-output pathways (ambiguity) in energy system diagram. In addition, in an energy system diagram, uncertainties can arias due to existence, inexistence (e.g. with or without labor and service), or partial existence (vagueness) of each energy/material pathway into the system. Accordingly, if the knowledge about understudied system improved to certainty about existence or inexistence of pathways and their interaction, model uncertainty can be reduce to partial existence of pathways (pathways' quantity and

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[23] There is also another type of uncertainty as a result of incomplete or missing data. This type of uncertainty can be handled using Dempster-Shafer or evidence theory (Shafer 1976) which is out of the scope of this study.

quality) which is the same as data uncertainty of E_i and Tr_i (solar transformity is a measure of energy quality (Odum 1996)).

In addition, model uncertainty can be related to discrepancy in the parameters and structure of formula-type emergy simulation, where solar emergy supporting the system is multiplied/divided by some average global data. The recent type of uncertainty can be studied with some critical review in emergy formulation (parameter and structure) of biophysical flows and storages and is out of the scope of this research.

Scenario uncertainties are related to the context in which various parameters and models are used. In general, scenarios correspond to different geographical, temporal and technological conditions of the system under study. Scenario uncertainty can be due to adaption of table-form UEVs from previous studies that have been done in different geographical-temporal region and with different production technology and also due to applying national emergy-money ratio of other countries to estimate labor and services. In addition parameter E_i is along with uncertainty for different scenarios (different production process of the same product, different transportation distance, different service life expectancy, etc.).

In summary, uncertainty in emergy synthesis can appear due to imprecision of data, ambiguity and vagueness of model, and variable scenarios which are used to estimate E_i, Tr_i parameters in Equation (2). Different sources of uncertainty those can be arisen through table-form and formula-type emergy analysis process have been summarized in Table 6-1.

From this table it's realized that, uncertainty in emergy synthesis is epistemic and fuzzy in nature as a result of imprecision data used for E_i, Tr_i parameters and ambiguity and vagueness in emergy model that cannot be described in probabilistically. Accordingly, fuzzy set theory will be applied to model vagueness, fuzziness, and epistemic uncertainty in emergy synthesis. In addition, scenario analysis can be performed in conjunction with fuzzy logic to consider uncertainty of inventory data used for *Ei* parameters based on different scenarios. This will help to distinguish the imprecision and fuzziness uncertainty which is inherent in emergy (model and data) from the scenario uncertainty which is due to compiling LCI, in final result of Em-LCA.

Table 6-1 Different sources of uncertainty in table-form and formula-type emergy analysis process

Emergy Model	*Data*	*Model*	*Scenario*
Formula-Type	Imprecise average global data, conflict global baseline, and imprecise data inventory (Ei)	Parameters and structure of formula-type UEV model	Various geographical, technological and temporal scenarios for E_i
Table formed	Imprecise background UEVs (adapting UEVs from previous studies) and imprecise data inventory (Ei)	Ambiguity and vagueness of energy system diagram (Number, type, interaction, existence, inexistence, or partial existence of different energy pathways)	Adapting UEVs from previous studies with different geographical, technological and temporal scenarios, various scenarios for E_i

6.3 Uncertainty Modeling

Human understanding of physical process in the environment is based on vague concepts and imprecise human reasoning (Taheri and Zarei 2011). As a result, uncertainty is an inevitable and undesirable part of scientific models and studies related to environmental systems (Tesfamariam and Sadiq 2006). More complex the system is, the more imprecise and inexact will be the information to characterize that system (Ross 2004).

The uncertainty typology and definition varies due to different communities and study areas (e.g. artificial intelligent, environmental science, engineering), and often, conflicting taxonomies has been presented (e.g., Klir and Yuan 1995; Ross 2004). Ross (2004) stated that, uncertainty in a piece of information can be manifested in several different forms: it can be of the form of fuzzy information (not sharp, unclear, imprecise, approximate), or vague information (not specific, amorphous), it can be ambiguous (too many choices, contradictory), it can be in the form of ignorance (lack of knowledge, dissonant, not knowing something), or it can be due to natural variability (conflicting, random, chaotic, unpredictable).

Often, uncertainty as a consequence of system randomness and natural variability (e.g. number of different species in an ecological area or concentration of toxic substance in a lake) is addressed based on probability theory and/or statistical theory. However, epistemic uncertainty due to lack of distinctiveness (imprecision, fuzziness, vagueness, ambiguity) is handled by possibility or fuzzy sets theory. Moreover, Bayesian theory is applied, where probability describes as a degree of belief or measure of strength. In addition, epistemic uncertainty due to lack of knowledge, conflict and confusion, incomplete data, or information based on expert's knowledge to overcome missing data is addressed by Dempster-Shafer or evidence theory (Shafer 1976).

Therefore, imprecision associated with fuzziness, vagueness or ambiguity can be handled more efficiently by applying possibility approach, where fuzzy numbers can be interpreted by possibility distributions (as compared to classical probability distributions). Fuzzy-based uncertainty modeling is a generalized form of interval analysis[24] where fuzziness is addressed by assigning a possibility values, within the interval [0, 1] (Sadiq, Al-Zahrani, et al. 2004; R. Tan et al. 2004). It is necessary to mention that, possibility distribution can also address beliefs and expert judgments, and unlike probability distribution does not necessarily result from any specific mathematical rules (Tan et al. 2004).

6.3.1 Fuzzy sets

This section aims to present the basic axioms, operations and properties of fuzzy arithmetic uncertainty modeling. Fuzzy-based uncertainty modeling helps in addressing deficiencies inherent in binary logic and provides more efficient computational framework in propagating uncertainties throughout analysis (Mauris and Lasserre 2001; Sadiq, Husain, et al. 2004). In fact, fuzzy set is an extension of the traditional set theory that represents a set with boundaries that is not precise and each variable x can be a member of this set (fuzzy number) with a certain degree of membership μ proportionate to the degree of plausibility or truth.

The membership concept in fuzzy logic *is not a matter of affirmation or denial, but rather a matter of degree* (Sadiq, Al-Zahrani, et al. 2004). Membership function allows assigning a level of membership for any variable (x) that can describe imprecision, fuzziness, or ambiguity of that variable. In other words, a fuzzy number is assigned to a variable to represent uncertainty, and that fuzzy number describes the relationship between an uncertain quantity x and a membership function μ, within the ranges 0 and 1 (Zadeh 1965). Klir and Yuan (1995) States that to be qualify as a fuzzy number, a fuzzy set needs to be normal, convex and bounded (see Klir and Yuan 1995 for definitions of these terminologies).

[24] Interval analysis represents each value as a range of possibilities.

One of the important characterizations of fuzzy numbers (sets) is the impression of $\boldsymbol{\alpha}$-cut. The $\boldsymbol{\alpha}$-cut of a fuzzy set A is a crisp set A^{α} that contains all the elements of the universal set *X* whose membership grades in *A* are greater than or equal to the specified value of an $\boldsymbol{\alpha}$, i.e., $A^{\alpha} = \{x \mid \mu_x \geq \boldsymbol{\alpha}\}$(Klir and Yuan 1995). Operations on the fuzzy number can be performed on the real number or the membership function (μ_x). Possibilistic uncertainty propagations and operations can be carried out on the fuzzy numbers using *fuzzy arithmetic*.

In the context of fuzzy arithmetic, the arithmetic operations are not fuzzy, while the numbers on which the operations are performed are fuzzy and, hence the result outputs of the arithmetic operations are fuzzy (Ross 2004). Fuzzy arithmetic has been selected for this study as it is computationally simple, robust to moderate changes in the shapes, and does not require particular assumption for correlations among inputs.

Klir and Yuan (1995) stated that, fuzzy arithmetic is based on two properties of fuzzy numbers:

(1) Each fuzzy number can fully and uniquely be represented by its $\boldsymbol{\alpha}$ -cut;

(2) $\boldsymbol{\alpha}$ -cuts of each fuzzy number are closed intervals of real numbers for all $\boldsymbol{\alpha} \in (0, 1]$.

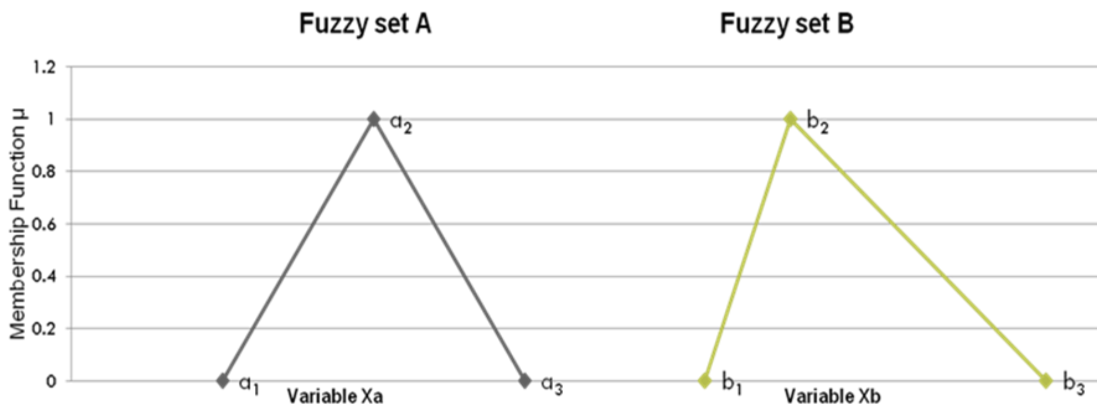
Accordingly, once the interval numbers is obtained, a well-established operation of interval arithmetic can be utilized at each possibility level (Ferson and Hajagos 2004). Some typical fuzzy arithmetic operations for two triangular fuzzy numbers (TFNs) have been indicated in Figure 6-1. Fuzzy numbers are uncertain numbers for which, in addition to knowing a range of possible values, we can define some values as more plausible, or more possible than other. Accordingly, it is possible to assign various shape of membership function (e.g., bell, triangular, trapezoidal, Gaussian, etc.) to a set of fuzzy UEVs; However, the selected shape should be justified by available information (Tesfamariam et al. 2006).

6.3.2 Fuzzy-based emergy synthesis

To develop fuzzy arithmetic modeling for emergy synthesis (and later for Em-LCA technique), UEVs of different substances (including raw material and energy flux or monetary pathways) that join together to make a resource or product can be considered as fuzzy numbers. These UEVs can be extracted from previous studies or calculated based on different inventory data. In order to simplify the implementation of fuzzy uncertainty modeling in emergy values, triangular possibility distributions or triangular fuzzy numbers

(TFNs) have been proposed in this research (for more information about this shape of fuzzy number see Giachetti (1997)).

A TFN, *Ai*, can be represented by three points (a_i, b_i, c_i) on the universe of UEVs, indicating the *minimum* (lower bound), *most likely* (mode), and *maximum* (upper bound) values, respectively. The assigned membership function to each fuzzy set embodied all fuzziness of a particular UEV of an input/output pathway of an understudied system. Development of the UEVs membership functions is based on essence of a fuzzy property or operation of UEVs.



Operators	[a,b] Formulae	Results
Summation	A+B	$(a_1+b_1, a_2+b_2, a3+b_3)$
Subtraction	A-B	$(a_1-b_3, a_2-b_2, a_3-b_1)$
Multiplication	AxB	$(a_1xb_1, a_2xb_2, a_3xb_3)$
Division	A/B	$(a_1/b_3, a_2/b_2, a_3/b_1)$
Scalar product	Q.B	(Qxb_1, Qxb_2, Qxb_3)

[a]A=(a_1, a_2, a_3); B=(b_1, b_2, b_3)
[b]The values of A and B are positive, if negative numbers are used, the corresponding min and max values have to be selected
$a_1 < a_2 < a_3; b_1 < b_2 < b_3; a_i$ and b_i $(i = 1$ to $3) > 0; n > 0; Q > 0$

Figure 6-1 Common fuzzy arithmetical operations using two TFN (adopted from Tesfamariam and Sadiq 2006)

Often, emergy synthesis applied for a new system by adapting UEVs form previous studies. In order to assign a membership function to previously computed UEVs, it is necessary to take a look at their evaluation process (formula-type or table-form) to capture all measurement approximation (data, model, and scenario) that makes the obtained UEVs imprecise, vague or fuzzy. Some of these measurement approximations were discussed in previous sections and summarized in Table 6-1.

To fuzzify a UEV of a product, it must be represented as a range of possibilities. Accordingly, instead of considering an uncertain UEV as a real number of X, UEV can be described as an interval arithmetic $[a,b]$ which contains X:X lies between a and b . For example, instead of estimating the UEV of a product as 2.0E+10 sej/J, it might be certainly expressed as a value between 1.97E+10 and 2.03E+10 sej/J. Hence, the real value of X (e.g. the real value of X can be the most commonly used UEV for a product) can be considered as the most likely value with the degree of membership equal to 1, the range of minimum a and maximum b values with a corresponding degree of membership equal to 0 can be estimated. As a result UEV of a product is no longer stated as a single number, but as arithmetic intervals which represent imprecision. In other words, the size of the intervals expresses the extent of uncertainty.

The range of possible values or extent of uncertainty can be determined by calculating upper and lower endpoints. The upper bound and lower bound of a UEV can be estimated based on approximations arising from measurement errors and tolerances of data (i.e. E_i ,Tr_i, or average global values in formula-type) used in calculating the UEVs. Accordingly, significant E_i, Tr_i, and average global values, those are large enough to have significant influence on final result, can be considered as intervals (to describe measurement errors and tolerances of data). These interval values can then be aggregated using arithmetic operation (see Figure 6-1) to obtain interval arithmetic, upper and lower endpoints $[a,b]$, for each UEV.

Often, for a particular energy pathway (i.e. secondary pathway such as human made product) to an understudied system, a list of UEVs (table-form) can be extracted from previous studies. By applying fuzzy arithmetic, it is possible to consider a list of UEVs for a pathway (with different possibility degree), instead of choosing a single value as a most plausible and ignoring other possible UEVs.

To develop TFN membership function for a list of table-form UEVs related to a particular pathway (that might be mentioned in different studies), a separate TFN must be assigned to each UEV (of UEVs list related to that pathway). The UEV's upper and lower endpoints are estimated by aggregating approximations, measurement errors and tolerances of data (i.e. E_i and Tr_i) used to calculate that UEV. Later the TFNs can be ranked, and proportional weight can be assigned to the fuzzified UEVs based on the plausibility or relevancy of their data inventory, model, and scenario to the understudied system.

For example, the UEV of a particular product that was previously measured in an analogous temporal and geographical scenario (according to examined system) are ranked higher than the UEV of the same product but based different geographical and temporal specifications. Then, the normalized weights are multiplied by TFNs using scalar product operation. Ultimately, the weighted TFNs are summed up in order to obtain a single UEV membership function (TFN) for a product.

Table 6-2 shows the UEV's TFN development process for Canadian concrete production based on a list of concrete specific energy values (UEVs) extracted from different studies. It is necessary to mention that, in some cases a UEV from a study could be more accurate (less fuzzy with less measurement errors or tolerances) as compared to another one. However, at the same time it could be less relevant (less plausible) according to the specific characteristics (e.g. temporal and geographical scenarios, etc.[25]) of an under studied system. As a result, to adapt a UEV from a previous study, both fuzziness and relevancy can be taken into account. Therefore, it is possible to consider all previously calculated UEVs, including an accurate or less fuzzy UEV with low adaptability potential (lower weight) or fuzzier UEVs with high adaptability potential.

In order to develop a single TFN for a complex product which implicate a complicated network of significant pathways (energy, material, money), it is necessary to consider all data

[25] Relevancy criteria and specific characteristics of an understudied system can be varied for different systems and must be defined by decision maker. This can introduce a new source of uncertainty. As a result this study recommends use of formula-type UEVs for Em-LCA in order to avoid subjectivity.

approximations, measurement errors and tolerances of E_i and Tr_i through all pathways. However, expressing all data approximations and measurement errors accurately, is very difficult, if not impossible. Especially when the original studies of background UEVs and their measurement process are not accessible or UEV calculation process and data inventory are not transparent.

On the other hand, estimating a range of possible UEVs for basic products (formula-type UEVs) such as earth sedimentary materials and minerals can be more convenient, because of transparency in related parameters and models of formula-type UEVs. Accordingly, by expressing measurement errors and tolerances of all parameters used in approximating a formula-type UEV as an arithmetic interval, it is possible to estimate upper bound and lower bound of those parameters. Later, by applying arithmetic operations a single TFN can be defined for each formula-type UEV. In addition, some sources of uncertainty can be reduced, as background UEVs that were obtained from formula-type models are not dealing with uncertainty due to scenario relevancy (e.g. due to variable temporal and geographical scenarios) of previous studies.

Table 6-3 shows the UEV's TFN development process based on formula-type UEVs of primary pathways into a concrete product. The primary pathways contribute more significantly in concrete UEV estimation includes: limestone, clay, sand, and gravel. In order to notice all the pathways that contribute in concrete production refer to Pulselli et al. (2008). Indeed, to capture the ultimate uncertainty of a product UEV, it's possible to propagate uncertainty of sensitive pathways those contributes considerably more than other pathways in final result (this must be test by conducting a primarily sensitivity analysis).

These four raw materials (limestone, clay, sand, and gravel) are physical flows of earth cycle into a process. In general, baseline crustal cycling value of 1.69E+9 seJ/g on the 15.83E24 seJ/yr global emergy baseline are assigned as the default identical UEV (equal emergy per unit mass) for these sedimentary materials (unless for clay which has 50% loss in its sedimentary cycle) (H. T. Odum 2000). As a result, if the value of 1.69E+9 seJ/g (3.38E+9 seJ/g for clay) consider as the most possible UEV (with membership equal to 1), the same UEV's TFN can be approximated for each of these pathways. First, the minimum (lower bound) and maximum (upper bound) values of each parameter are expressed based on measurement errors and tolerances of that parameter (e.g. crustal turnover can be expressed as a value between 2.38E-3 and 2.88E-3 cm/yr). Then, UEV's minimum and maximum values are evaluated using related arithmetic operation (i.e. multiplying four parameters' TFN noted in column 3-6 of Table 6-3). UEV's TFN then can be applied to characterize the total uncertainty of UEV of concert product.

6.4 Case study of a paved road system

As it was discussed in previous section, estimating a range of possible UEVs for basic products (formula-type UEVs) is mathematically more convenient. Accordingly, to characterize and propagate uncertainly due to emergy analysis of a system, the analyzer needs to trace back far enough to elicit all basic pathways using advance technique such as LCA. By applying Em-LCA framework and with the aid of life cycle inventory (LCI), instead of propagating uncertainty due to significant products applied in road construction (e.g. asphalt or concrete), uncertainty due to basic pathways such as limestone, sand stone, clay, petroleum, and water, can be characterized.

The value of uncertainty characterization of emergy result can be noticed as it is applied to assist environmental decision-making; specifically when the results of analysis for two or more alternative are close and could be very sensitive to variable data, models, and scenarios. In this section, the application of fuzzy-based uncertainty modeling has been applied in combination with Em-LCA for a paved road system.

6.4.1 Identifying Em-LCA scope

A road system in BC, Canada, has been selected, to study different paved road alternatives, and to highlight the effects of different sources of uncertainties in the final result of Em-LCA and decision-making. Accordingly, emergy synthesis will be applied as an impact indicator to evaluate cumulative environmental impact of different alternatives paved road system, and to provide a comprehensive framework to evaluate different life cycle stages and their associated impacts within the same quantitative framework.

The energy system diagram of a roadway from design to construction and operation & maintenance/rehabilitation phase has been developed (energy system diagram of a paved road life cycle was shown in Figure 5-2). In this study cradle-to-grave impact of a paved road system will be analyzed. Only one impact category, life cycle recourses inputs (upstream impacts), have been considered (as it was shown in previous chapter this impact category is dominant in a life cycle of a road system). Recourses inputs to a road pavement have been analyzed as energy resources for geo-biosphere work and services needed for resources production. The greater the emergy flow necessary to sustain a paved road system, the greater the quantity of solar energy exploited and greater the environmental impact through roadway life cycle.

For the general Canadian roadway design, the period of 50 years lifespan has been considered. The functional unit has been defined as the construction, maintenance, rehabilitation and use of 1 km of a 2-lane roadway over the period of 50 years. Minor and routine roadway maintenance includes activities such as joint and crack sealing and patch repairs has been considered.

Pavement rehabilitation activities have been considered at years 18 and 35. The first pavement rehabilitation (at year 18) expected to implicate removing 40 mm of the existing pavement coat and replacing it with one 50 mm lift of asphalt. The second overlay (at year 35) is anticipated to implicate removing 80 mm of the existing pavement layer and replacing it with 100 mm of placed in two lifts. In addition replacing 100 mm concrete for sidewalk have been presumed.

6.4.2 Inventory analysis

An Athena library has been used as a Canadian database to obtain background data for the roadway life cycle inventory (LCI). Accordingly, a 1-km of 2-lane roadway has been designed with 2 different pavement options (concrete and asphalt pavement material) and assembled in Athena Impact Estimator for Highway. Selected materials for granular layers and paved shoulders are identical and based on common road practices in BC area for both options. All design requirements have been considered based on BC Standard Specifications for Highway Construction[26]. Roadway cross section that assigned into the Athena Impact Estimator, for both design options, has been indicated in Figure 6-2.

[26] http://www.th.gov.bc.ca/publications/const_maint/contract_serv/standard_specs/Volume_1_SS2012.pdf

Table 6-2 UEV's TFN development process for concrete

Studies	*Year*	*UEV[1] (seJ/kg)*	*Country of study*	*Sources of uncertainty*			*Triangular fuzzy numbers (TFNs) E+12*	*Relevancy Weight*
				Data	**Model**	**Scenario**		
1	1992	1.78E+12	Thailand	Ready mix concrete	Emergy analysis model was oversimplified	Good and services assessed using national emergy-money ratio	[1.6, 1.78, 2.4]	0.6
2	1995	2.268E+12	USA	Concrete block	Emergy analysis model was oversimplified, UEV value without labor and services	-	[2.0, 2.26, 2.3]	0.7
3	1998	2.58E+12	USA	Ready mix concrete	Complicate and conservative assessment of infrastructures for transportation	Services assessed using national emergy/money ratio	[2.0, 2.58, 2.6]	0.8
4	2001	1.23E+12	Sweden	Ready mix concrete	Does not consider the entire production process	Analysis based on national context, locally available energy sources and national emergy/money ratio	[1.12, 1.23, 1.8]	0.3
5	2007	1.81E+12	Italy	Ready mix concrete	Emergy/money ratio was not used	-	[1.78, 1.81, 2.45]	0.9
6	2012	1.89E+12	Canada	Ready mix concrete	Emergy/money ratio was not used	-	[1.8, 1.89, 2.4]	1

Concrete UEV's TFN: [1.79, 2.00, 2.39]E+12

[1] UEVs has been updated relative to the global baseline 15.83E+24 seJ/yr (Odum et al. 2000) and rounded to two decimal places to distinguish the variance

Table 6-3 UEV's TFN development process for significant concrete substance

Item	***UEV (kg/seJ)***	***Parameter 1***	***Parameter 2***	***Parameter 3***	***Parameter 4***	***TFN Multiplication***	***UEV TFN****
		Crustal turnover (cm/yr)	Density of crust (g/cm3)	Crustal area (cm2)	Soil formation (fraction)		
Limestone	1.69E+12	[2.38,2.40,2.88]E-3	[2.57, 2.60, 2.62]	[1.49, 1.50, 1.51]E+18	[0.98, 1, 1]	[8.93, 9.36, 11.4]E+15	[1.39, 1.69, 1.77]E+12
Clay	3.38E+12	[2.38,2.40,2.88]E-3	[2.57, 2.60, 2.62]	[1.49, 1.50, 1.51]E+18	[0.46, 0.5, 0.52]	[4.19, 4.68, 5.92]E+15	[2.77, 3.38, 3.78]E+12
Sand	1.69E+12	[2.38,2.40,2.88]E-3	[2.57, 2.60, 2.62]	[1.49, 1.50, 1.51]E+18	[0.98, 1, 1]	[8.93, 9.36, 11.4]E+15	[1.39, 1.69, 1.77]E+12
Gravel	1.69E+12	[2.38,2.40,2.88]E-3	[2.57, 2.60, 2.62]	[1.49, 1.50, 1.51]E+18	[0.98, 1, 1]	[8.93, 9.36, 11.4]E+15	[1.39, 1.69, 1.77]E+12

***UEV TFN for earth sedimentary cycle can be determined by dividing global baseline (15.83E+24 seJ/yr) on** multiplication of **parameters** 1-4 (H. T. Odum 2000)

Table 6-4 and Table 6-5 summarize results of the inventory analysis (resource input) over roadway lifetime for both paved road options. The mass and energy flows to a roadway system can be modeled as energy pathways in the roadway energy system diagram to visualize the energy pathways and their interaction (as it was shown in Figure 5-2). Inventory data from LCI was allocated to each flow and descriptions of different pathways from system diagram have been transferred into the emergy evaluation tables. As the understudied case is the real project and the information related to the model or energy system diagram (existence or inexistence of different pathways and related possible interactions) can be considered as certain, the overall uncertainty can be reduce to the quantity and property of each pathway which is the same as data uncertainty of E_i, Tr_i.

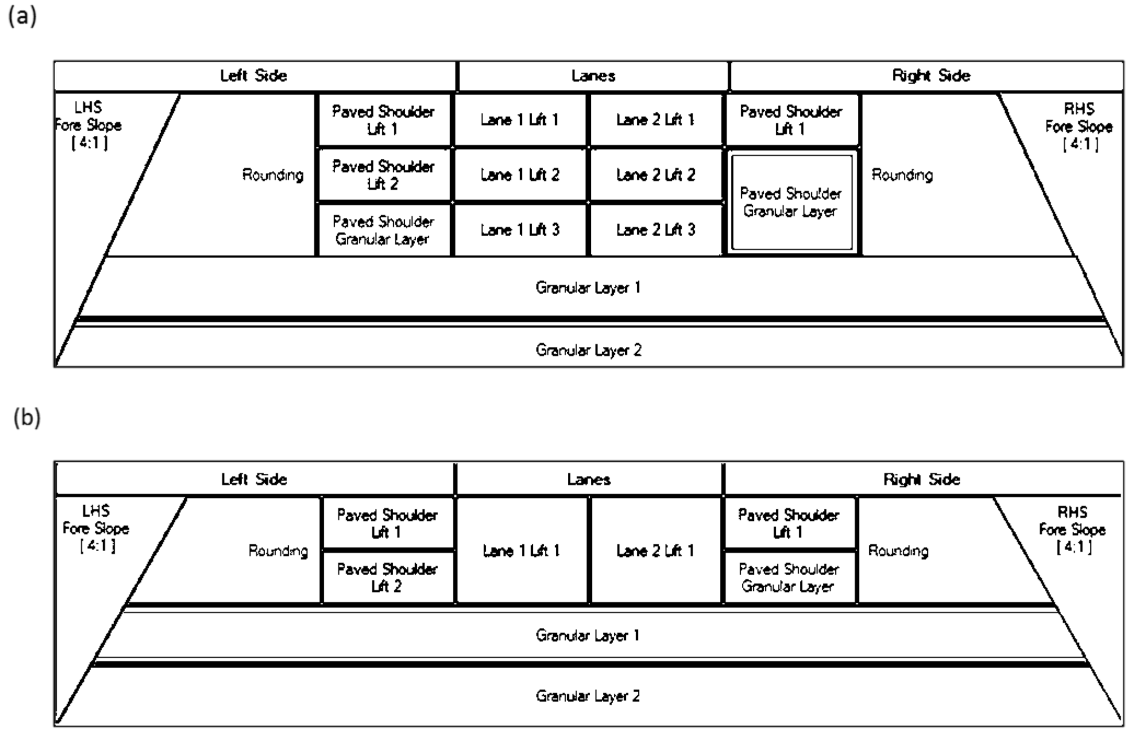


Figure 6-2 Road way cross section (a) asphalt pavement (b) concrete pavement

Uncertainty due to inventory data or $E_{i,}$ variability can be addressed by considering three different scenarios, i.e.: *conservative scenario*, *optimistic scenario*, and *conventional scenario*. Conventional scenario is based on standard LCI framework and project information that was summarized in Table 6-4 and Table 6-5, while conservative and optimistic scenarios have been created base on LCI considering maximum and minimum possible amount for each inventory items. Variability in different scenarios for roadway life cycle is significantly sensitive to transportation distance during construction and rehabilitation phase (plant to site, site to stockpile, and equipment depot to site), traffic load (average number and type of car and their fuel consumption), and pavement material quality (e.g. fly ash percentage of concrete pavement).

As most of the energy pathways to the roadway that have been obtained from LCI are basic primary biophysical flows and storages such as fossil fuels, and minerals, formula-type UEVs can be applied to convert mass and energy to emergy value. Then, uncertainty due to UEVs of inventory data (Tr_i) can be addressed as a fuzzy number by a triangular membership function (TFN) as it was described in 6.3.2 and Table 6-3. Accordingly, formula-type UEVs proposed in literature for minerals and petroleum products have been fuzzified and TFNs membership function assigned. In order to assign a membership function to the pathway UEVs, all parameters incorporate in UEV formula can be fuzzified. Then a single TFN can determined by applying fuzzy arithmetic operation, as it was indicated in Table 6-3.

It is necessary to mention that, before performing uncertainty modeling, emergy analysis has been carried out primarily using average data. Then, a sensitivity analysis has been done to recognize more sensitive values to emergy analysis process. sensitivity analysis has been perform by gradually assuming a variation of the pathways UEVs by ±10%, ±20%, …, ±50%, and assessing to what extent such a variation affected the final emergy value. In fact, fuzzy uncertainty modeling is only meaningful for the more sensitive UEVs; as compared to less sensitive values those do not play a noticeable role in final result and corresponding uncertainty (cannot alter the result considering ±50% variation). As a result, fuzzy uncertainty modeling has been carried out only for sensitive data.

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Table 6-4 Life cycle resource use for roadway with asphalt pavement

Resource Use	***Manufacturing***		***Construction***		***Maintenance***		***Operating Energy***		***Total***
	Material	Transportation	Material	Transportation	Material	Transportation	Annual	**Total**	
Limestone kg	2.5E+05	-	-	-	-	-	-	**-**	**2.5E+05**
Clay & Shale kg	2.7E+04	-	-	-	-	-	-	**-**	**2.7E+04**
Iron Ore kg	5.3E+03	-	-	-	-	-	-	**-**	**5.3E+03**
Sand kg	8.9E+03	-	-	-	-	-	-	**-**	**8.9E+03**
Ash kg	2.8E-03	-	-	-	-	-	-	**-**	**2.8E-03**
Gypsum kg	1.4E+04	-	-	-	-	-	-	**-**	**1.4E+04**
Coarse Aggregate kg	1.4E+06	-	-	-	-	-	-	**-**	**1.4E+06**
Fine Aggregate kg	3.9E+07	-	-	-	6.8E+06	-	-	**-**	**4.6E+07**
Water L	6.4E+05	-	-	-	-	-	-	**-**	**6.4E+05**
Obsolete Scrap Steel kg	3.8E+04	-	-	-	-	-	-	**-**	**3.8E+04**
Coal kg	1.1E+04	1.6E+02	5.7E+03	6.1E+02	1.2E+03	1.9E+02	2.8E+05	**1.4E+07**	**1.4E+07**
Wood Fiber kg	1.2E-01	-	-	-	-	-	-	**-**	**1.2E-01**
Uranium kg	1.2E-02	1.4E-03	4.8E-02	5.2E-03	1.1E-02	1.6E-03	3.8E+00	**1.9E+02**	**1.9E+02**
Natural Gas m3	4.1E+04	5.3E+02	1.9E+04	2.0E+03	2.5E+04	6.2E+02	1.9E+06	**9.6E+07**	**9.6E+07**
Natural Gas as feedstock m3	3.1E+02	-	-	-	-	-	-	**-**	**3.1E+02**
Crude Oil L	5.6E+04	1.3E+04	4.7E+05	4.8E+04	6.5E+04	1.0E+04	1.4E+05	**6.9E+06**	**7.6E+06**
Crude Oil as feedstock L	7.1E+05	-	-	-	5.0E+05	-	-	**-**	**1.2E+06**
Prompt Scrap Steel as feedstock kg	2.4E+04	-	-	-	-	-	-	**-**	**2.4E+04**

Table 6-5 Life cycle resource use for roadway with concrete pavement

Resource Use	***Manufacturing***		***Construction***		***Maintenance***		***Operating Energy***		***Total***
	Material	Transportation	Material	Transportation	Material	Transportation	Annual	**Total**	
Limestone kg	1.3E+06	-	-	-	-	-	-	**-**	**1.3E+06**
Clay & Shale kg	1.5E+05	-	-	-	3.8E+03	-	-	**-**	**1.5E+05**
Iron Ore kg	3.0E+04	-	-	-	1.3E+03	-	-	**-**	**3.1E+04**
Sand kg	4.9E+04	-	-	-	3.4E+01	-	-	**-**	**4.9E+04**
Ash kg	1.1E-02	-	-	-	1.2E+00	-	-	**-**	**1.2E+00**
Gypsum kg	7.9E+04	-	-	-	4.9E-01	-	-	**-**	**7.9E+04**
Coarse Aggregate kg	8.0E+06	-	-	-	-	-	-	**-**	**8.0E+06**
Fine Aggregate kg	2.9E+07	-	-	-	2.5E+06	-	-	**-**	**3.2E+07**
Water L	2.1E+06	-	-	-	3.1E+05	-	-	**-**	**2.4E+06**
Obsolete Scrap Steel kg	3.8E+04	-	-	-	-	-	-	**-**	**3.8E+04**
Coal kg	5.4E+04	2.0E+02	5.0E+03	6.0E+02	1.1E+05	9.2E+01	2.8E+05	**1.4E+07**	**1.4E+07**
Wood Fiber kg	7.8E-01	-	-	-	1.0E+02	-	-	**-**	**1.0E+02**
Uranium kg	1.1E-02	1.7E-03	4.2E-02	5.1E-03	2.2E-02	7.8E-04	3.8E+00	**1.9E+02**	**1.9E+02**
Natural Gas m3	1.7E+04	6.5E+02	1.6E+04	2.0E+03	1.2E+05	3.0E+02	1.9E+06	**9.6E+07**	**9.6E+07**
Natural Gas as feedstock m3	1.4E+03	-	-	-	1.7E+05	-	-	**-**	**1.7E+05**
Crude Oil L	3.8E+04	1.7E+04	4.1E+05	4.7E+04	4.7E+04	6.8E+03	1.4E+05	**6.9E+06**	**7.5E+06**
Crude Oil as feedstock L	7.8E+04	-	-	-	3.4E+05	-	-	**-**	**4.2E+05**
Prompt Scrap Steel as feedstock kg	2.4E+04	-	-	-	-	-	-	**-**	**2.4E+04**

6.5 Impact assessment Results

Fuzzy-based emergy accounting for environmental impact assessment (upstream impact) through roadway life cycle and with two different pavement options has been summarized in Table 6-6 and 6-7. Fuzzy uncertainty modeling has been performed for sensitive flows (limestone, aggregate, crude oil, and gasoline), considering three scenarios for all inventory data i.e.: scenario 1 optimistic approach (minimum traffic load, transportation distance, and best material quality) scenario 2 conventional approach (average traffic load, transportation distance, and best material quality), and scenario 3 conservative approach (maximum traffic load, transportation distance, and poor material quality). The result of Em-LCA for different pavement options can be indicated by triple TFN diagram (for scenario 1, 2, and 3) as it shown in Figure 6-3 and Figure 6-4. In addition, Figure 6-5 to 6-7 indicate difference between the total yield emergy values (total emergy investment in the life cycle of the road (Y)) for different paved road options under different scenarios.

The results show that, total yield emergy value of road system based on most possible UEVs ($\boldsymbol{\alpha}$-cut 1) and conventional scenario for asphalt pavement is about 7.5% more than concrete pavement (1.74 E+20 seJ for asphalt pavement as compared to 1.61E+20 seJ for concrete pavement). Accordingly, the total yield emergy value results for both pavement options are slightly close. From Figure 6-3 and Figure 6-4 we can realize that scenario uncertainty due to inventory data (mass and energy calculation) is not as significant as uncertainty due to UEVs (transformity and specific energy).

Figure 6-5 to Figure 6-7 indicate that the total yield emergy value for concrete paved road is less than asphalt paved road system considering UEVs with possibility more than 50% ($A^{\boldsymbol{\alpha}} = \{x \mid \mu_x \geq 0.5\}$). As a result, if the total yield emergy value has been considered as a life cycle upstream impact indicator, the asphalt pavement option bring about slightly greater impact as compared to the concrete pavement option, for all scenarios and for UEVs with possibility more than 50% ($A^{0.5} = \{x \mid \mu_x \geq 0.5\}$).

However, uncertainty due to formula-type UEVs can alternate the total yield emergy value result for different pavement option considering UEVs with possibility less than 50%. Accordingly, the result of this study reveals that, uncertainty inherent in emergy analysis process, even for alternatives with very close yield emergy value, cannot change the emergy analysis result and alter the better option, and indeed any decision based on that, considering

UEVs with confident equal or more than 50%. Accordingly, the results from this study indicate that uncertainty inherent in emergy analysis process, even for alternatives with very close total yield emergy values, cannot change the emergy results or alternate the options (considering UEVs with confidence equal or more than 50 percent). As a result, uncertainty due to imprecise formula-type UEVs (Tr_i) and inventory data (E_i) cannot reverse decision based on emergy results in this study.

6.6 Summary

The substantial controversy surrounded emergy analysis is the lack of studies for characterization and quantification of various uncertainties involved in the emergy evaluation process. Uncertainty can arise from three main sources, data, model, and scenario for emergy analysis of a complex environmental system. The embedded uncertainty in emergy evaluation process beside the lack of knowledge about the degree of certainty of the resulting output can undermine the reliability of emergy analysis' results. High level of uncertainties inherent in the emergy estimation can limited the adaption of emergy accounting to assist other environmental accounting method such as LCA. Applying a reliable uncertainty modeling as an integral part of emergy analysis to capture the vagueness/ fuzziness uncertainty inherent in the emergy synthesis can promote the wider adaption of emergy concept in environmental accounting and informed decision-making.

In this study, fuzzy arithmetic model has been developed to capture vagueness and fuzziness of UEVs data (Tr_i). In addition scenario analysis has been carried out to characterize uncertainty and imprecision due to inventory data (E_i) based on three different scenarios. Utility of a proposed model has been investigated through a roadway project case study. The proposed framework was applied as an integral part of Em-LCA framework to estimate the cumulative environmental impact through the life cycle of a roadway system with different pavement options (i.e. Canadian roadway with concrete and asphalt pavement).

It is believed that the proposed approach should permit the decision makers to assess the environmental impacts of different systems interacting with environment such as infrastructure system (e.g. road, bridge, building, etc) considering different source of uncertainties. The proposed approach is expected to act as tool for informed decision-making and to capture uncertainties in Em-LCA results. The structure presented in this chapter is a simplified application of the fuzzy arithmetic framework by assigning TFN to UEVs and considering conservative, conventional, and optimistic scenarios. The proposed framework can help decision makers to examine the effects and the degree of uncertainty due to different data and scenarios that can undermine the result output.

Table 6-6 Fuzzy-based uncertainty emergy modeling and scenario analysis for asphalt paved road

Resources (Unit)	*UEV (seJ/unit)*	*Scenarios (Unit)*			*Emergy (seJ)*		
		Optimistic	Conventional	Conservative	Scenario 1	Scenario 2	Scenario 3
Limestone (kg)	[1.39, 1.69, 1.77] E+12	2.47E+05	2.47E+05	2.47E+05	[3.43, 4.17, 4.37] E+17	[3.43, 4.17, 4.37] E+17	[3.43, 4.17, 4.37] E+17
Clay & Shale (kg)	4.10E+12	2.66E+04	2.66E+04	2.66E+04	1.09E+17	1.09E+17	1.09E+17
Iron Ore (kg)	4.43E+12	5.35E+03	5.35E+03	5.35E+03	2.37E+16	2.37E+16	2.37E+16
Sand (kg)	1.69E+12	8.85E+03	8.85E+03	8.85E+03	1.50E+16	1.50E+16	1.50E+16
Ash (kg)	2.35E+13	2.76E-03	2.76E-03	2.76E-03	6.48E+10	6.48E+10	6.48E+10
Gypsum (kg)	1.69E+12	1.42E+04	1.42E+04	1.42E+04	2.39E+16	2.39E+16	2.39E+16
Coarse Aggregate (kg)	[1.39, 1.69, 1.77] E+12	1.44E+06	1.44E+06	1.44E+06	[2.01, 2.44, 2.56]E+18	[2.01, 2.44, 2.56]E+18	[2.01, 2.44, 2.56]E+18
Fine Aggregate (kg)	[1.39, 1.69, 1.77] E+12	4.60E+07	4.60E+07	4.60E+07	[6.39, 7.77, 8.14] E+19	[6.39, 7.77, 8.14] E+19	[6.39, 7.77, 8.14] E+19
Water (L)	2.10E+09	6.37E+05	6.37E+05	6.37E+05	1.33E+15	1.33E+15	1.33E+15
Obsolete Scrap Steel (kg)	7.80E+12	3.78E+04	3.78E+04	3.78E+04	2.95E+17	2.95E+17	2.95E+17
Wood Fiber (kg)	1.40E+12	1.24E-01	1.24E-01	1.24E-01	1.73E+11	1.73E+11	1.73E+11
Prompt Scrap Steel as feedstock (kg)	7.80E+12	2.42E+04	2.42E+04	2.42E+04	1.89E+17	1.89E+17	1.89E+17
Natural Gas as feedstock (MJ)	8.05E+10	1.18E+04	1.18E+04	1.18E+04	9.49E+14	9.49E+14	9.49E+14
Crude Oil (MJ)	[9.06, 9.27, 9.47] E+10	3.14E+08	3.17E+08	3.20E+08	[2.85, 2.91, 2.97] E+19	[2.87, 2.94, 3.00] E+19	[2.90, 2.97, 3.03] E+19
Crude Oil as feedstock (MJ)	[9.06, 9.27, 9.47] E+10	5.08E+07	5.08E+07	5.08E+07	[4.60, 4.70, 4.81] E+18	[4.60, 4.70, 4.81] E+18	[4.60, 4.70, 4.81] E+18
Electricity (MJ)	3.35E+11	1.96E+05	1.96E+05	1.96E+05	6.59E+16	6.59E+16	6.59E+16
Hydro (MJ)	2.67E+11	7.22E+05	7.23E+05	7.24E+05	1.92E+17	1.93E+17	1.93E+17
Gasoline (MJ)	[1.11, 1.14, 1.21] E+11	4.53E+08	4.87E+08	5.05E+08	[5.01, 5.14, 5.48] E+19	[5.39, 5.54, 5.89] E+19	[5.58, 5.73, 6.10] E+19
LPG (MJ)	8.05E+10	9.87E+05	9.90E+05	9.93E+05	7.95E+16	7.97E+16	7.99E+16
Heavy Fuel Oil (MJ)	1.11E+11	3.24E+06	3.30E+06	3.36E+06	3.59E+17	3.66E+17	3.72E+17
Coal (MJ)	6.71E+10	5.46E+05	5.62E+05	5.82E+05	3.66E+16	3.77E+16	3.90E+16
Nuclear (MJ)	2.00E+11	9.21E+04	9.62E+04	1.01E+05	1.84E+16	1.92E+16	2.03E+16
Natural Gas (MJ)	8.05E+10	4.33E+06	4.42E+06	4.55E+06	3.48E+17	3.56E+17	3.66E+17
Diesel (MJ)	1.21E+11	2.05E+07	2.09E+07	2.28E+07	2.49E+18	2.53E+18	2.76E+18
Yield Emergy (seJ)					[1.54, 1.70, 1.78] E+20	[1.58, 1.74, 1.82] E+20	[1.60, 1.77, 1.85] E+20

Table 6-7 Fuzzy-based uncertainty emergy modeling and scenario analysis for concrete paved road

Resources (Unit)	***UEV (seJ/unit)***	***Scenarios (Unit)***			***Emergy (seJ)***		
		Optimistic	Conventional	Conservative	Scenario 1	Scenario 2	Scenario 3
Limestone (kg)	[1.39, 1.69, 1.77] E+12	1.35E+06	1.41E+06	1.63E+06	[1.87, 2.28, 2.38] E+18	[1.97, 2.37, 2.50] E+18	[2.27, 2.76, 2.89] E+18
Clay & Shale (kg)	4.10E+12	1.52E+05	1.52E+05	1.83E+05	6.22E+17	6.22E+17	7.51E+17
Iron Ore (kg)	4.43E+12	3.09E+04	3.09E+04	3.72E+04	1.37E+17	1.37E+17	1.65E+17
Sand (kg)	1.69E+12	4.93E+04	4.93E+04	5.98E+04	8.33E+16	8.33E+16	1.01E+17
Ash (kg)	2.35E+13	1.21E+00	1.21E+00	1.21E+00	2.83E+13	2.83E+13	2.83E+13
Gypsum (kg)	1.69E+12	7.88E+04	7.88E+04	9.57E+04	1.33E+17	1.33E+17	1.62E+17
Coarse Aggregate (kg)	[1.39, 1.69, 1.77] E+12	8.04E+06	8.04E+06	7.86E+06	[1.12, 1.36, 1.42]E+19	[1.12, 1.36, 1.42]E+19	[1.09, 1.33, 1.39]E+19
Fine Aggregate (kg)	[1.39, 1.69, 1.77] E+12	3.19E+07	3.19E+07	3.19E+07	[4.43, 5.39, 5.64] E+19	[4.43, 5.39, 5.64] E+19	[4.43, 5.39, 5.64] E+19
Water (L)	2.10E+09	2.41E+06	2.41E+06	2.61E+06	5.05E+15	5.05E+15	5.48E+15
Obsolete Scrap Steel (kg)	7.80E+12	3.78E+04	3.78E+04	3.78E+04	2.95E+17	2.95E+17	2.95E+17
Wood Fiber (kg)	1.40E+12	1.01E+02	1.01E+02	1.01E+02	1.41E+14	1.41E+14	1.41E+14
Prompt Scrap Steel as feedstock (kg)	7.80E+12	2.42E+04	2.42E+04	2.42E+04	1.89E+17	1.89E+17	1.89E+17
Natural Gas as feedstock (MJ)	8.05E+10	6.59E+06	6.59E+06	6.59E+06	5.31E+17	5.31E+17	5.31E+17
Crude Oil (MJ)	[9.06, 9.27, 9.47] E+10	3.10E+08	3.12E+08	3.16E+08	[2.81, 2.87, 2.93] E+19	[2.83, 2.89, 2.96] E+19	[2.86, 2.92, 2.99] E+19
Crude Oil as feedstock (MJ)	[9.06, 9.27, 9.47] E+10	1.77E+07	1.77E+07	1.77E+07	[1.60, 1.64, 1.67] E+18	[1.60, 1.64, 1.67] E+18	[1.60, 1.64, 1.67] E+18
Electricity (MJ)	3.35E+11	6.17E+05	6.17E+05	6.42E+05	2.07E+17	2.07E+17	2.15E+17
Hydro (MJ)	2.67E+11	2.33E+06	2.30E+06	2.39E+06	6.21E+17	6.12E+17	6.37E+17
Gasoline (MJ)	[1.11, 1.14, 1.21] E+11	4.44E+08	4.78E+08	4.95E+08	[4.91, 5.04, 5.37] E+19	[5.29, 5.43, 5.78] E+19	[5.47, 5.62, 5.99] E+19
LPG (MJ)	8.05E+10	2.09E+06	2.52E+05	2.56E+05	1.68E+17	2.03E+16	2.06E+16
Heavy Fuel Oil (MJ)	1.11E+11	2.44E+06	2.40E+06	2.77E+06	2.70E+17	2.65E+17	3.07E+17
Coal (MJ)	6.71E+10	1.45E+06	1.32E+06	1.72E+06	9.71E+16	8.82E+16	1.15E+17
Nuclear (MJ)	2.00E+11	9.56E+04	9.87E+04	1.05E+05	1.91E+16	1.97E+16	2.10E+16
Natural Gas (MJ)	8.05E+10	6.93E+06	6.93E+06	7.09E+06	5.57E+17	5.57E+17	5.71E+17
Diesel (MJ)	1.21E+11	1.93E+07	1.95E+07	2.13E+07	2.34E+18	2.35E+18	2.58E+18
Yield Emergy (seJ)					[1.42, 1.57, 1.64] E+20	[1.46, 1.61, 1.68] E+20	[1.49, 1.64, 1.71] E+20

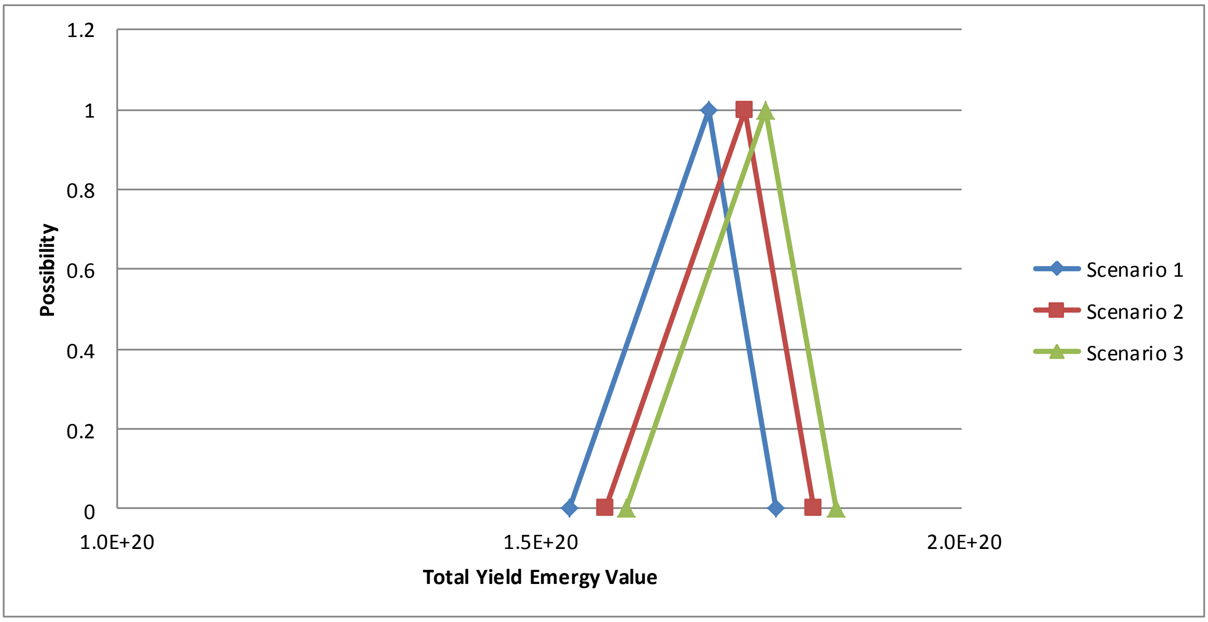

Figure 6-3 Yield emergy value of asphalt paved road

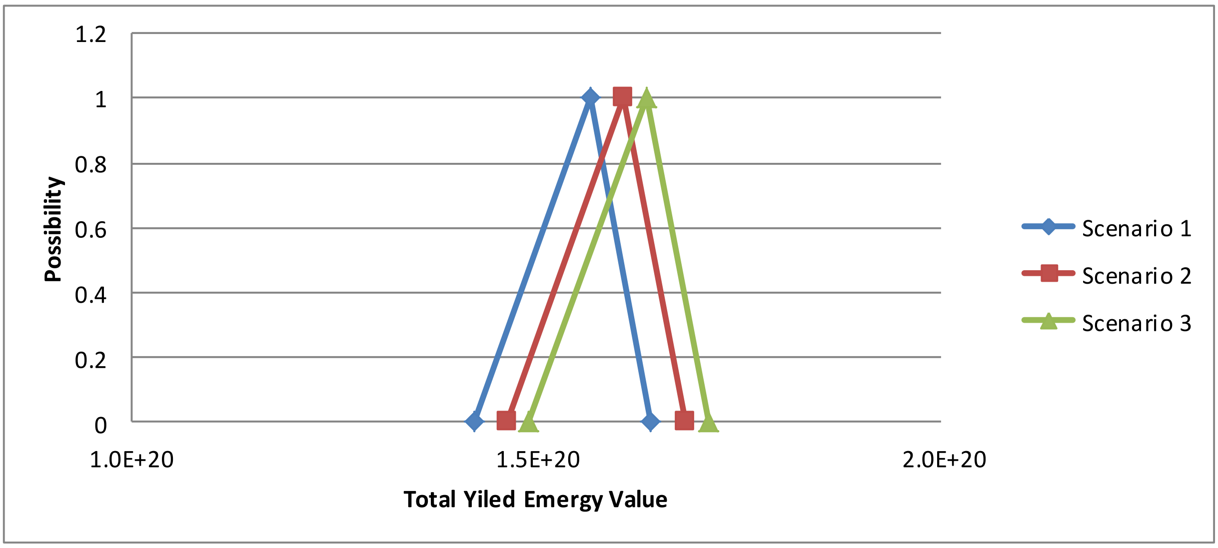

Figure 6-4 Yield emergy of concrete paved road

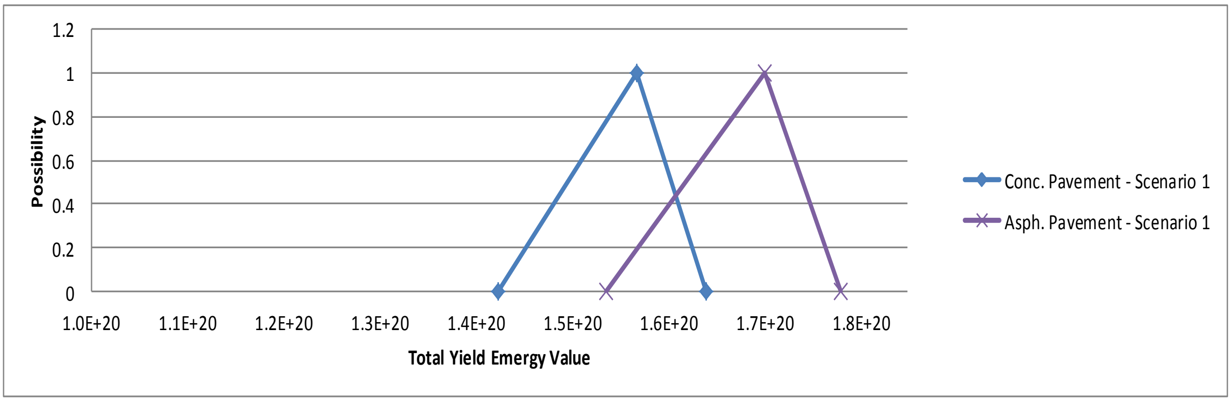

Figure 6-5 Yield emergy value of concrete and asphalt paved road under firs scenario

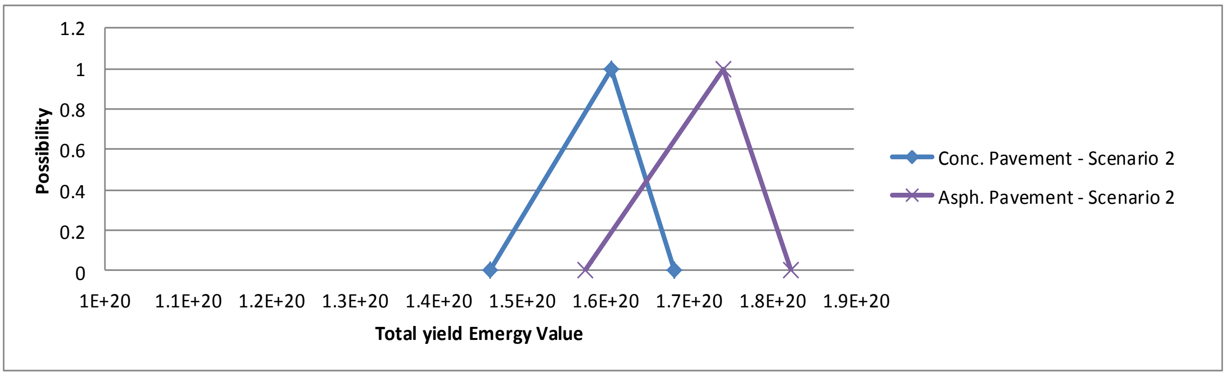

Figure 6-6 Yield emergy value of concrete and asphalt paved road under second scenario

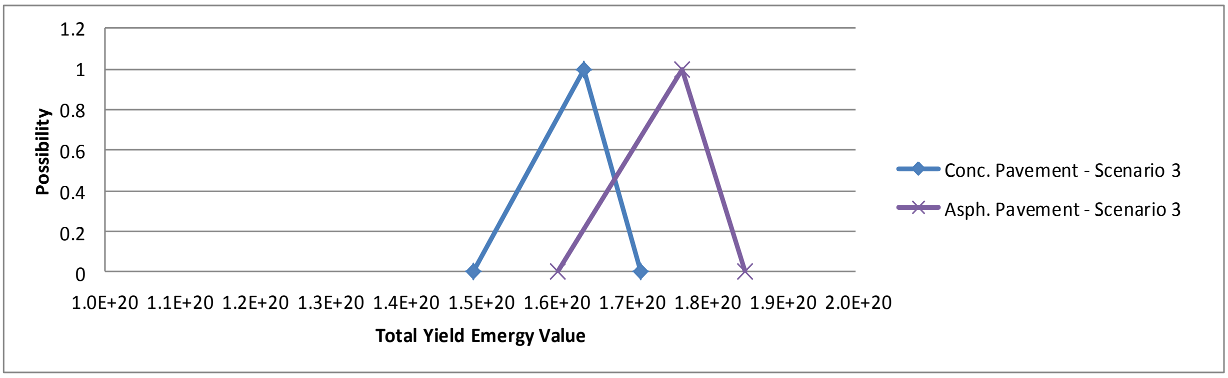

Figure 6-7 Yield emergy value of concrete and asphalt paved road under third scenario

Chapter 7 Conclusions

7.1 Summary

Motivation for this research stems from the recognition of the fact that applying an accurate sustainability appraisal framework over the life cycle of the built environment systems is crucial to develop effective asset management plans and support informed decision-making. The research proposed a sustainability appraisal framework based on emergy synthesis and LCA to measure a set of quantitative performance indicators to assess the TBL impacts over the life cycle of the built environment systems.

The Em-LCA framework was developed to assess and compare the performance of different building and infrastructure alternatives in meeting the TBL sustainability criteria. The developed Em-LCA framework was implemented for two main group of built environment systems (i.e., linear infrastructure and building systems) using cradle-to grave approach (i.e., from design and project planning to the end-of-life). The outcomes and major findings of the developed Em-LCA framework and its implementation for linear infrastructure and building systems can be summarized as following:

- In this research emergy synthesis has successfully been applied for engineering decision-making and adopted as a valuable complement to conventional LCA (and not a replacement) to offer a more holistic and donor-side perspective as compared to LCA's incomplete, pragmatic, and utilitarian user-side perspective.
- The proposed Em-LCA framework moreover expands the system boundaries from LCA's human-dominated boundary to emergy's natural ecosystem boundary considering the provision of primary resources and a large spectrum of life-supporting ecological services, biosphere‘s ecological assets, and human well-being. Accordingly, Em-LCA addresses some of the important sustainability goals that were neglected in conventional sustainability assessment tools and traditional asset management paradigms, by evaluating the role of ecosystem services in creating natural resources, dissipating the emissions and absorbing their impacts.

- The developed Em-LCA framework is capable evaluates the contribution of ecosystems to all human activities with quantitative unified measure. As a result Em-LCA addresses the major challenges of sustainable development in integrating TBL sustainability principles.
- Em-LCA framework considers a broad spectrum of the environmental aspects that have not been considered adequately in any existing sustainability appraisal tools. These aspects include environmental protection (such as healthy forests, clean waters, clean air, fertile soils, biodiversity, etc.) as well as biological capacity required to support resource consumption, human and natural loss, economic cycle, waste absorption, and emission dilution.
- In this research, the Em-LCA technique has been developed to consider three main impact categories based on emergy algebra: (1) Recourses inputs or upstream impacts including renewable and non-renewable resources. (2) Waste and emission or downstream impacts. (3) Associated socio-economic impacts including monetary costs and purchased labor and services. Integrating the effects of environmental upstream, downstream, and socio-economic impacts in a unified and unbiased measure and without using any subjective weighting/scoring technique is an important contribution of this research.
- The effects of upstream, downstream, and socio-economic impacts aggregated in several emergy-based end point indicators (e.g., ELR, ESI, E_P, E_D). Accordingly, classic emergy indicators have been slightly changed to integrate the contribution of all three impact categories for a built environment system, and to provide valuable information to support asset management decision-making.
- Uncertainty modeling using fuzzy-based methods and scenario analysis has been employed to address the current gaps in knowledge for uncertainty characterization in emergy synthesis and Em-LCA. The results of this study enhance and improve the application of emergy synthesis and LCA and provide robust basis to facilitate environmental decision-making under uncertainty.

- The proposed Em-LCA framework is capable to assess the performance of building and infrastructure services and assets in meeting the TBL sustainability criteria. Case studies were conducted to demonstrate the implementation of Em-LCA to assess the sustainability performance of two main group of built environment systems, i.e., linear infrastructure systems (road systems) and building systems. The findings from the case studies have important implications for generalizing and developing a decision support tool for future sustainability assessment in the context of built environment and asset management.
- The results from the conducted case studies used as a basis to create an MS Excel-based decision support system for future evaluation of buildings and linear infrastructure systems. A complete list of inventory data of common building and infrastructure, and Em-LCA calculation are assigned to 8 spreadsheets to organize and analyze the data in tabular form as following:
    - One spreadsheet for resource use inventory data and upstream impacts
    - Three spreadsheets for emission released to air and water and waste discharged on the land and their downstream impacts (airborne, waterborne, and solid waste spreadsheets)
    - One spreadsheet for life cycle cost and socio-economic impacts,
    - One spreadsheet for emergy based indices,
    - One spreadsheet for sensitivity analysis, and
    - One spreadsheet for fuzzy-based uncertainty modeling and scenario analysis.
- By applying Em-LCA as an asset management decision support tool, different building systems (such as high-rises and mid-rise complex, retail and office building, various structural systems, and various scenario for linear infrastructure systems (such as different pavement options, construction methods, etc.) can be analyzed and compared.
- The results of this research support the idea that, Em-LCA can be applied as a framework to select the most sustainable and technically applicable asset

management solution at the design level of built environment systems, constructing and developing new urban and neighborhood areas, as well as renovating and rehabilitating existing built environment systems.

- Finally, Em-LCA framework provides improved and enhanced understanding about short- and long-term effects of built environment systems. As a result it can be used to facilitate long-term policy decisions and for asset management in contrast to the traditional, subjective, and incomplete overall assessment (e.g. single-criterion decision-making).

7.2 Contributions

The contribution of this research included fundamental and conceptual enhancement to sustainability appraisal of built environment systems, integrating emergy synthesis and LCA approach, and asset management decision-making. The contribution of this research can be expressed based on three main following modules.

7.2.1 Framework

The contributions of this work included developing an innovative, comprehensive, holistic and quantitative sustainability appraisal framework to provide more accurate and reliable information to support decision-making for effective and sustainable asset management. As this work demonstrated, this can be achieved through integrating and improving emergy synthesis and LCA approaches and pursuing 5 steps of Em-LCA framework that were discussed in Chapter 3 .

The developed Em-LCA framework has several advantages as compared to existing tools, as it provides more comprehensive and quantitative framework with minimum subjectivity, covers all life cycle phases of built environment systems and TBL sustainability principals and related performance indicators. In addition, the proposed Em-LCA framework is capable to integrate TBL sustainability principals in a quantitative manner and aggregate cumulative effects of varying environmental and socio-economic impacts without using subjective weighting/scoring methods. Moreover, Em-LCA framework benefits of the donor-side perspective that consider the provision of primary resources and a large spectrum of life-supporting ecological services, and encompass wider boundaries beyond the human-dominated boundaries.

Uncertainty has not been well reported in both emergy synthesis and LCA. This work introduced a novel and much needed method for uncertainty propagation along with regular Em-LCA modeling. Accordingly, Em-LCA has been improved by advanced uncertainty modeling techniques to offer more reliable sustainability assessment results and to provide accurate information to support informed decision-making related to the built environment systems and asset management.

The foundation stones of the developed framework were three advance models, i.e. *LCA*, *emergy synthesis*, and later *fussy logic*, which interact and complement each other under the Em-LCA framework. As a result of this integration, the accuracy and informativeness of data resulting from sustainability assessment of built environment systems were improved.

7.2.2 Implementation

The developed Em-LCA framework has been successfully implemented for assessing the sustainability of built environment systems. Accordingly two groups of studies have been conducted. In the first study, Em-LCA framework was applied to evaluate the sustainability of building systems. In this investigation, the aim was to assess and analyze two different residential buildings (i.e., multi-unit residential and single-family house) based on different scenarios in four Canadian providences (i.e., BC, Ontario, Alberta, and Quebec). In another study, Em-LCA framework has been used to assess the sustainability of linear civil infrastructure systems. Two different scenarios for a road construction project have been studied.

7.2.3 Validation

The reliability of the Em-LCA results has been validated using fuzzy-based uncertainty modeling and scenario analysis. Accordingly, attempt was made in order to assess the reliability of the results of Em-LCA framework and to characterize and document the uncertainties involved in the Em-LCA framework. Investigating uncertainty in emergy synthesis and Em-LCA framework is an important contribution of this research work. In addition, fuzzy-based uncertainty modeling and scenario analysis were applied for Em-LCA of a transportation infrastructure system. A paved road with two pavement options (i.e., asphalt and concrete) was analyzed to highlight the impacts of propagation of different sources of uncertainties in Em-LCA evaluation process and asset management decision-making.

7.3 Limitations and challenges

Significant efforts have been made to address the shortcomings and deficiencies of existing sustainability appraisal tools in the context of built environment and to develop an accurate and holistic sustainability appraisal framework to overcome those deficiencies. However, the most important limitation of the current research lies in the fact that Em-LCA framework has been implemented for two types of built environment systems. Attempts were made to select very generic representatives for building and road systems. A number of possible future studies to generalize and validate the developed Em-LCA framework for all types of built environment systems and for different regions in the word are apparent. Indeed, any new framework such as Em-LCA requires conducting more case studies to simplify the details before it can be widely accepted and used. Accordingly, the following limitations can be identified:

- The implementation of Em-LCA framework has been explored for a few, although, the most important built environment systems.
- The UEVs have been used in this study collected from previous studies.
- Uncertainty and variability through downstream impact assessment that deals with vague and imprecise values such as DALY, PDF, wind speed, surface runoff energy, etc., were neglected.

7.4 Recommendations

Improvements to this work can be recommended in following directions:

- More broadly research is needed to compile a complete inventory data for different built environment systems.

- A number of possible future studies are apparent in order to apply the proposed fuzzy-based uncertainty modeling to develop a complete set of TFN for all UEVs that are used to convert inventory data.
- Considerably more work will need to be done to determine and characterize uncertainty of downstream impact assessment process. Uncertainty can arise due to using some inherently variable environmental data such as DALY and PDF, wind speed, surface runoff energy in downstream impact assessment process. These values can be variable based on different climatic and geographical scenarios. Future research should therefore concentrate on the characterizing and propagating uncertainty of environmental data used for downstream impact assessment.
- Further work needs to be done to establish a new set of emergy-based indicators specific for built environment systems.
- The *time value* should be investigated in future studies. In addition, further research will need to be conducted in order to incorporate the factors of *resource scarcity* or *resource generation speed* in emergy-based indicators. The evidence from this study suggests that incorporating time dimension besides considering the work of ecosystem in creating natural resources, dissipating emissions, and absorbing waste is essential for widening the use of emergy synthesis and Em-LCA in engineering decision-making and future practices.

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Appendices

Appendix A Green Building Rating Systems

A.1 LEED green building rating system

This scoring system that known more commonly by its acronym of LEED (Leadership in Energy and Environmental Design) has been developed by United States Green Building Council's (USGBC's), a national coalition of building industry professionals, contractors, policy makers, owners and manufactures. LEED is a standardized green building certification system that was issued and released in 1998 (LEED NC v1.0) and is now being used to rate specific building typologies, sectors, project scopes. LEED rating system is available for project with a building component in the following areas (Calkins 2009):

- LEED-NC, New Construction and Major Renovation Project; this system is the original LEED rating system that was designed to lead high performance commercial projects include offices, institutional buildings such as libraries, museums, and churches, and high-rise residential buildings (4 or more habitable stories). It can also be used as rating system for schools, hotels, healthcare, multiunit residential buildings, governmental buildings, recreational facilities, laboratories, manufacturing plants, and other types of building. LEED for new construction has also different subcategories including LEED for Schools, LEED for Healthcare, and LEED for Retail: New Construction and Major Renovations (LEED-MR).
- LEED-EB, Existing Building Operations & Maintenance; LEED-EB provides a set of performance criteria for the existing buildings undergoing improvement work or little to no construction and for their sustainable operation and maintenance. The performance criteria cover building system upgrades where the majority of the building surfaces remain unchanged.
- LEED-CI, Commercial Interiors Projects; this system was designed to evaluate interior spaces that are undergoing a complete interior fit-out of at least 60% of the

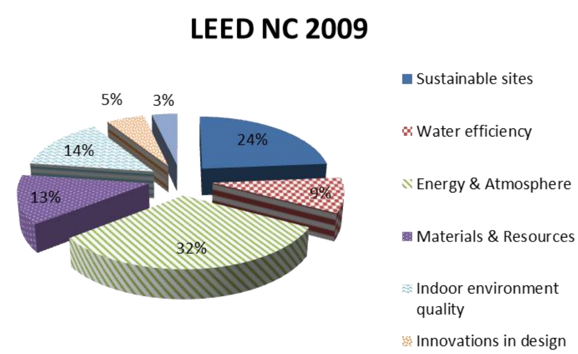
certifying gross floor area. There are two rating systems in this category: LEED for Commercial Interiors and LEED for Retail: Commercial Interiors.

- LEED-CS, Core & Shell Projects; this system provides criteria for Buildings that are undergoing new construction or major renovation on its exterior shell and core mechanical, electrical, and plumbing units but not a complete interior fit-out.
- LEED-H, Homes; the system offers standards for homebuilding practices, including two sections for low-rise (1-3 stories) residential buildings and mid-rise (4-6 stories) residential buildings.
- LEED-ND, Neighborhood Development; the system provides criteria for development and retrofit of neighborhoods, neighborhood design integrating principals of green building and smart growth. LEED-ND emphasizes land use and environmental considerations in the US focusing on site selection, design and construction elements bringing buildings and infrastructure together into a neighborhood. LEED-ND evaluate and rate the neighborhood to its landscape as well as its local and regional context (Haapio 2011). The pilot LEED-ND was launched in 2007, while the actual rating system a few years later, in 2010.

These LEED rating systems evaluate environmental performance for design, construction and operation of buildings from a whole building perspective over its life cycle (Yellamraju 2011a). The USGB council stated that the main goal of LEED is *to promote buildings that are environmentally responsible, profitable and healthy places to live and work*. They have tried to develop alliances with industrial and educational organization as well as federal, state and local governments to facilitate the adoption of green building (Calkins 2009). LEED has provided green building rating framework for design, construction and operation. Over the years, LEED has shown a substantial growth and earned a national and international recognition. The number of registered LEED™ projects reached form 100 registered buildings and 12 certified projects in 2000 to more than 6,000 registered projects and more than 850 certified projects worldwide by 2009 (Tatari and Kucukvar 2011). Recently, LEED certification has been become mandatory for publicly funded projects in certain US states. LEED projects have been established in over 90 different countries around the world (Lee

2010). In addition, LEED has been applied as a reference framework to adapt similar rating tool for local conditions in Canada (LEED Canada), Mexico (LEED Mexico), Brazil (LEED Brazil), and India (LEED India).

The LEED rating system is based on credits and points and the system evaluates the performance of the building through different building performance credits (Castro-Lacouture et al. 2009). The latest version of LEED framework (LEED v3 2009) rates buildings by assigning credit that are weighted based on seven key building performance parameters: Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environmental Quality (IEQ), Innovation in Design (ID), and Regional Priority (RP) (USGBC 2009). Points are assigned to achieve credit requirements based on each of these seven key parameters. Figure A-1 indicates point distribution based on seven performance categories for two different schemes, LEED NC and CI 2009. Prerequisites and credits of the LEED latest version (LEED-NC 2009) have been described in seven topics as following (Kubba 2009; USGBC 2009; Yellamraju 2011b).



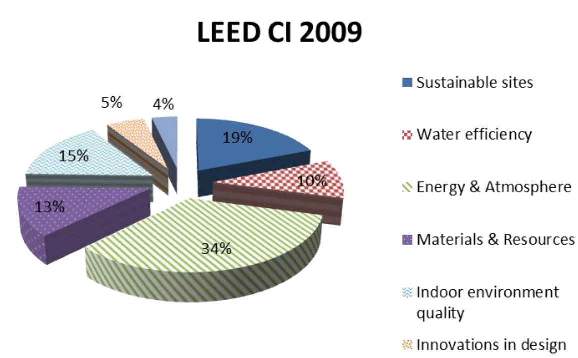


Figure A-1 Point distribution based for two different LEED schemes LEED NC and CI (2009)

Sustainable Sites (SS)

This performance criterion can provide some guidance and instructions to lead designers and project managers on how to select, design, and manage project sites. The certain prerequisite for this category is pollution prevention of construction activities. Regarding to the site development and selection this category rewards building on previously developed land (Brownfield redevelopment), developing density and community connectivity, and designing regionally appropriate landscape with access to public transportation, bicycle storage, changing rooms, as well as maximizing parking capacity and open space. The category specifically encourages applying management practices for storm water quality and quantity control, besides reducing of heat island effects, erosion, waterway sedimentation, airborne dust generation and light pollution, as well as protecting or restoring habitat. The category also credits utilization of low-emitting and fuel efficient vehicle for construction activities and site preparation. The total credit that a building can gain from sustainable site performance is up to 26 points.

Water Efficiency (WE)

Buildings have brought about a significant drop in the water level of underground aquifers as a result of potable water consumption. The aim of this performance criterion is to increase water efficiency within buildings and to reduce the burden on municipal water supply and wastewater systems (USGBC 2009). Water use reduction (20%) is the prerequisite of this category. The WE credits encourage applying several strategies such as innovative wastewater technology, water efficient landscaping and irrigating by using high efficiency fixtures, reusing rain water, etc. A total of up to 10 points can be achieved in this category.

Energy and Atmosphere (EA)

This category of credits emphasizes on energy alternatives and conservation strategies that can reduce overall energy consumption of buildings. It also encourages monitoring energy consumption and applying on-site renewable energy systems. In order to qualify for consideration of this category credits, fundamental commissioning of building energy is required. This performance credits are weighted most heavily and a maximum of 35 points can be achieved in this category.

Materials and Resources (MR)

This category of credits offers several strategies to minimize the amount of waste generated by building activities during construction and operation phases. It rewards applying sustainable materials that have rapidly renewable content, composed from recycled materials, and are from regional sources. The *MR* credit also encourages minimization of land-filling and incineration of building disposal. The prerequisite factor to qualify for this category credits is storage and collection of recyclables. A total credit up to 14 points can be obtained in *MR* category.

Indoor Environmental Quality (EQ)

This category of credits aims to improve the overall quality of building indoor environment where people spend a large portion of their lives. It rewards designing healthy and comfortable indoor environment by providing improved ventilation. The *EQ* credits also encourage monitoring outdoor air to provide suitable lighting and thermal comfort for all occupants. Optimized use of day-lighting accessible outdoor views for occupants will be also credited. In order to qualify for *EQ* credits, two prerequisites are required: Minimum indoor air quality performance and environmental tobacco smoke control. A maximum credit 15 points can be gained in this category.

Innovation in Design (ID)

This category of credits has been designed to provide opportunities for qualified projects to achieve extra points. Innovation in Design (ID) points can be earned by satisfying one or more compliance paths: the innovation in design and/or exemplary performance paths (USGBC 2009). Applying innovative strategies or design plans to achieve significant, measurable environmental performance beyond the LEED credit requirements, and/or offering prerequisite or credit that allows exemplary performance[27] as specified in the LEED reference guide, can qualify a project for *ID* points. Moreover, one additional point can be achieved by having a LEED Accredited Professional (LEED AP) in a project team.

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[27] Exemplary performance points are available through expanded performance or scopes are noted in the LEED Reference Guide for Green Design & Construction, 2009 Edition and in LEED-Online.

Regional Priority (PR)

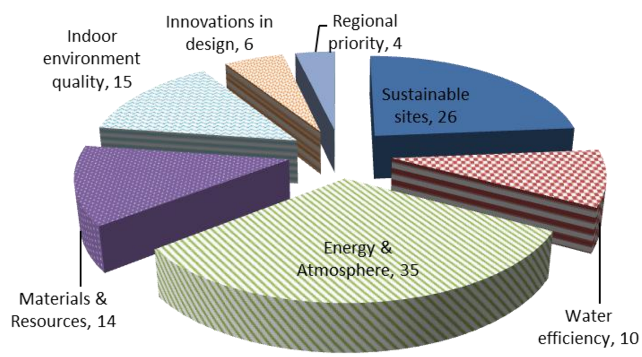
This category of credits that introduced in the latest version of LEED framework (LEED v3, 2009) aims to address geographically-specific environmental priorities. These credits will be assigned with regard to the project region based on six *RP* credits identified by the USGBC regional councils. One point is awarded for each *RP* credit and up to 4 points can be achieved under this category.

Based on the above credit categories a total score is calculated by adding credits achieved upon satisfying one or more performance criteria. Overall score of 100 base points plus 10 possible bonus points for innovation and regional can be achieved (Kubba 2009). Accordingly, buildings will be rated in four levels of certifications based on their earned points. The LEED 2009 certifications are awarded according to the following scale:

- Certified: 40–49 points
- Silver: 50–59 points
- Gold: 60–79 points
- Platinum: 80 points and above

Allocation of points between credits (credit allocation) is based on the potential environmental impacts and human benefits of each credit with respect to a set of impact categories. The impacts are defined as the environmental or human effect of the design, construction, operation, and maintenance of the building. A combination of approaches, including energy modeling, life-cycle assessment, and transportation analysis, can be used to quantify each type of impact (USGBC 2009). According to the latest revision of LEED, credits have been weighted with the relative emphasis on the reduction of energy consumption and greenhouse gas emissions associated with building systems, transportation, the embodied energy of water, the embodied energy of materials, and where applicable, solid waste (Kubba 2009; USGBC 2009).

It is necessary to mention that the details of the credit allocation vary slightly among individual LEED rating systems. For example, LEED for Existing Buildings considers credits related to solid waste management, while LEED for New Construction doesn’t. As a result the overall environmental footprint and the relative allocation of points could be different according to each rating system (USGBC 2009). LEED rating system framework and point allocation for LEED-NC and LEED-MR has been indicated in Figure A-2.



LEED for NC. and MR.	Points
Sustainable Sites	26
Water Efficiency	10
Energy and Atmosphere	35
Materials and Resources	14
Indoor Environmental Quality	15
Innovation in Design	6
Regional Priority	4
	110

LEED rating	Points required
Platinum	80 and above
Gold	60-79
Silver	50-59
Certified	40-49
*No label**	*39 and below*

Figure A-2 LEED rating system framework

Since the inception of LEED rating system in 1998, there have been several argues among the construction and building professionals regarding to its pros and cons. A recent study conducted by New Building Institute (NBI) and USGBC regarding to the energy performance of LEED buildings found the average of 28% energy reduction comparing to the national average (Turner and Frankel 2008). Newsham et al. (2009) conducted a re-analysis of data provided by NBI and USGBC (2008) and pointed out that, although, LEED buildings used 18–39% less energy per floor area, 28–35% of LEED buildings used more energy than their conventional counterparts. They have moreover demonstrated that, the energy performance of LEED buildings had little correlation with certification level of the building, or the number of energy credits achieved by the building at design time. Scofield (2009) criticized both above researches and stated that the site energy and source energy used by the LEED office buildings are statistically equivalent by their conventional counterparts. Research done in 2009 stated that the annual CO_2 reduction from energy efficiency and renewable material of LEED buildings was approximated 2.9 million tons (Watson 2009). In contrast, Scofield (2009) stated that LEED buildings, on average, are not delivering energy reduction, as a result, are not lowering greenhouse gas emission associated with building operation.

Researches related to financial returns of LEED buildings pointed out higher rent premium and resale value as well as 3.6% higher occupancy (Burr 2008). Case studies related to occupant productivity as a result of better indoor air quality and day-lighting of LEED buildings, shows 55% increase in productivity and 2.88 fewer sick days (N. G. Miller and Pogue 2009).

Ahn (2007) reported that building certified with LEED benefits of minimizing operating and maintenance costs (long-term cost saving), increasing employee health, productivity, and satisfaction, and improved indoor environment quality. However, this research also explains that based on construction companies' perception the cost of green buildings is substantially more than conventional counterparts. In addition, research conducted by Kats (2003) investigated the costs and financial benefits of green buildings. It resulted that high performance certified LEED buildings required higher initial investment (0 and 8) with respect to the level of LEED certification. Kats (2003) moreover investigated green premium levels versus level of green certification for offices and schools and found the average green cost premium of 0.66% for LEED Certified, 2.11% for LEED Silver, 1.82% for LEED Gold, and 6.5% for LEED Platinum.

ColEman (2004) conducted a comprehensive research about the values of LEED consumption as a green building rating system. In that research the aspects of green versus sustainable building have been investigated and resulted that, the LEED scope dose not explicitly consider socio-cultural and economic issues and mostly rely on local and transient market forces rather than global and longer term goals of sustainable building.

Several studies argues that the LEED approach to design green building is more mechanical than practical and LEED certification process does not necessarily lead to green building (Matthiesen and Morris 2004; T. M. Smith et al. 2006b). A critical report by National Institute of Standards and Technology (NIST) expresses that LEED "*does not fulfill its goal of providing a standard of measure*" (C. W. Scheuer and Keoleian 2002). This report concluded that LEED rating framework does not follow an integrated scoring/weighting to compare life cycle assessment results, and "*does not provide a consistent, organized structure for achievement of environmental goals*". In contrast, some other studies state that, LEED certification process can provide an integrated framework that facilitate primary basis for green building design (Kubba 2009; Yellamraju 2011).

Overall despite several researches have reported the benefits of LEED green building rating system, there are conflicting views between construction and building professionals about long-term cost benefits, significant environmental impacts mitigation such as reducing energy consumption and greenhouse gas emission, as well as health and productivity benefits of LEED green buildings.

A.2 BREEAM rating system

Building Research Establishment Environmental Assessment Method (BREEAM) is the first building environmental certification system and the most widely recognized measures of a building's environmental performance that was established and operated by the Building Research Establishment (BRE) in 1990 in the UK. The number of buildings certified with BREEAM reached to 200,000 in total by 2011 (BREEAM 2011). Recently, BREEAM certification has been become mandatory for all new housing projects in the UK.

BREEAM is a performance based assessment method and certification scheme that aims to provide a credible, environmental label for buildings. It has been developed to set an accessible, holistic and balanced measure of environmental impacts and sustainability issues to determine and ensure the buildings environmental performance (Anderson et al. 2009).

BREEAM (2011) stated that the primary aim of this rating system is to address a certification process, to measure, evaluate and reflect buildings' environmental performance in an independent, cost effective and robust manner. This tool enables developers, designers and building managers to apply a transparent, flexible, easy to understand and straightforward scoring system to demonstrate the environmental credentials of their buildings. BREEAM rating system covers a range of building types, including offices; industrial premises; retail outlets; schools, etc. (Lee and Burnett 2008). BREEAM has been applied as a reference model to adapt similar rating frameworks for local conditions in Canada, New Zealand, Australia, Norway, Singapore, Hong Kong, and etc. (Larsson 2000). For instance BREEAM Gulf has been adapted for Middle East local market and weightings were changed based on local environmental issues (e.g. water is the key issue, rather than energy as in the standard UK schemes) (J. Parker 2009a).

BREEAM (2011) stated that their rating system can be applied to assess the environmental life cycle impacts of any type of building, new and existing, at the design, construction and use stages. Type of built environment that can be rated based on the scope of the BREEAM latest version, 2011 New Construction, can be summarized as following:

- Commercial sector: Offices, industrial and retails (e.g. shopping center, restaurant, café)
- Public sector: Educational building including schools, colleges and universities, health care such as hospitals and clinics, prisons and law courts
- Multi-residential accommodation sector: Residential institutions such as residential care home, sheltered accommodation, residential college/school, and military barrack
- Other building sectors: Residential institutions including hotel/hostel, and training center, non-residential institutions including art gallery, museum, library, and worship place, assembly and leisure such as cinEma, theatre/music/concert hall, exhibition/conference hall as well as, indoor or outdoor sports/fitness and recreation, and other building like transport hub, research and development building, and crèche

In addition to BREEAM for new construction, *BREEAM In-Use* scheme has been developed for building managers to reduce the running (operational) costs and improve the environmental performance of occupied/unoccupied ‘existing buildings’. BREEAM In-Use can also be applied for minor refurbishment, renovation, and fit-out projects. This BREEAM scheme covers a range of building types, including commercial, industrial, retail and institutional buildings.

In addition, to provide opportunity for the project to show their environmental, social, and economic (TBL) benefits and to consider other sectors of built environment, *BREEAM*

Communities has been developed. BREEAM Communities focuses on mitigating the overall impacts of development projects within the built environment and address the sustainability issues of urban communities and living areas at the planning stage of the development process (Haapio 2011). BREEAM Communities scheme has been established to assist planners and developers to improve, evaluate, and independently certify the sustainability of 'project proposals' at the planning stage of the development process and to design urban communities with high quality of life and low environmental impact.

BREEAM addresses a broad range of categories and criteria including aspects related to energy and water use, the internal environment (health and well-being), pollution, transport, materials, waste, ecology and management processes. This tool sum the points scored in different impact areas to derive a single figure that can be described on a scale ranging from 'poor' to 'excellent' (Harris 1999). In general, BREEAM rating system determines the overall performance of a building project based on four elements that was shown in Figure A-3 and described as follow (*BREEAM 2011 Technical Manual* 2011):

1. BREEAM assessment issues and credits: To address environmental impact of a building nine environmental categories, plus a tenth category called 'innovation', and forty nine assessment issues subcategories defined in BREEAM (New Construction scheme 2011). A value of 'BREEAM credits' assigned to each assessment issue and where a building meets performance levels defined for that issue can obtain its related credit. Table B-4 summarized nine BREEAM major categories of criteria for design and procurements as well as assessment issues subcategories and their related credits. Awarded credits for a building must be determined by the assessor in accordance with each of the environmental and assessment issues. Then achieved credit percentage (achieved credit to maximum available credit) can be calculated for each of the tenth environmental issue.
2. The environmental section weightings: BREEAM weighting system determined based on a combination of consensus based weightings and ranking by a panel of experts. BREEAM weighting system applied to determine the relative impact of the BREEAM environmental issues (sections) and to calculate their contribution to the

overall BREEAM score. BREEAM Environmental section weightings based on the BREEAM New Construction scheme (2011) are:

- Management: 12%
- Health & Wellbeing: 15%
- Energy: 19%
- Transport: 8%
- Water: 6%
- Materials: 12.5%
- Waste: 7.5%
- Land Use & Ecology: 10%
- Pollution: 10%
- Innovation (additional): 10%

To calculate overall environmental section score, the percentage of 'credits' achieved in each section is multiplied by its related section weighting. Then the section scores are added together to give the overall BREEAM score. Indeed, a higher score indicate a less environmentally damaging building.

3. BREEAM rating benchmarks: The BREEAM rating benchmark represents a reference to understand typical sustainability performance of buildings and compare an individual building's performance with other BREEAM rated buildings. BREEAM rating benchmarks can be defined based on score percentage that are summarized in the below list:

    - Outstanding: 85%
    - Excellent: 70%
    - Very good: 55%
    - Good: 45%
    - Pass: 30%

– Unclassified: <30%

The overall score from previous section can be compared to the BREEAM rating benchmark levels to certify for the relevant BREEAM rating (See Figure A-4).

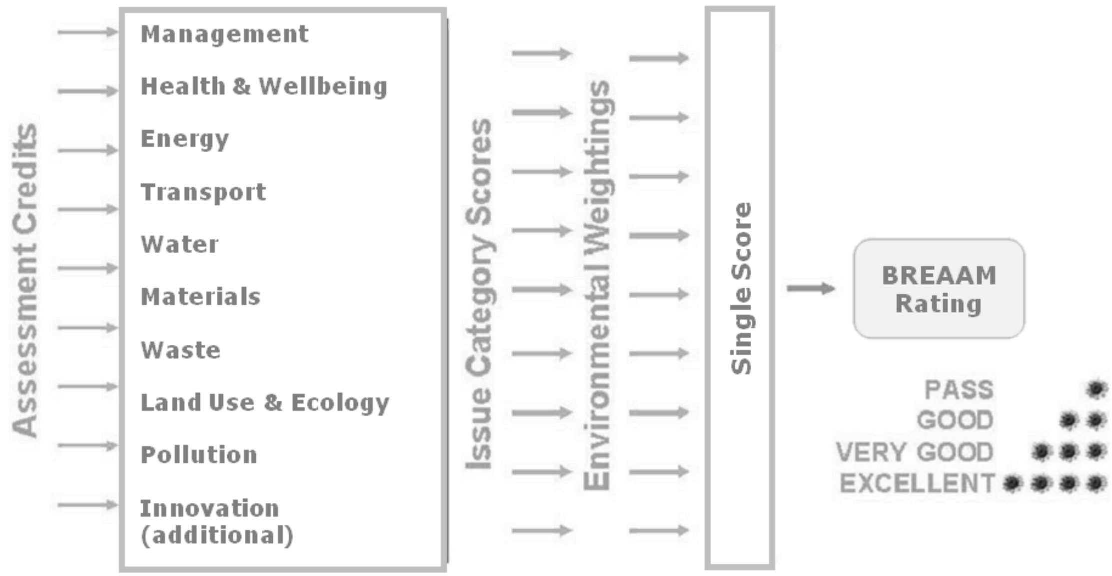


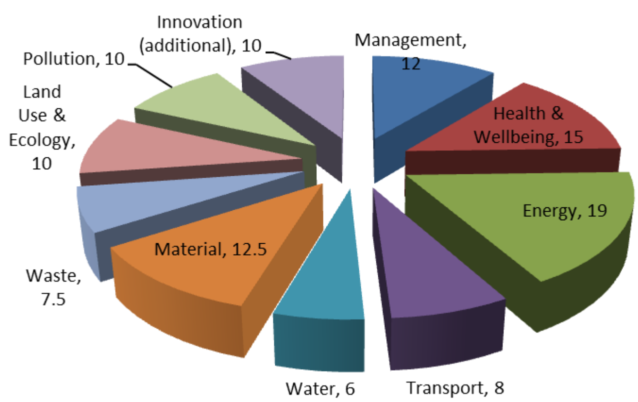
Figure A-3 BREAM sustainability assessment framework

4. The minimum BREEAM standards: BREEAM sets minimum acceptable levels of performance to be qualified for a particular BREEAM rating benchmark. To concede whether a building is qualified for the obtained rating, it is necessary to verify that all related minimum standards have been met. For example a building with excellent rating needs to achieve minimum credits under different environmental assessment issues (e.g. minimum 6 credits regarding to reduction of CO_2 emission and so on).

Table A-1 BREEAM major categories of criteria for design and procurements

Management	*Health & Wellbeing*	*Energy*	*Transport*	*Water*	*Materials*	*Waste*	*Land Use & Ecology*	*Pollution*
Sustainable Procurement (8)	Visual Comfort (4 or 6)	Reduction of CO_2 Emission (15)	Public transport accessibility (1-5)	Water consumption (5)	Life cycle impacts (1-6)	Construction waste management (4)	Site selection (2)	Impact of refrigerants (3)
Responsible Construction Practices (2)	Indoor Air Quality (6)	Energy Monitoring (1 or 2)	Proximity to amenities (1)	Water monitoring (1)	Hard landscaping and boundary protection (1)	Recycled aggregate (1)	Ecological value of site & ecological features (1)	NOx Emissions (1-3)
Construction Site Impacts (5)	Thermal Comfort (2)	External Lighting (1)	Cyclist facilities (1 or 2)	Water leak detection and prevention (2)	Responsible sourcing of material (3)	Operational waste (1)	Mitigating ecological impact (2)	Surface water runoff (5)
Stockholder Participation (4)	Water Quality (1)	Low and zero carbon technology (5)	Maximum car parking facilities (1 or 2)	Water efficient equipment (1)	Insulation (2)	Speculative floor and finishes (1)	Enhancing site ecology (1-3)	Reduction of night time light pollution (1)
Life Cycle Cost and Service Life Planning (3)	Acoustic Performance (2, 3or 4)	Energy Efficient cold storage (2)	Travel plan (1)		Designing for robustness (1)		Long term impact on biodiversity (1-3)	Noise attenuation (1)
	Safety and Security (2)	Energy efficient transportation system (2)						
		Energy efficient laboratory system (1-5)						
		Energy efficient equipment (2)						
		Drying space (1)						

One of the main specific characterizations of BREEAM rating system is certification process which is based on complex weighting system and can be only done by a BREEAM licensed assessors. BREEAM assessor is eligible to assess the evidence against the credit criteria, determines the BREEAM rating based on quantifiable sustainable design achievements, and report it to the BRE, who validate the assessment and issue the certificate (Fowler and Rauch 2006; Parker 2009b). Gu et al. (2006) stated that, BREEAM uses a slightly more complex algorithm comparing to the other rating systems. Eszter Gulacsy asserts that BREEAM applies more academic and rigorous approach to the environmental sustainability of buildings, comparing to the simpler approach such as LEED.



REEAM area	Weighting
Management	12%
Energy use	19%
Health and well being	15%
Transport	8%
Waste	7.5%
Land use & ecology	10%
Pollution	10%
Materials	12.5%
Water	6%
	100%

BREEAM rating	Points required
Outstanding	≥ 85%
Excellent	≥ 70%
Very good	≥ 55%
Good	≥ 45%
Pass	≥ 30%

Figure A-4 BREEAM rating system framework

Some studies argues that BREEAM dictates very specific and exact requirements technologies or strategies, despite other rating system such as LEED that consider designers discretion to meet the required standards (ISEMA 2010). In addition, BREEAM assess absolute performance due to minimize the overall emission of CO_2 and assign credits based on *absolute values* while other rating system such as LEED seek to determine the improvement in the design (as a percentage) and allocate credits based on *percentage improvement* (Lee and Burnett 2008). For instance, BREEAM mandates maximum energy usage targets of about 70 kWh/ m^2 per year, in contrast LEED requires buildings improve energy efficiency savings by 15-60 % over a base case.

A report by Inbuilt Ltd (2010) conducted a detailed credit comparison to find the significant differences and similarities of BREEAM 2008 and LEED 2009. The report pointed out several different in credits and main focuses areas. For example it was shown that BREEAM emphasized more on cyclist safety, water, and acoustics rather than LEED, while LEED focus more on occupant comfort and internal pollution issues. It also described that both BREEAM and LEED rating system are constrained measure tool, especially in calculating carbon and energy savings. While BREEAM calculate credits based on a target to acquire zero carbon emissions, LEED emphasize on energy cost saving and links credits to the US Dollar (J. Parker 2009b). It means that if the exchange rate becomes unfavorable, then the building's rating based on LEED could suffer.

In a research conducted by Lee and Burnett (2008) energy assessment methods based on three rating system (HK-BEAM[28], BREEAM and LEED) have been compared. They declared that, although BREEAM relies on actual consumption figures, the two other rating systems are based on simulation results. The result also demonstrated that, achieving credits under BREEAM rating system is most difficult because BREEAM relatively sets a more aggressive reduction target to meet performance criteria. Gu et al., (2006) also rEmarked BREEAM as the most ecological indicator-based building environmental assessment method.

A.3 Green Globes rating system

The inception of Green Globes™ assessment and rating system rooted in the BREEAM publishing in Canada in 1996, by the Canadian Standards Association (CSA), for Existing Buildings. It was initially developed in cooperation with one of the BREEAM creator, ECD Energy and Environment, as a rating and assessment system for monitoring and assessing green building in Canada, called Green leaf (Kubba, 2009). Green Globes™ was released in Canada in January 2002.

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[28] Hong Kong Building Environmental Assessment Method that was developed based on BREEAM framework (Fowler and Rauch 2006)

The Green Globes system is now applied in Canada and the USA. In Canada Green Globes for Existing Buildings is operated by the Building Owners and Managers Association of Canada (BOMA) under the brand name 'BOMA BESt', while all other Canadian Green Globes products are owned and operated by ECD Energy and Environment Canada Ltd. Green Globes was brought in to the US market as an alternative to the LEED rating system. Green Globes™ US was adapted from Green Globes Canada in 2004 that is owned and operated by the Green Building Initiative (GBI), an accredited standards developer under the American National Standards Institute (ANSI) (Green Globes 2012a) .

One of the original intentions of Green Glob development was to allow building professionals and owners to self-assess the performance of their existing building (Kubba, 2009). For this purpose, Green Globes system has been established as a web-based self-assessment performance assessment software tool that delivers an online assessment protocol, rating system and a user-friendly interactive guidance for green building design, operation and management (Smith et al. 2006). Since its initial establishment, Green Globes comprises of a series of questionnaires with respect to the each project delivery phase as well as the role of user in design team (e.g. civil engineer, architect, or landscape architect, etc.). Using Yes/No/Na type questionnaires for each stage of project delivery, the program offers an interactive, flexible and affordable assessment tool and guidance reports. Green Globes evaluates and rates the environmental performance of new and existing buildings, and interior fit-ups and consists of 5 different assessment schemes (Green Globes 2012b):

- Design of New Buildings or Significant Renovation
    - US version: Green Globes® for New Construction (NC) provides building sustainability assessment, education and feedback throughout the design-build-commission project life cycle for new commercial buildings.
    - Canadian Version: Green Globes Design™ for New Buildings and Retrofits Rating System provides certification and awards for green building design and management
- Management and Operation of Existing Buildings
    - US version: Green Globes® for Continual Improvement of Existing Buildings (CIEB) delivers a comprehensive assessment tool for evaluating, rating, and improving the environmental footprint and/or sustainability of commercial buildings.

- Canadian Version consist of :
    - Office Buildings (BOMA Canada - BOMA BESt) provides certification and awards for office buildings, shopping centers, open air retail and light industrial properties
    - Multi-residential Buildings
    - Light Industrial Buildings

- Building Emergency Management Assessment: Green Globes BEMA, which is maintained by ECD Energy and Environment Canada and provides a performance measurement and benchmarking tool to evaluate the emergency management of assets with respect to disasters and incidents of all kinds.
- Building Intelligence: The Building Intelligence Quotient (BIQ™) which is developed by Continental Association for Building Automation (CABA) to evaluate and measure the "value" of intelligent building performance
- Fit-Up: Green Globes Fit-up which is established by ECD Energy and Environment Canada to integrate sustainable principles in the design of new or the remodeling of existing commercial interiors.

The main propose of Green Globes building rating system is to provide an assessment tool for characterizing a building's environmental performance and energy efficiency. The system also aims to provide guidance for green building design, operation, and management. Accordingly, Green Globes rating system for new building was developed under seven areas of building environmental performance: *Project management*, *Site*, *Energy*, *Water*, *Resources*, *Emissions* and *Indoor Environment*. Green Globes rating system for 'existing buildings' also follows the same areas of assessment excepting Site Impact. Green Globes rating system determines the overall performance of a building project based on four stages and will be described in below based on Green Globes Design for New Buildings and Retrofits (2004):

1. Selecting project stage; a total of eight design phases are supported in A Green Globes questionnaire was allocated to each of the eight project stages. In addition, numerical

assessment scores have been allocated to two of the eight project phases: Schematic design phase and construction document phase.

2. Completing questionnaire; Green Globes questionnaire correlates to a checklist with a total of 1,000 points listed in seven modules (project management, site, energy, water, resources, emissions, and indoor environment). Number of points to quantify overall building performance has been assigned to each area as are indicated in Table B-4. The Green Globes scoring process for environmental categories can be done by completing online questionnaire with logical sequence of approximately 150 questions.
3. Rating and reports; after completing Green Globes survey, an automatic report will be produced providing building projected rating and feedbacks. A rating of one or more (maximum for Canada is 5 while for the US is 4) Green Globes can be obtained by a building based on percentage of applicable pointes that have achieved. Building percentage rating will be reported for each area of assessment as well as building overall score.
4. Green globes rating and certification; if automated report indicates a predicted rating of minimum 35 percent of 1000 available points, it is possible to order a third-party assessment. A building must be assessed by an independent third party, affiliated and trained by Green Globes, in order to earn a formal Green Globes rating report and certification.

One of the most important features of Green Globes comparing to other rating system is that it was designed to be cost effective and affordable. A study conducted by the University of Minnesota comparing Green Globes and LEED recognized both rating system very similar (Smith et al. 2006a). The research stated that, 80-85 percent of the performance categories that points allocated to them have been addressed in both systems. The study also characterized Green Globes rating system as more flexible and user friendly and less costly and time-consuming comparing to the LEED that is more rigid and complex system. The study concluded that while Green Globes has greater emphasize on energy efficiency, LEED focuses more on materials choices.

Table A-2 Green Globes assessment areas and related weighting and scoring

Area and sub-area of assessment		*Points score*
A	**Project Management (5%)**	**50**
A1	Integrated design process	20
A2	Environmental purchasing	10
A3	Commissioning	15
A4	Emergency response plan	5
B	**Site (11.5%)**	**115**
B1	Development areas	30
B2	Ecological impacts	30
B3	Watershed features	20
B4	Site ecology enhancement	35
C	**Energy (38%)**	**380**
C1	Energy performance	100
C2	Reduce energy demand	114
C3	Integration of energy efficient systems	66
C4	Renewable energy sources	20
C5	Energy-efficient transportation	80
D	**Water (8.5%)**	**85**
D1	Water Performance	30
D2	Water conserving features	45
D3	On-site treatment of water	10
E	**Resources (10%)**	**100**
E1	Low impact systems and materials	40
E2	Minimal consumption of resource	15
E3	Reuse of existing building	15
E4	Building, durability, adaptability and disassembly	15
E5	Reduction, reuse and recycling of demolition waste	5
E6	Recycling and composting facilities	10
F	**Emission, Effluent & Other Impacts (70%)**	**70**
F1	Air emissions	15
F2	Ozone depletion	20
F3	Avoiding sewer and waterway contamination	10
F4	Pollution minimization	25
G	**Indoor Environment (20%)**	**200**
G1	Ventilation system	55
G2	Control of indoor pollutants	45
G3	Lighting	50
G4	Thermal comfort	20
G5	Acoustic comfort	20

Another important characteristic of Green Globes comparing to other rating system is that, any construction team member with general knowledge about buildings can assess building applying Green Globes web-based self-assessment tool. Green Building Initiative (GBI) encourage building professionals to carry out a life cycle assessment to evaluate life cycle impact of design choices and to award points in the resources section. Accordingly, Green Globes recommends using LCA tools, Athena[29] at the Schematic design stage and BEES (Building for Environmental and Economic Sustainability) at the construction documentation stage (Fowler and Rauch 2006).

Malin (2005) has argued that Green Globes is more comprehensive than LEED in terms of technical content, including points for issues such as optimized use of space, acoustical comfort, and an integrated design process. Moreover, Kibert (2008) discuses that, although Green Globes structure is similar to LEED in many aspects, Green Globes address some additional issues such as project management, life cycle assessment (LCA), deconstruction, emergency response planning, adaptability, durability, and noise control.

However, despite rating system such as LEED, Green Globes does not consider project performance strategies and innovations, which are not mentioned in Green Globes questionnaires. For instance, points are granted for exterior lighting to avoid glare or sky glow, while for the project without exterior light, project neither achieve point nor penalize (Kubba, 2009). In addition, while the available numbers of point in rating system such as LEED are fixed, the total potential number of points achieved based on Green Globes is adjustable with respect to the project location (Kibert 2008).

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[29] ATHENA® *EcoCalculator for Building Assemblies*

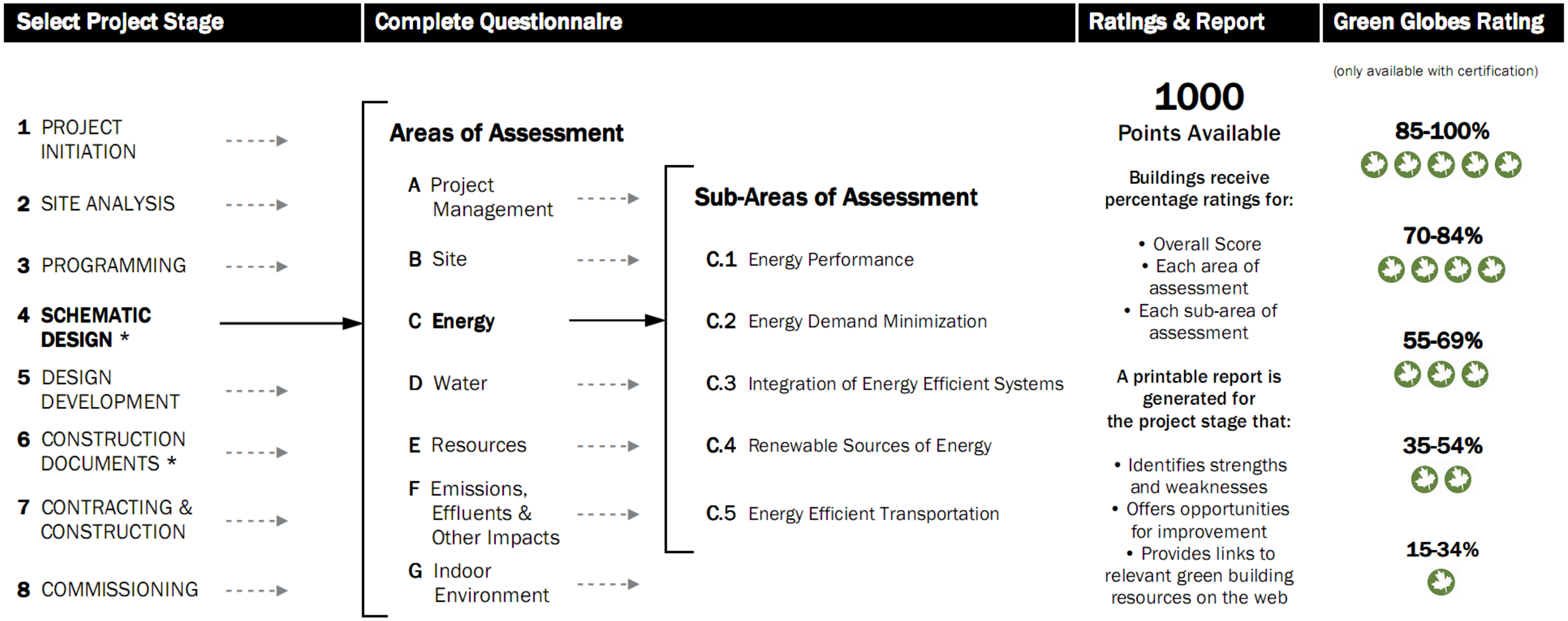


Figure A-5 Green Globes assessment framework

However, despite rating system such as LEED, Green Globes does not consider project performance strategies and innovations, which are not mentioned in Green Globes questionnaires. For instance, points are granted for exterior lighting to avoid glare or sky glow, while for the project without exterior light, project neither achieve point nor penalize (Kubba, 2009). In addition, while the available numbers of point in rating system such as LEED are fixed, the total potential number of points achieved based on Green Globes is adjustable with respect to the project location (Kibert 2008).

A.4 SB-Tool building performance rating system

SBTool (Sustainable Building Tool), formerly known as GBTool (Green Building Tool), is an international generic framework for rating the sustainable performance of buildings and projects. It established qualitative and quantitative measures to evaluate sustainable design achievements and assess energy and environmental performance of buildings. SBTool is the software implementation of the Green Building Challenge (GBC) assessment method that has been under development since 1996 through the work of more than 20 countries, and is currently led by the members of International Initiative for a Sustainable Built Environment (iiSBE). SBTool is a computer support system in the form of a spreadsheet (Ruiz and Fernández 2009a) that involves a consensus of different viewpoints from participants operating in widely differing environmental, climatic, economic, and socio-cultural regions (Cole 2001).

One of the most important feature of SBTool that sets it apart from existing assessment systems is that, the system has been designed to be adapted according to the variety of priorities, technologies, building traditions and even cultural values that exist in various regions and countries (Cole et al. 2002). SBTool system is a rating framework or toolbox, designed to allow third parties to adapt locally relevant rating systems by establishing parameter weights that reflect the varying importance of issues in the region, and relevant benchmarks by occupancy type, in local languages.

Larsson (2012) reported that SBTool is a generic framework that can only become a rating tool if a third party adjusts it to suit the unique conditions applicable to a building type in specific region by defining scope and setting weights, context and performance benchmarks. To apply SBTool, each country cooperates with a third party team to establish region-specific and site-specific context factors and criteria benchmarks. Consequently, as an international rating system, SBTool has been designed to enable of user-defined scoring scales and weights to replace the defaults provided in the start-up version and to reflect regional conditions, industry consensus, practices, and goals. However, the calibration to local conditions should not destroy the value of SBTool common structure and terminology.

SBTool addresses different life cycle phases of planning, design, construction and assess new and renovation projects, large projects and single buildings, residential and commercial, as well as new and existing construction with different types of building and occupancy, (independent housing, semi-detached housing, supermarket, hospital, laboratory, small industry, warehouse, hotel, office, inside car park, etc.) (iiSBE 2007a; Ruiz and Fernández 2009b). According to SBTool 2012 this rating system combines of two distinct assessment modules that are linked to phases of the life-cycle; one carried out in the pre-design phase of *site assessment*,; and the other carried out in the design, construction or operations phases of *building assessment* (Larsson 2012b). SBTool can also be applied for mixed-use project comprises of up to three different types of occupancy in a single project (Ruiz and Fernández 2009b). Accordingly, "*parameters can be calibrated for up to three occupancy types, within a single building or as separate structures in a large project"* (Larsson 2012b).

Building's environmental performance assessment framework in SBTool have been structured hierarchically into three levels; first level consists of eight core *Performance Issues* that have been further divided into two level of *Performance Categories*, *Performance Criteria* (McKay 2007). Performance levels are evaluated based on performance score/value that can be vary by location and often by building type. The performance value scoring system is ranged from negative to positive points and assigned in a range of -1 (worst) to +5 (best). Negative point represents deficient condition below the performance benchmark and given to indicate levels of unsatisfactory performance, while 0 addresses the benchmark for the minimum acceptable performance level and are given for standard practices, and 5 indicates best practice and a level of performance that is considerably in advance of the current target.

At the first level of SBTool assessment framework, "sustainability performance" is addressed in two main phases and totals eight core *Performance Issues* listed in below:

- Issues and categories S, pre-design phase only
  - Site location, available services and site characteristics
- Issues and categories A to G, design, construction and operations phases
  - A site regeneration and development, urban design and infrastructure energy and resource consumption
  - Energy and resource consumption
  - Environmental loadings
  - Indoor environmental quality
  - Service quality
  - Social, cultural and perceptual aspects
  - Cost and economic aspects

Each performance issue comprises of several *Performance Categories* that were placed in the second level of SBTool framework and are further divided to 125 *Performance Criteria*. Performance categories are generic and broadly applicable, while performance criteria are building- and region- specific. Consequently, the tool is designed to activate and deactivate the different criteria to be assessed, depending on the region and phase the project is at and the type of occupancy chosen. Larsson (2012) described that, SBTool scope can be adapted to be as narrow or as broad as intended, ranging from 120 criteria to half a dozen.

Larsson (2012) stated that, "*the scoring process in SBTool relies on a series of comparisons between the characteristics of object building and national or regional references for* *minimally acceptable practice, "good" practice and "best" practice"*. Then the criteria scores can be derived through the weighting of the scores, multiplying each value by its appropriate weight. Weights indicate the relative importance of active parameters throughout the system. According to SBTool 2012 weighting system the fundamental factors considered to generate weights include the following aspects (Larsson 2012b):

a. Extent of potential effect

b. Duration of potential effect

c. Intensity of potential effect

d. Importance of primary system directly affected

Weightings at the category and issue levels can either drive following the defaults or can be calculated by the third party national teams to customize the local needs. SBTool authorized third parties the ability to adjust the automated calculated weights derived based on above factors, up or down a maximum of 10%. However, at the lower levels, criteria are automatically weighted following the default procedure of SBTool. One reason is that there are more than 120 criteria that could be active, and it would be impractical to assign weights for each one separately (iiSBE 2011a). Accordingly, default weights have been provided, and then third parties can turn off the weight for individual criterion if it appears to be inapplicable to the purpose of the assessments (iiSBE 2008).

To give some objective basis to these weights, a scale of 1 to 3 was defined according to estimate the extension of the potential effect (global = 3, urban = 2 and building = 1), the intensity of the potential effect (direct = 3, indirect = 2 and weak = 1) and the duration of the potential effect (> 50 years = 3, > 10 years = 2, < 10 years = 1) (Ruiz and Fernández 2009b). Performance issues and categories based on SBTool 2010 as well as an example set of weights established for a project in Atlantis were summarized in Figure A-6 (iiSBE 2011b).

Table A-3 SBTool performance issues and categories

Performance issues and categories		*Weight*
A	**Site Suitability and Development**	**13.7%**
A1	Site Suitability	10.5%
A2	Urban Design and Site Development	3.3%
B	**Energy and Resource Consumption**	**15.1%**
B1	Total Life Cycle Non-Renewable Energy	3.8%
B2	Electrical peak demand	3.1%
B3	Use of Materials	4.5%
B4	Use of potable water, storm water and grey water	3.8%
C	**Environmental Loadings**	**22.3%**
C1	Greenhouse Gas Emissions	4.7%
C2	Other Atmospheric Emissions	3.3%
C3	Solid and Liquid Wastes	3.2%
C4	Impacts on Project Site	4.8%
C5	Other Local and Regional Impacts	6.3%
D	**Indoor Environmental Quality**	**16.1%**
D1	Indoor Air Quality	2.6%
D2	Ventilation	5.2%
D4	Day lighting and Illumination	3.9%
D5	Noise and Acoustics	2.0%
E	**Service Quality**	**23.5%**
E1	Safety and Security During Operations	13.3%
E2	Functionality and efficiency	5.8%
E3	Controllability	1.3%
E4	Flexibility and Adaptability	1.5%
E5	Optimization and Maintenance of Operating Performance	1.6%
F	**Social and Economic Aspects**	**6.3%**
F1	Social Aspects	4.0%
F2	Cost and Economics	2.3%
G	**Cultural and Perceptual Aspects**	**2.7%**
G1	Culture & Heritage	1.3%
G2	Perceptual	1.4%

SBTool scoring-weighting procedure as it was shown in Figure A-7 can be summarized in following 5 steps:

1. Criteria are scored according to the following benchmarks:
   -1 = Deficient
   0 = Minimum acceptable performance
   +3 = Good Practice
   +5 = Best practice
2. Criteria scores are weighted;
3. Category scores can be derived through the aggregating of the weighted scores of constituent criteria;
4. Issue scores are the total of weighted category scores.
5. The overall building score is obtained through the weighted scores of issues. Total results are present in the standardized scale between − 1 and 5.

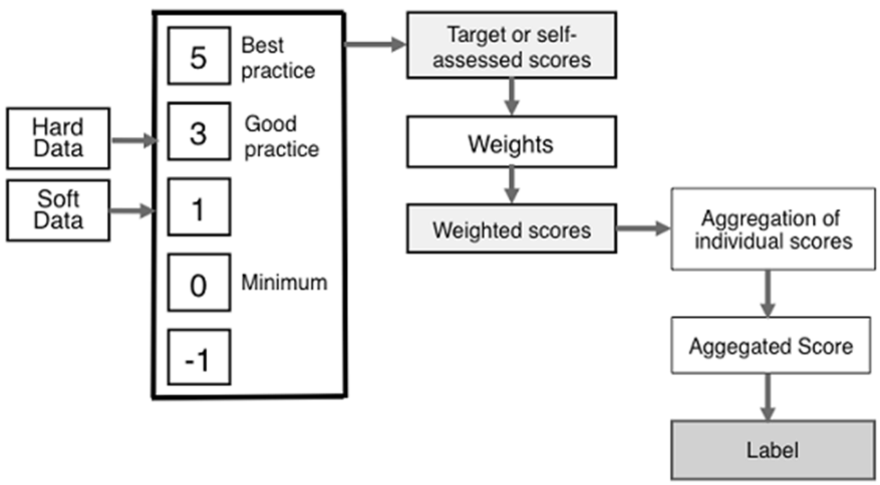


Figure A-7 SBTool assessment framework (addopted from iiSBE 2011b)**.**

This is necessary to mention that criteria can be assessed and scored quantitative or qualitative (Ruiz and Fernández 2009b). A score can be assigned for quantitative values, comparing the quantitative value, achieved from standard method/tool such as generic LCA, with the target value which represents the highest scoring. The evaluation of qualitative criteria is based on the alternative chosen among four possibilities to obtain a score of − 1 to 5 as discussed above. Finally, SBTool produces both relative performance result and absolute results; the system provides an estimation to local industry on the state of performance in the region, while also provides absolute data to reflect global sustainability and to permit international comparisons (iiSBE 2007b).

Ruiz and Fernandez (2009) recognized SBTool as a comprehensive rating method that consider triple bottom line sustainability impact (environmental, economic and social) and can be applied for a wide range of different types of buildings in different life cycle phases of the project. Lee and Burnett (2005) distinguished it as *"the most comprehensive environmental assessment framework for building that explicitly includes the core elements of sustainable development"*.

Todd and Geissler (2001) compared environmental performance tools and pointed out that scope of GBC (basis of SBTool) has been extended beyond the building level by considering community needs, despite of other rating system such as LEED. They stated that GBC indicates environmental implications more clearly, and can be revised at the direction of the International Framework Committee. They further declared that GBC framework can surrogate estimation methods in the absence of data. For instance, when a country or region do not have access to embodied energy databases for building materials, estimating methods has been provided to fill this gap.

Chang et al. (2007) recognized SBTool as the most useful generic framework that can apply as a reference and basis for developing a domestic assessment method. Crawley and Aho (1999) pointed out that the nesting structure (criteria and subcriteria) is the most important feature of SBTool basic framework that can accommodate the large variation in information and detail available on buildings. On the other hand, they revealed that most users found the SBTool difficult to use because of its complex framework. Fowler and Rauch (2006) also concede that, due to the flexibility inherent in the application of SBTool, it requires greater technical expertise to implement comparing to the other rating systems.

A.5 CASBEE rating systems for sustainable built environment

Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) is a tool for assessing and rating the environmental performance of buildings and built environment and was release in 2001. CASBEE has been developed to provide suitable consideration for issues and problems peculiar to Japan and Asia (CASBEE 2012). Xiaoping et al. (2009) stated that CASBEE development has been deeply influenced by the GBTool. CASBEE has been established as a joint industrial/government/academic project under the support of the Japanese ministry of Land, Infrastructure, Transport and Tourism. The CASBEE Research Committee and its affiliated sub-committees (e.g. sub-committee on energy review) constituted at Japan Sustainable Building Consortium (JSBC) providing overall project operation.

The major goal that has been followed by CASBEE developer is developing as simple as possible assessment framework to award high assessments to superior buildings, and to be applicable for a wide range of building types. One of the most important characterizations of CASBEE is that it was developed based on architectural design process and corresponding to the entire building life cycle, starting from the pre-design stage and continuing through design and post design stages (CASBEE 2012). Accordingly CASBEE is composed of four following assessment tools with specific purpose and target users (CASBEE 2012):

- Tool-0 CASBEE for Pre-design: it was developed in order to address project primary issues such as the basic environmental impact of the project and selecting a suitable site, and to evaluate environmental performance of a project at the pre-design stage.
- Tool-1 CASBEE for New Construction (CASBEE-NC): it was developed in order to assess a building based on the design specification and the anticipated performance during its design process. It is in fact a self-assessment check system that can also serve as a labeling tool if a building has been evaluated further by an expert third-part.
- Tool-2 CASBEE for Existing Building (CASBEE-EB): it was developed in order to address performance issues of existing building stocks, based on their operation records for at least one year after completion.
- Tool-4 CASBEE for Renovation (CASBEE-RN): it was developed in order to respond growing demand for building stock renovation in Japan. This tool can be

used to generate proposals for existing buildings operation monitoring, commissioning and upgrade design.

Another important specific characterization of CASBEE is developing various versions according to the specific purposes and with different applications including CASBEE for detached houses, for temporary construction, for urban development, for cities, for heat island effect , CASBEE brief versions encompassing CASBEE-NC brief version, CASBEE-EB brief version, CASBEE-RN brief version, and CASBEE for urban development brief version, and CASBEE local government versions (CASBEE-Nagoya, CASBEE-Osaka, CASBEE-Yokohama etc.) that used by some local governments in Japan and provide modified weighting coefficients to address local conditions, such as climate and prioritized policies (CASBEE 2012).

CASBEE offers a more comprehensive perspective to sustainability assessment of built environment (stage 4 environmental assessments) by taking urban development and cities into consideration. CASBEE for URBAN DEVELOPMENT has been developed to address broader assessments, and to adopt holistic approach delivered through the urban areas. This CASBEE version can be applied for recent city-center redevelopment projects that "*have been planned for integration with their surrounding districts and delivering positive effects for the environment, like promoting the use of area energy networks*" (CASBEE 2012). In addition CASBEE for Cities has been developed to comprehensively evaluate the effectiveness of the city's policies and environmental measures, and objectively assess the environmental performance of cities, using TBL sustainability performance criteria (CASBEE 2012).

Another important specific characterization of CASBEE is offering the unique "Built Environment Efficiency (BEE) approach" representing the performance evaluation criteria. It presents a new concept for built environment sustainability assessment distinguishing *Built Environment Quality* from *Built Environment Load* (Fowler and Rauch 2006). Accordingly, CASBEE divided and understudied built environment into two spaces, internal and external, using the hypothetical site boundary. Inside the boundary, living amenity for the building users, can be evaluated based on Built Environment Quality *(Q)* concept while negative aspects of environmental impact beyond the hypothetical enclosed space to the outside, the public property, can be assessed using the Built Environment Load *(L)* Concept (CASBEE 2012).

CASBEE covers the four assessment fields: (1) Energy efficiency; (2) Resource efficiency; (3) Local environment; (4) and Indoor environment. These main assessment fields can be classified and re-categorized as following (Fowler and Rauch 2006):

- *Built Environment Quality (BEE numerator Q)*

- Q-1 Indoor environment (noise and acoustics, thermal comfort, lighting and illumination, and air quality)
- Q-2 Quality of services (functionality and usability, amenities, durability and reliability, flexibility and adaptability)
- Q-3 Outdoor environment on site (preservation and creation of biotope, townscape and landscape, and outdoor amenities)

- *Built Environmental Load (BEE denominator L)*

- LR-1 Energy (thermal load, use of natural energy, efficiency of systems, and efficient
- operations)
- LR-2 Resources and materials (water conservation, recycled materials, sustainably harvested timber, materials with low health risks, reuse and reusability, and avoidance of CFCs and Halons)
- LR-3 Off-site environment (air pollution, noise and vibration, odor, sunlight obstruction, light pollution, heat island effect, and local on local infrastructure)

Further, the core concept of CASBEE, the value of BEE (Building Environment Efficiency), can be achieved based on Q and L as the two assessment categories. BEE, as indicated in Equation (1) is an indicator to evaluate the sustainability of the green building and can be calculated from Q (built environmental quality) as the numerator and L (built environment load) as the denominator (CASBEE 2012).

$$\text{Built Environment Efficiency (BEE)} = \frac{\text{Q (Built Environment Quality)}}{\text{(L)Building Environmental Loadings}} \quad \textbf{(8)}$$

To operate CASBEE rating system, the assessor should fill out two assessment forms, the Main Sheet and the Score Sheet, at each design stage. Score Sheet is divided into sections representing the assessment categories indicated above. Assessment categories or major items (e.g. Q-1, LR-3), are subdivided into one to three stages ("medium-level item," "minor item," and "detailed item," respectively) and total of 54 assessment items (e.g. thermal comfort) allocated to these categories (IBEC 2007a). Each single assessment items can be evaluated by a scoring policy. Scores can be achieved using the scoring criteria for each assessment item based on two indicators of *Q* representing the Built Environment Quality and *LR* representing the level of performance in minimizing built environment load imposed outside the hypothetical boundary (JaGBC 2011).

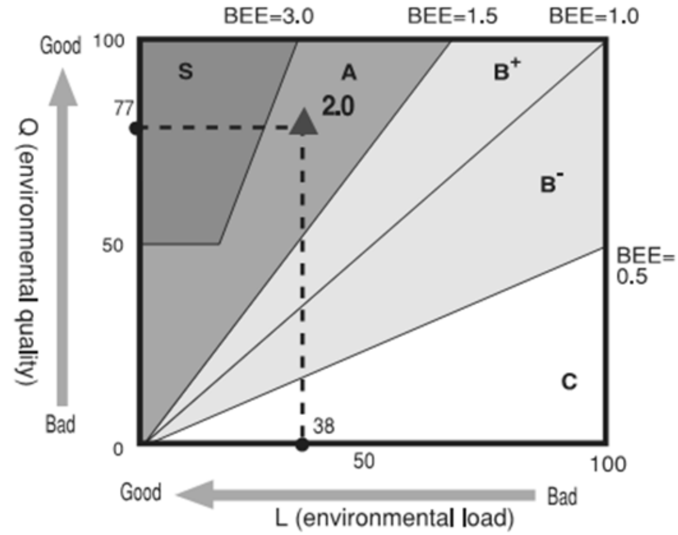
A five-level scoring system is used and each CASBEE criterion is scored from level 1 representing a minimum level of technical and social standards achievement to level 5 defined as meeting all requirements at the time of assessment, and a score of level 3 indicates an "average" or typical technical and social levels at the time of the assessment. The scores of subdivision assessment items under each assessment category summed up to identify which efforts in which category are excellent or poor (JaGBC 2011). Scoring results of medium-level items are indicated with bar charts in Assessment Result Sheet.

Then, the scores for each assessment item are multiplied by the ‘weighting coefficient’, and aggregated into SQ; total weighted scores for *Q* or S*LR*; total scores for *LR* respectively. Weighting coefficients were determined based on the statistically processed results. Accordingly, a number of questionnaires sent to stakeholders of CASBEE (e.g. CASBEE for Detached House) including owners, housing suppliers, administrative officials, and scholars to collect different expert opinions related to the relative importance of major items or assessment categories Then the weighting coefficients among major items (e.g.Q3 and Q2) were determined based on a statistical technique of the analytic hierarchy process (AHP).

The weighting coefficients resulting from this statistical process reflect the differences in senses of values among individuals in their own capacity. Further, SQ and SLR can be calculated using weighted scores of major items (IBEC 2007b). For example, SQ = 0.4 SQ1 + 0.3 SQ2 + 0.3 SQ3 and LR = 0.4 SLR1 + 0.3 SLR2 + 0.3 SLR3, where *SQi* represents score for *Qi* category and *SLRi* indicates score for *LRi* category (CASBEE 2011). As *SQ* represents the total weighted score of Built environment quality (*Q)* category, the numerator *Q* can derived from *SQ*. Similarly, the denominator of environmental load (*L*) can be determined from *SLR* (CASBEE 2012). As a result BEE value can be calculated based on (9:

$$\mathrm{BEE} = \frac{25 * (\mathrm{SQ} - 1)}{25 * (5 - \mathrm{SLR})} \quad \textbf{(9)}$$

Based on BEE value, results are presented on a spider web graph, by plotting *L* on the x axis and *Q* on the y axis as it was shown in Figure A-8. As it was demonstrated in this Figure, BEE value represents the gradient of the line joining the point with coordinates equal to the *Q* and *L* values to the origin (Q=0, L=0). The higher the *Q* value and the lower the *L* value, the steeper the gradient and the higher performance achievement. Accordingly, the best built environment practices will fall in the section representing highest quality and lowest environmental load. Finally, the under studied built environment can be classified corresponding to regions divided according to the line gradient in five ranks (according to the BEE value) from C (poor) through B- (slightly poor), B+ (good), A (very good), and S (excellent) (IBEC 2007b).



Ranks	Assess ment	BEE value, etc.	Expression
S	Excelle nt	BEE >= 3.0, Q >= 50	★★★★★
A	Very Good	3.0 > BEE >= 1.5	★★★★
B+	Good	1.5 > BEE >= 1.0	★★★
B-	Slightly Poor	1.0 > BEE >= 0.5	★★★
C	Poor	BEE < 0.5	★

Figure A-8 CASBEE rating system framework

According to the CASBEE website statistics the numbers of CASBEE assessment reports have been submitted to the local governments reached from only 174 cases in 2004 to over 6600 as of December 2011, and the number of CASBEE certified buildings reached to the number of 193. It can be realized that CASBEE as a voluntary-basis evaluation tool has gained more attention and used by more construction companies, design offices, real-estate developers, for checking the environmental performance of their buildings (CASBEE 2012).

CASBEE rating system operation requires documentation of quantifiable sustainable design achievements which are assessed by trained, first-class architects, which have passed the CASBEE assessor examination. Lee (2011) stated that CASBEE as a most recent scheme offers relatively more liberal performance scales, as compare to the earlier developed shames such as LEED whit more stringent scale. In this research benchmarking energy use of different building environmental assessment schemes has been studied and found out, CASBEE use different performance indicators by applying predicted annual energy consumption as an indirect indicator of the incurred environmental impact. On the other hand, BREEAM adopts CO2 emission, which is directly related to global warming, and

LEED adopts the energy cost budget (ECB) approach, which involves converting energy use into energy cost (Lee 2011).

One of the most important differences of CASBEE to other rating system is that, it has considered three sectors of built environment, i.e. housing scale, building scale and urban scale. Despite other rating systems, CASBEE distinguish inside and outside the building boundary considering both living amenity for the building users as well as public property and building surrounding. Moreover some unique versions of this rating system have been developed to provide a deep insight into sustainability issues of urbanization. For instance, CASBEE-HI (Heat Island) has been developed to evaluate efforts in buildings to alleviate heat island phenomena and climate change effect associated with urbanization. Accordingly, *BEE-HI* has been presented as a building environment efficiency indicator to improve outdoor thermal comfort within a building site (*QHI*) and heat island load emitted from the building site to its surroundings (*LHI*) (Oguro et al. 2006).

Furthermore, CASBEE for Urban Development (CASBEE-UD) focuses on the assessment of areas of development as a whole; buildings conglomeration phenomena, as well as several other issues related outdoor spaces (Haapio 2011). By applying CASBEE-UD evaluation of "new towns" development is possible. CASBEE-UD offers broader assessments as compared to the other rating systems in context of urban system, i.e. BREEAM Communities and LEED for Neighborhood Development (LEED-ND), by adopting holistic approach delivered through the urban area (CASBEE 2012). It is necessary to mention that CASBEE-UD was the first available assessment tools for urban communities that released on the market, followed by BREEAM Communities and then LEED-ND.

Haapio (2011) investigated all three rating system that cover urbanization issues, CASBEE-UD, BREEAM Communities, LEED-ND, and compare them according to the used categories and ratings, region of the origin, and site location. In this research it was shown that, the most fundamental category within CASBEE-UD is *Infrastructure*. In addition, resources and energy, ecology, and well-being (only in CASBEE) have been taken into consideration by CASBEE-UD. On the other hand, the *Infrastructure and Transportation* categories are emphasized more in BREEAM Communities. In contrast LEED ND emphasized more on *Infrastructure and Ecology*.

In addition, the latest CASBEE tool, referred to as CASBEE-City has been developed in cooperation with Promotion Council of Low Carbon Cities (PCLCC), to assess and disclose actual condition of a city. Such assessment and disclosure result could provide valuable information to the public and improve citizens' understanding of the sustainability issues of their city and urban area (JaGBC 2011). CASBEE for City further aims to present a market mechanism to encourage local governments and other stakeholders to make more appropriate local policy and strategy to address specific urban and environmental issues (JaGBC 2011). Murakami et al. (2011) described that CASBEE-City has been developed based on the concept of environmental efficiency and aims to address a combined evaluation of a city embracing two aspects: "*the environmental load imposed by the city on the wider environment outside its boundary, and the quality of life (environmental, social, and economic) inside the city*". Accordingly within the CASBEE framework a sustainable city is the one with low environmental load and high quality (Murakami et al. 2011).

Xiaoping et al. (2009) investigated CASBEE and 5 other rating systems and pointed out that, CASBEE is largely dominated by the government, while LEED, SBTool, BREEAM are all established by non-profit third party. Although CASBEE is available in English and offers an additional comparison from an international perspective, it has relatively low flexibility to apply as an universal standard rating system in the overseas (Fowler and Rauch 2006; Xiaoping et al. 2009b). In comparison, SBTool recognized as a universal rating system with high flexibility following by LEED and BREEAM with moderate flexibility to address sustainability issues around the world (Xiaoping et al. 2009b). However, Fowler and Rauch (2006) stated that, CASBEE could be potentially applicable in the overseas (e.g. U.S. market) by adopting the unique "BEE approach" for assessing sustainability performance of built environment.

Appendix B AHP-Based Life Cycle Assessment[30]

B.1 Overview

Analytic hierarchy process (AHP) is a common multi-criteria decision-making (MCDM) technique that can be used to assign relative weights to various sustainability (sub)criteria and aggregate those estimates to determine an arbitrary measure or index of sustainability (Khan et al. 2002). The AHP provides an organized description of the hierarchical interaction or connection among the elements (impacts, criteria or alternatives). It always begins with a goal statement and then develops a decision tree through top to bottom (Sadiq and Tesfamariam 2008; Sadiq et al. 2003; Sadiq et al. 2010).

This study uses an integrated framework of AHP and LCA in the selection of a sustainable flooring system in Tehran (Iran). A survey was carried out in Tehran to shortlist available flooring systems options commonly used in the city. Three types of block joisted flooring systems include: concrete, clay, and polystyrene blocks, were investigated. TBL sustainability criteria - environmental, economic, and socio-political were applied in the analysis. Each alternative was investigated using TBL main criteria that were further divided into following thirteen sub-criteria:

(1) Environmental impacts

   a. Resource depletion
   b. Wastes and emissions
   c. Waste management
   d. Climate change
   e. Environmental risk

[30] A version of Appendix B published by the journal of Construction and Building Materials (see Reza et al. 2011)

f. Embodied energy
g. Energy loss

(2) Economic impacts
a. Material cost
b. Construction cost
c. Occupation and maintenance cost

(3) Socio-political impacts
a. Social acceptance
b. Vulnerability of area
c. Building weight

A sustainability index (SI) was used as a quantitative measure for sustainability, which was calculated for each alternative using AHP-LCA framework based on above (sub)criteria. The flooring system with the maximum SI value was selected as the most sustainable solution.

B.2 Multiple-Criteria Decision-making (MCDM)

In the last three decades, multi-criteria decision-making (MCDM) research in different disciplines has grown exponentially. Hwang and Yoon (1981) are one of the pioneers who reviewed MCDM methods and applications. Figueira et al. (2005) surveyed 52 leading experts who researched the state of the art in MCDM. MCDM methods have been used mainly to rank predefined alternatives as possible solution of a given problem.

1. Analytic Hierarchy Process (AHP) was originally proposed by Saaty (1980). AHP is a systemic method commonly used for decision-making (Dey 2002; Golden et al. 1989; Sadiq 2001; Saaty 2001). AHP can solve complex decision-making problems involving few alternatives with numerous criteria. The process of comparing the relative importance or preference of a parameter (objectives or criteria) with respect to other parameter is based on pair-wise comparisons. One of the major advantages of the AHP is using pair-wise comparisons to determine weights and derive priority index in comparison to other weighting methods where weights are assigned arbitrarily. The AHP can apply to convert subjective assessment of relative weights (importance, likelihood, or preference) to a set of priority ratio scale and overall

scores (Sadiq et al. 2003). Usually a hierarchical model is developed to degenerate complex problems into simpler and manageable elements which create different hierarchical layers or levels. The first level of each hierarchy is a goal or an objective, whereas at the last level there is an evaluation of alternatives. The intermediate layers contain criteria and sub-criteria (Tesfamariam and Sadiq 2006). AHP consists of following five stages (Zahedi 1986):

1. Break down a problem into a hierarchy of ultimate goal, (sub)criteria, and alternatives;
2. Collect basic input data for all (sub)criteria and alternatives to make pair-wise comparisons;
3. Evaluate the relative weights of each (sub)criterion. A linguistic measure of importance used for pair-wise comparisons is provided in Table B-1 (Saaty 1988). According to nine-point intensity scale, a decision maker is able to generate pairwise comparisons among (sub)criteria and alternatives and derive relative importance of factor.
4. Aggregate weights and scores to establish a ranking of alternatives. The aggregated score are in the range of [0 1]. The alternative with the maximum value will be considered as a preferred alternative.
5. In addition, the reliability and validity of data needs to be investigated using sensitivity analysis.

Table B-2 Fundamental scale for developing priority matrix (Saaty 1988)

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over other
5	Strong importance	Experience and judgment strongly favor one activity over other
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of highest possible order of affirmation
1,2,4,6,8	Intermediate values	

Saaty (1996) proposed pair-wise comparisons at each level in the hierarchy using a reciprocal matrix. This generates a set of matrices in the form of Equation (10). In this equation, $\hat{A}$ is reciprocal matrix and each entry (a_{ij}) of A indicates the relative importance of an element i compared to element j using a scale 1-9 (Saaty 1977, 1980).

$$\hat{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{10}$$

For upper right hand matrix triangle, pair-wise comparison indices a_{ij} needs to be defined by the decision maker, while the lower left hand matrix triangle is derived as it represents the reciprocal ($a_{ij} = 1/a_{ji}$). For all diagonal entries for ($i = j$), $a_{ij} = 1$.

There are several mathematical techniques that can be used to calculate the vector of priorities (*weights*) from matrix, such as, eigenvector, geometric mean, and arithmetic mean. Preliminary investigation has been shown that there is no significant difference based on the selection of a specific technique. Normalization based on geometric means of the rows has been recommended because it provides an easy approach to obtain approximate priorities (weights) (Saaty 2001). In this method, the normalization is required for each column of the matrix and then averaging over each row.

One of the common issues in generating pair-wise comparison matrix is non-consistency; that is $\forall\ i, j$: $a_{ij} \neq w_i/w_j$. To ensure consistency in the pair-wise comparisons and associated weight estimation, a consistency value is recommended. In pair-wise comparison matrices, the eigenvalue λ and eigenvector W (priority vector) value may help solving eigenvalue Equation (11).

$$(A - \lambda)W = 0 \tag{11}$$

In equation 11, W is the priority vector which is associated with the matrix of comparisons and n is dimension of this matrix. Saaty (1980) recommended a maximum eigenvalue $\lambda_{max}>n$ for inconsistent matrices. If consistency index (CI) is sufficiently small, the estimate of the weight w is acceptable. The consistency index is defined as following:

$$CI = (\lambda max - n)/(n - 1) \tag{12}$$

where CI is consistency index that indicates whether a decision maker assigns consistent values (comparison) in a set of evaluation (Tesfamariam and Sadiq 2006). The final inconsistency in pair-wise comparison is computed using consistency ratio (CR)

$$CR = CI/RI \qquad (13)$$

where RI is the random index, determined by averaging CI of a randomly generated reciprocal matrix (Saaty 1980).

B.3 Method Description

A case study for the selection of flooring systems in Tehran is presented in this section using an integrated AHP-based cradle-to-grave LCA. Make a decision to select the best system is based on a single measure called *sustainability index* (SI). A step-by-step methodology is presented in following sections.

B.3.1 Definition of goal and scope

Main goal of this study is to evaluate and select a flooring system of a building based on environmental, economic, and social impacts. Flooring systems provide a fundamental function of sheltering and helps against temperature fluctuations, UV exposures and precipitation. Moreover floors are structural components that transfer dead and live loads to beams and columns.

For this study, a survey was carried out in Tehran which is the capital city of Iran with a total area of 18,814 km^2. In recent decades Tehran has grown significantly and become the largest city of Iran. According to 2006 census, the city has a population of 13 million and a population density of 10,330/km^2 in urban area (Statistical Center of Iran, 2006 Census). Due to unchecked growth in terms of population and industrialization, the city is facing serious issues such as overcrowding, air pollution, and increasing demands of urban facilities, infrastructures, and housing. The construction industry has expanded exponentially and become one of the key drivers of the Tehran's economy (Willis and Asgary 1997). Uncontrolled population growth mainly owes to immigration from other cities to Tehran and that has been causing unsustainable expansion of construction and building industry. Tehran being located in a high risk earth quake zone has made the situation more complicated for construction industry (Brberian et al. 1992). The history of seismic activity shows a high likelihood of a significant seismic event in Tehran and its surrounding areas (Willies and Asgari 1997). According to Air Quality Control Company (AQCC) report, Tehran is one of the poorest ranked cities in the world in terms of air pollution (Fardi 2001). This is happening due to excessive consumption of resources and high production rates of greenhouse gases (such as CO_2). It is estimated that about 27 people die each day from pollution-related diseases in Tehran (BBC Persian News online, 2006). Wasteful use of energy and uncontrolled immigration from other city has been identified as the main reason for air pollution and the government is seeking short-term strategies to confront the problem (Farahani and Sattary 2006). Tehran is the center of political and economic activities in Iran and its growth requires more deliberation based on sustainable development approach.

Main objective of this research is to select a flooring system among available options that provides a sustainable preference for construction industry in Tehran. Three block joisted flooring systems were selected. The block joisted floors are most common systems that are used for typical buildings with 1 to 7 stories. The basic difference among various types of block joisted floors is the type of block material that may include concrete, clay, or expanded polystyrene. Block has the biggest portion in these flooring systems dimension and volume. Therefore, to evaluate and compare the environmental, economic, and sociopolitical impacts of these flooring systems, the life cycle of floor's block from extraction of material to the demolition of building and to the disposal was studied. The functional unit used for construction phase has been defined as the construction of 1 square meter (m^2) horizontal floor area over the design period of 30 years.

B.3.2 Inventory analysis

Knowing the impacts is the most important question that must be asked while developing a life cycle inventory. A comprehensive inventory of impacts described in terms of TBL criteria, resulting from all inputs and outputs in different phases of life cycle analysis are developed. Three databases, namely, CML baseline 2000, SETAC, and LEED™[31] and three international standards, ISO 14042 (2000), ASTM E1991 (2005), and ASTM 2129 (2003), were used to collect data for life cycle process units and their associated energy and mass flows and data on emissions and discharges into the receiving water, soil, and air. Data related to economic concerns under TBL were collected from the Iranian construction list of price range which is published annually by President Deputy Strategic Planning and Control (2009). In addition, the data on socio-political factors was solicited based on interviewing with 5 experts (project Manager) which worked continues years in construction industry in Tehran. Proposed LCA took into account raw material extraction, material production, building construction, building occupational, and decomposition phases.

B.3.3 Data analysis and impact assessment

Knowing the relative importance of a material/product impact compared to the other materials/ products impact is a critical question for sustainability assessment of building materials. Environmental impacts associated with building material/ product that are achieved from inventory analysis have been assessed and compared using international standards for LCA and sustainability assessment (ISO 14042, ASTM E1991, and ASTM 2129). While Data economic impacts associated with building material/ product have been scored and compared applying Iranian construction list of price range and socio-political factors have been evaluated and compared based on data collected by interviewing 5 project managers in Iran who have significant construction industry experience in Tehran. Data have been collected from this step will be applied to determine the relative importance or relative preference weights of a material/ product impact compared to the other material/ product impact.

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[31] LEED™ is a registered trademark of the US Green Building Council. LEED stands for *Leadership in Energy and*

Environmental Design

AHP was used as a decision-making tool to assess and aggregate relative weights of various impacts. The burdens and impacts which listed in inventory phase are characterized and classified as general categories, and TBL (sub)criteria hierarchically structured and developed. Figure B-1 provides three levels of the proposed hierarchical model. The goal of the study is defined at the first level. In the second level, TBL criteria for sustainability, environmental, economic and socio-political factors are considered. Each of these main criteria is subdivided into numerous sub-criteria which achieved from inventory analysis phase. This model and its other intermediate levels are discussed in the following sections.

Applying AHP and pair-wise comparison matrices, the relative importance weight was assigned to each (sub)criterion. Different alternatives have varying levels of impact with respect to different (sub)criteria. Accordingly, the relative weights were assigned to each alternative with respect to the lowest level sub-criteria, using pair-wise comparisons. Finally, the ranking of alternatives was conducted and the impacts of various (sub)criteria were assessed and aggregated as a single measure, sustainability index (SI).

B.3.4 Environmental impacts

Environmental impacts were divided into seven sub-criteria at level IV. These sub-criteria involves: (a) Resource depletion (RD), (b) waste and emissions (WE), (c) waste management (WM), (d) climate change (CC), (e) environmental risk (ER), (f) embodied energy or *emergy* (EM), and (g) energy loss (EL).

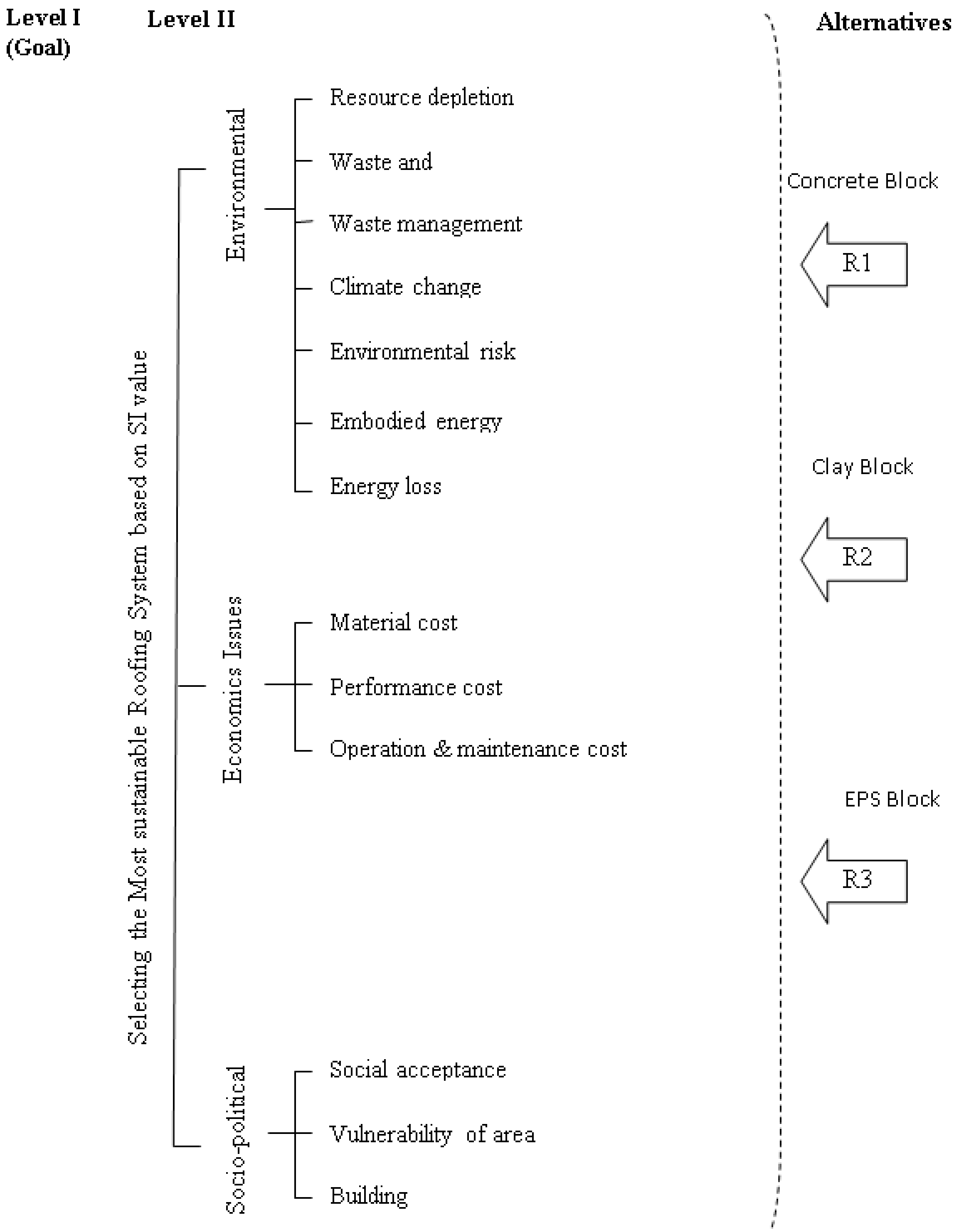


Figure B-1 AHP-based LCA model

a. Resource depletion

The term refers to the exhaustion of renewable and non-renewable resources. To reduce the resource depletion, the alternatives with less raw material and energy consumption and with more renewable and recyclable resource usage should be chosen. The functional unit of this term was assumed resource consumption per unit production or construction process. Therefore, more relative preference weight will be assigned to an alternative with less potential for resource depletion. In the 4th level of classification hierarchy, the RD has been divided into four sub-criteria:

1. Primary energy consumption (PEC) (MJ/kg): the energy needed to manufacture the building product. It is the summation of direct energy consumption in extraction of material, production process, manufacturing process, and transportation between different phases
2. Renewable raw material (RRM) consumption (kg/ unit production)
3. Water use (WU) (liters/kg)
4. Combustion value (CV) (MJ/kg): the amount of energy the raw material would have produced if burnt as a fuel.
5. Loss factor (LF) (%): the percentage of material that is usually lost during storing, transporting, and mounting of the product.

Resource depletion summary for each alternative is summarized in Figure B-2. In addition, the alternative normalized relative weights, based on RD impacts, are provided in Figure B-4 (large value of weight represents less RD impact).

b. Waste and emissions (WE)

Construction and building industry has not only become one of the major resource consumption industries but also a major source of pollution over the life cycle. Environmental pollution can be characterized based on different types of wastes and emissions that may occur in each phase over the life cycle. Accordingly, WE factor is subdivided to 4 sub-criteria based on life cycle: (a) Extraction and production, (b) building site (construction phase), (c) building interior (occupation phase), and (d) waste (demolition and disposal phase). Alternatives were compared qualitatively due to lack of quantitative data in terms of material environmental pollution. Based on available databases such as USEPA, the alternatives can be classified as *good*, *bad*, and *worst* in terms of waste and emissions. Alternatives normalized relative weights based on WE impacts achieved from pairwise comparisons are provided in Figure B-5 (large value of weight shows less WE impact).

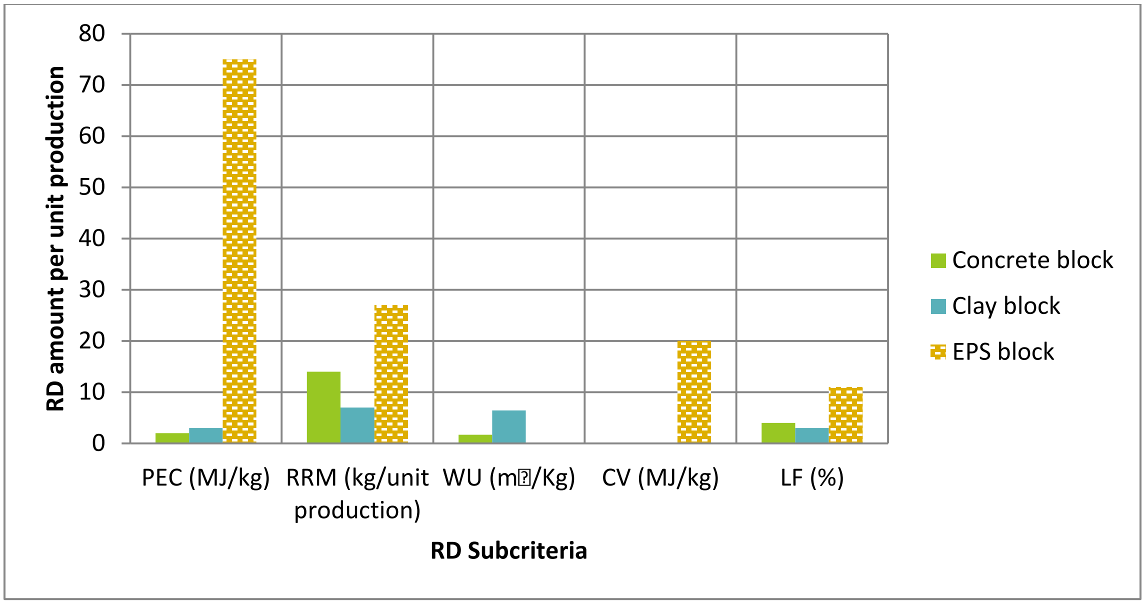
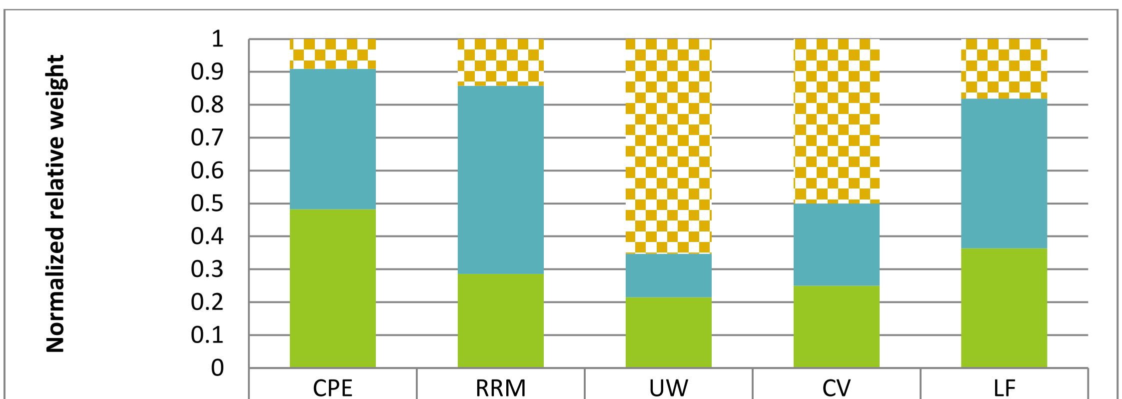
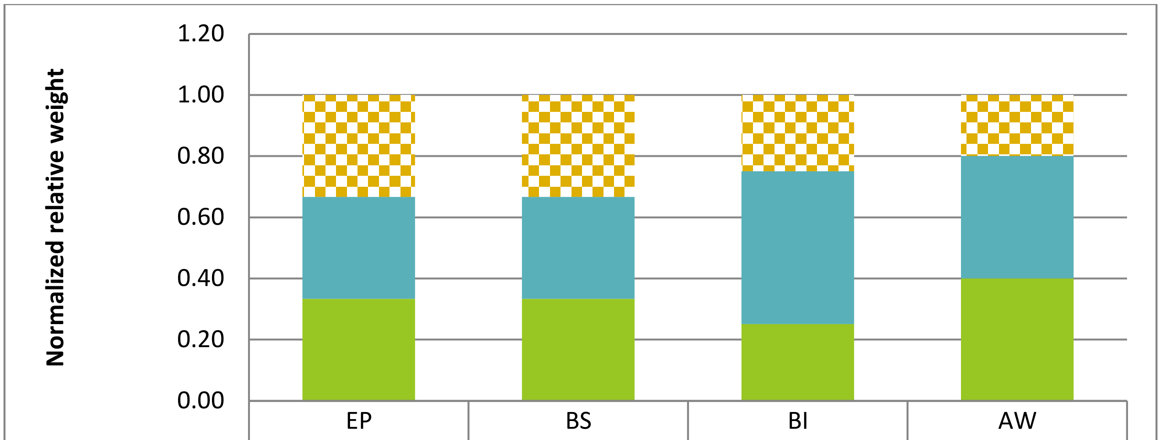


Figure B-3 Resource depletion for each alternative



	CPE	RRM	UW	CV	LF
EPS block	9.08E-02	0.1429	0.6529	0.5	0.1818
Clay block	0.427	0.5714	0.1324	0.25	0.4545
Concrete block	0.4822	0.2857	0.2147	0.25	0.3636

Figure B-4 Relative weights based on RD impacts



	EP	BS	BI	AW
EPS block	0.33	0.33	0.25	0.2
Clay block	0.33	0.33	0.5	0.4
Concrete block	0.33	0.33	0.25	0.4

Figure B-5 Relative weights based on WE impacts

c. Waste management (WM)

Waste management plays an important role to mitigate environmental impacts, such as resource depletion, and environmental pollution. The ultimate goal of waste management is to maximize reuse and recycling and to minimize disposal. Reuse and recycling can help conserve natural resource and ecologies, reduce pollution, save energy, and reduce the need for landfill and incineration and the pollution produced by these technologies. While reuse refers to the use of the whole component again, with the same function, recycling is done by melting or crushing the component, which then enters into a new manufacturing process. If it is not possible to reuse or recycle a building component, the waste manager should find a way to dispose. Waste management is subdivided into different sub-criteria at next hierarchy levels as defined below:

1. Reuse potential
2. Recycling

2.1. Recycling potential

2.1.1. Suitability for recycling

2.1.2. Benefit from recycling

2.2. Re-melting potential

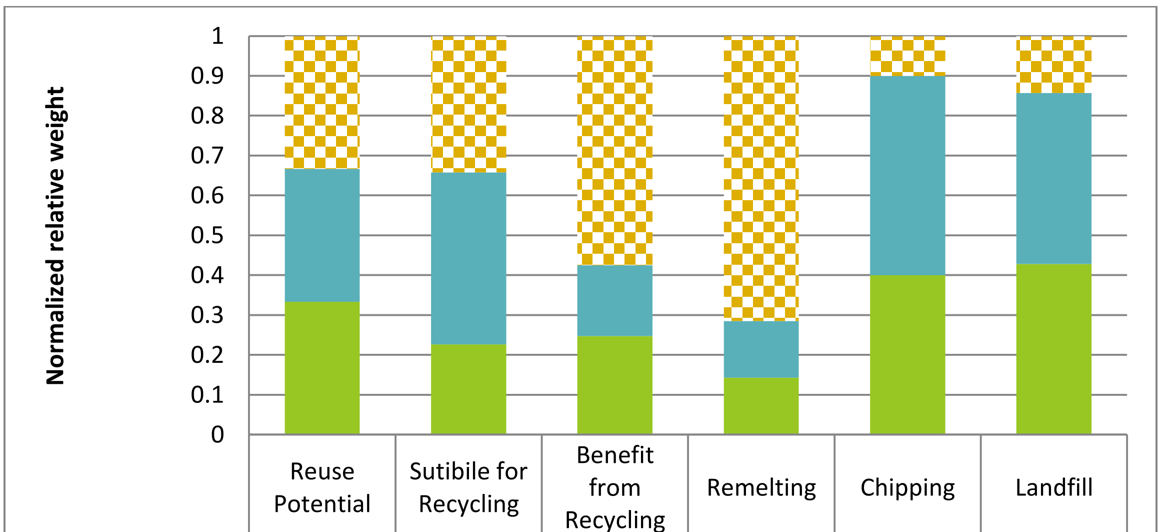
2.3. Chipping potential

3. Disposal

3.1. Landfill

3.2. Incineration

Alternatives were scored after a qualitative comparison according to available data in terms of construction waste management. Normalized relative weights of alternatives based on WM impacts derived from pair-wise comparison matrices, are provided in Figure B-6 (large value of weight shows more practical option).



	Reuse Potential	Sutibile for Recycling	Benefit from Recycling	Remelting	Chipping	Landfill
EPS block	0.33	0.34	0.57	0.71	0.10	0.14
Clay block	0.33	0.43	0.18	0.14	0.50	0.43
Concrete block	0.33	0.23	0.25	0.14	0.40	0.43

Figure B-6 Relative weights based on WM impacts

d. Climate change (CC)

Climate change is one of the most challenging issues which caused by increasing concentrations of air emission like CO_2, CH_4 and NOx. Climate change is one of the direct consequences of emission and discharge which may occur through the construction life cycle. Generally, climate change is manifested through four main groups of environmental impacts: Global warming, acidification, ozone depletion, and photochemical oxidation. While global warming may increase as a result of greenhouse gas effects and can cause ozone depletion, the acidification is mostly related to material/process acidification potential and in some cases increase by photochemical oxidation. The CC impact is subdivided into four sub-criteria in the next level.

1. Greenhouse gases (GHG) are combination of CO_2, CFCs and NOx which emitted into the environment. Generally the functional unit of greenhouse gases was assumed in term of equivalent CO_2 emitted per unit construction product or process.
2. Ozone depletion (OD) is usually occurred by CFCs and NOx. Its functional unit is NOx emitted per unit construction product process.
3. Acidification potential (AP) is represented by the group of substance mainly SOx and NOx. The functional unit can be taken as SO_2 emitted per unit construction product or process.
4. Photochemical oxidizing potential (POP) agents are generally very corrosive and are described as smog. The functional unit of was assumed the amount of NOx emitted per unit construction process.

Climate change sub(criteria) for each alternative are summarized in Figure B-7. In addition, alternatives normalized relative weights based on CC impacts, which derived from pair-wise comparison matrices, are given in Figure B-8 (large value of the weight shows less impact).

e. Environmental risk (ER)

Environmental risk refers to the likelihood of impacts on the natural environment throughout the construction life cycle. Impacts on natural environment generally represent safety risk, human health risk, and ecological risk. To evaluate the environmental risk for each alternative, the most important toxic emissions are classified in Table B-4. Environmental risk can be subdivided into three main sub-criteria in the hierarchy next levels:

1. Human health risk (HHR) is usually due to material toxicity or toxic emissions during material life cycle. Therefore, human health risks can be determined based

on material toxicity index which usually represented by USEPA's reference dose (RfD) for non-carcinogenic and by slop factor (SF) for carcinogenic effects. Among different exposure routes, the air exposure is the most critical one which contributes more than half of the total HHR in the construction life cycle. HHR is sub-divided into two main sub-criteria: cancer and non-cancer risks. Alternatives are compared relatively based on chemical RfD for non-cancer and chemical SF for cancer chronic effects (the unit of both factor is milligrams of substance per kilogram body weight per day (mg/kg/day)].

2. Ecological risks (ECR) can be determined based on pollutant hazard index. Moreover, the hazard index for each pollutant can be measured based on air emission standards or water quality criteria. In the present study, alternatives were compared based on Tehran's air emission and water quality standards to assess their potential threat to ecological entries.

3. Safety risk (SR) was subdivided into two sub-criteria: injury potential and flammability. Alternatives are compared relatively based on each block weight, shocking absorption and material flashpoint to evaluate their relative safety risks.

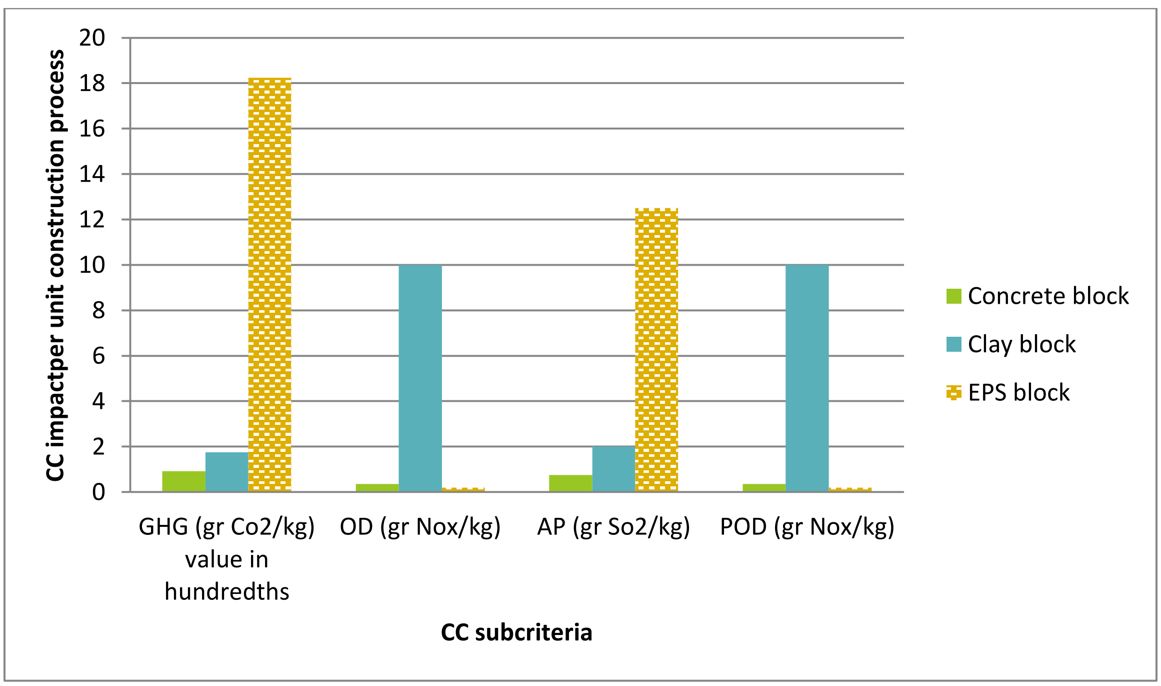


Figure B-7 Contribution to climate change impacts for each alternative

Alternatives normalized relative weights based on ER impacts which achieved from pair-wise comparison matrices are provided in Figure B-9 (large weight shows less environmental risk).

Table B-3 Waste management hierarchal tree

Block Type	*Toxic Emission*	*HHR*		*ECR*
		Cancer	Non-cancer	
Concrete Block	Chrome compounds	✓	✗	✓
	Dust	✗	✓	✓
	Thallium	✗	✓	✓
Clay Block	Dust	✗	✓	✓
	Fluorides	✗	✓	✓
	Sulphur	✗	✗	✓
EPS Block	Benzene	✓	✓	✓
	Ethan Ethylene	✓	✓	✓
	Styrene	✓	✓	✓
	Aliphatic hydro Carbone	✓	✓	✓
	Aromatic hydro Carbone	✓	✓	✓
	Ethyl Benzene	✗	✗	✓
	Pentane	✗	✗	✓

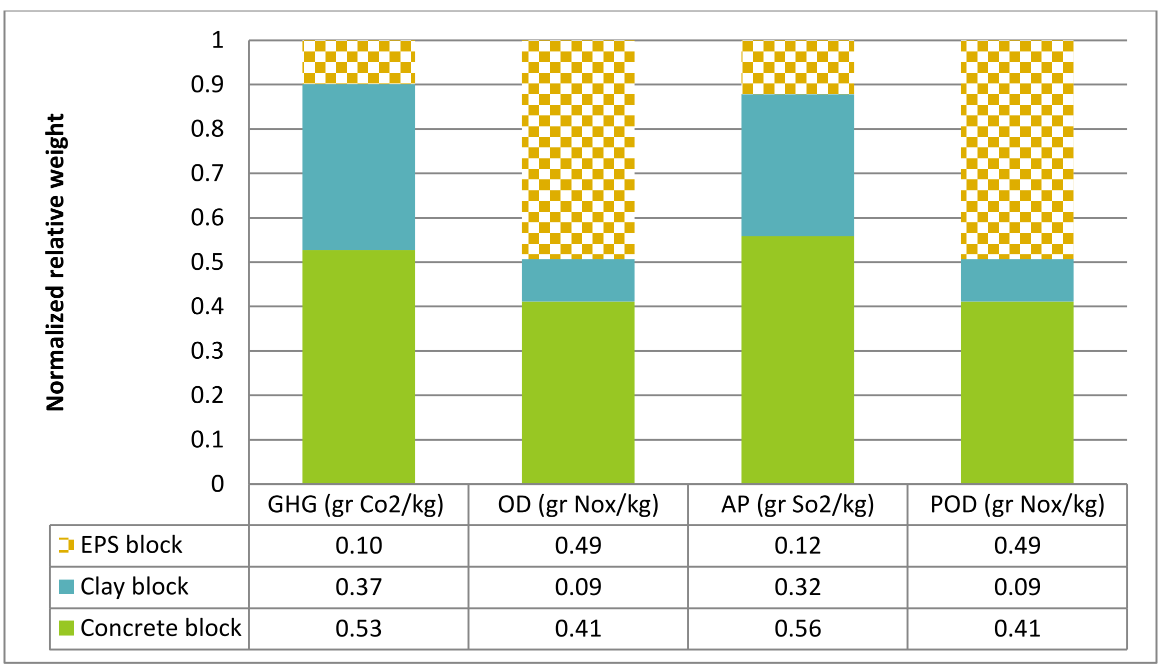
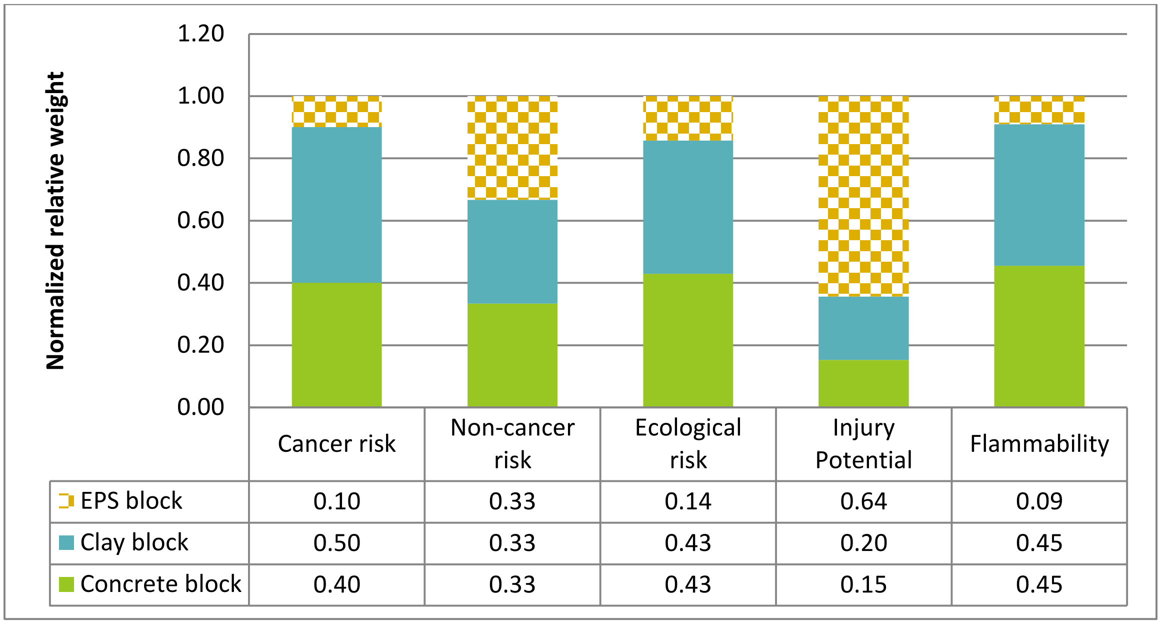


Figure B-8 Relative weights based on CC impacts



	Cancer risk	Non-cancer risk	Ecological risk	Injury Potential	Flammability
EPS block	0.10	0.33	0.14	0.64	0.09
Clay block	0.50	0.33	0.43	0.20	0.45
Concrete block	0.40	0.33	0.43	0.15	0.45

Figure B-9 Relative weights based on environmental risk (ER)

f. Embodied energy

Embodied energy is the amount of energy consumed during the life cycle of a product from the extraction of raw material to the disposal. This term represents the environmental impact of process or activity during its life cycle and also measures the effectiveness of recycling and particularly contribution to CO_2 emissions. In this study, the functional unit of embodied energy was assumed as energy used per unit construction product/process.

g. Energy loss

In this study, energy loss represents the energy wasted during the construction or building occupation. It is directly dependant on building design and material property. In this study, energy loss was measured based on material property or block thermal conductivity coefficient.

After normalization and calculating the relative preference of alternatives according to each environmental criterion, the next step of AHP-based impact assessment is to make a decision about relative importance of environmental sub-criteria. Table B-4 presents the weights of basic environmental indicators based on their relative importance. Finally, by aggregating weights, a set of alternatives ranking can be achieved based to environmental concerns.

Table B-4Weighting schemes for environmental indicators

Basic environmental Indicators	*Level*	*Relative importance weight*	*Group*
Energy Source	4	0.3531	
Renewable raw material	4	0.2028	
Use of Water	4	0.1537	Resource depletion
Combustion value	4	0.1276	(RD)
Loss factor	4	0.1628	
Extraction & production	4	0.138	
Building site	4	0.1708	
Building interior	4	0.4082	Waste & emission
As waste	4	0.2829	(WE)
Reuse potential	4	0.5816	
Recycling	4	0.309	Waste management
Disposal	4	0.1095	(WM)
Greenhouse effect	5	0.5	
Ozone depletion	5	0.5	Climate change (CC)
Acidification potential	5	0.3333	
Photochemical oxidation	5	0.6667	
Human health risk	4	0.3	
Ecological risk	4	0.3997	
Safety risk	4	0.3003	
Cancer	5	0.6667	Environmental risk
Non-cancer	5	0.3333	(ER)
Injury potential	5	0.75	
Flammability	5	0.25	
Resource depletion	3	0.1011	
Waste & emission	3	0.1546	
Waste management	3	0.1004	
Climate change	3	0.198	Environmental
Environmental risk	3	0.1905	concern
Embodied energy	3	0.1308	
Energy loss	3	0.1246	

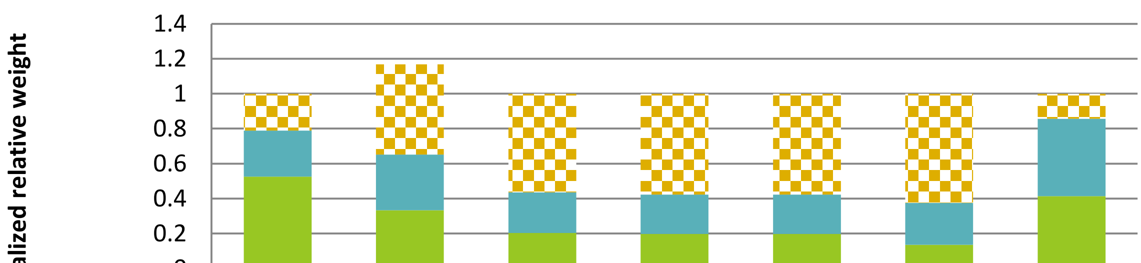
B.3.5 Economic concerns

Economic issue is the second criterion of sustainability and has been divided to three sub-criteria at level IV. These sub-criteria involves: (1) Material cost (MC), (2) construction cost (PC) and (3) occupation and maintenance cost (OMC).

Therefore, life cycle costs or economic score of a building element can be calculated by the summation of material costs per unit production, construction cost per unit building, and occupation and maintenance cost per unit building.

1. Material cost
    1.1. Material unit price
    1.2. Material affordability
2. Construction cost
    2.1. Construction unit price
    2.2. Construction speed (time has usually direct effect on ultimate costs)
3. Occupation and maintenance cost
    3.1. Durability of building element based on creep resistant and Young's modulus
    3.2. Chemical resistant of building element based on corrosion potential
    3.3. Water resistant of building element based on water absorption

Alternatives' normalized relative weights related to economic concerns are shown in Figure B-10 (large weight shows better economic option). After normalization and calculating the relative preference of alternatives according to each economic criterion, the next step is to establish the relative importance of economic sub-criteria. Weights of basic economic indicators are summarized in Table B-5. Finally, by aggregating all weights related to economic concerns, a set of alternatives relative weights was achieved.



	Material unit price	Material affordability	Construction unit price	Construction speed	Durability	Chemical resistant	Water resistant
EPS block	0.2105	0.5146	0.563	0.5774	0.5774	0.625	0.1428
Clay block	0.2632	0.3198	0.2324	0.2251	0.2251	0.2385	0.4437
Concrete block	0.5263	0.3333	0.2046	0.1975	0.1975	0.1365	0.4136

Figure B-10 Relative weights based on economic concerns

Table B-5 Weighting schemes for economic indicators

Basic Economic Indicators	*Level*	*Relative importance weight*	*Group*
Material unit price	4	0.5	Material cost
Material affordability	4	0.5	
Construction price	4	0.5	Performance cost
Construction speed	4	0.5	
Durability	4	0.4638	Operation & maintenance cost
Chemical resistance	4	0.2552	
Water resistance	4	0.2809	
Material cost	3	0.5455	Economic concern
Performance cost	3	0.2727	
Operation & maintenance cost	3	0.1818	

B.3.6 Socio-political concerns

A social and political issue is the third main criterion of sustainability and has been divided to three sub-criteria at level IV. The sub-criteria involves: (1) Social acceptance, (2) vulnerability of area and (3) building weight. So aggregation of all three aspects provides an overall picture of socio-political score.

1. Social acceptance subdivided into two groups: (a) Aesthetic and (b) Noise pollution potential. However, ability to construct fast and durability may define as other factors which were avoided to repeat in this category.
2. Vulnerability of area subdivided into: (a) Natural anthropological disaster and (b) social factors like religious and cultural factors.
3. Building weight is one of the important factors because it can reduce the building earthquake absorption. To reduce the lateral force of earthquake in building, a structure engineer should try to minimize the building structure weight. On the other hand, reduce the weight of beams and columns may cause instability in building structure, the best way is to decrease the weight of floor components such as blocks which have no contribution as bearable elements. Building weight factor in this study is directly related to each block's material density or specific weight.

Alternatives normalized relative weights based on socio-political concerns are provided in Figure B-11. After normalization and calculating the relative preference of alternatives according to each socio-political criterion, the next step of AHP-based impact assessment is to make a decision about importance of socio-political factors. Weights derived based on the relative importance of basic socio-political factors are summarized in Table B-6. Finally, by aggregating weights of all factors related to socio-political concerns, relative weights of alternatives were obtained.

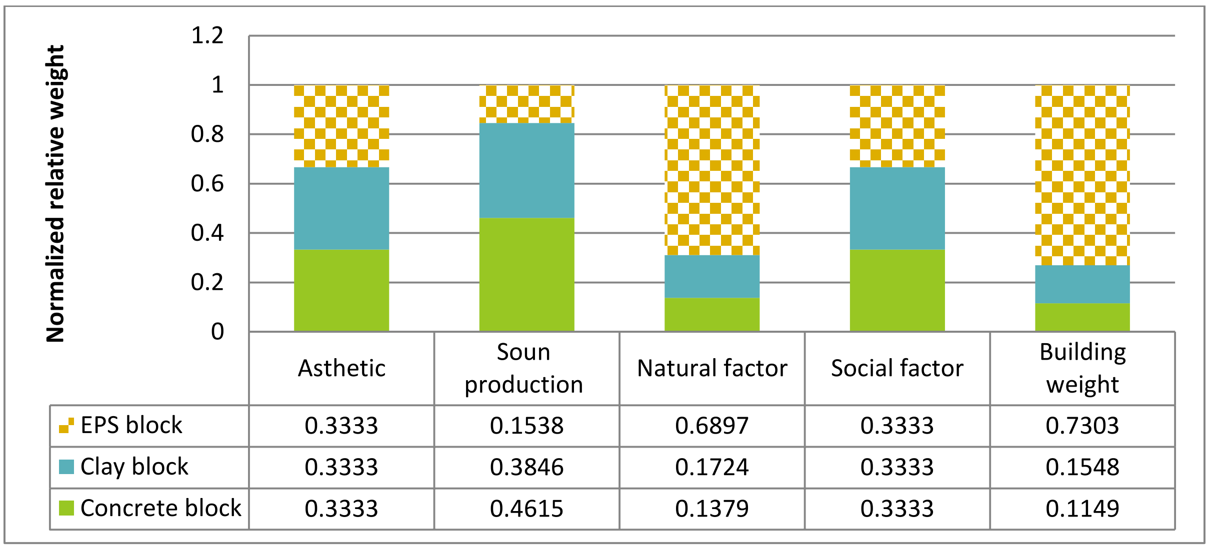


Figure B-11 Relative weights based on socio-political concerns

Table B-6 Weighting schemes for socio-political indicators

Basic socio-political Indicators	*Level*	*Relative importance weight*	*Group*
Aesthetic	4	0.3	Social acceptance
Sound production potential	4	0.7	Vulnerability of area
Natural factor	4	0.75	
Social factor	4	0.25	Socio-political concern
Social acceptance	3	0.15	
Vulnerability of area	3	0.316	
Building weight	3	0.534	

B.4 Results and Summary

Relative weights of alternatives were achieved using TBL sustainability criteria through aggregation of indicators and alternatives weights (Figure B-12). To facilitate the comparison between alternatives, they were plotted in a TBL sustainability ternary graph (Figure B-13). Three sustainability criteria can group to evaluate SI, which is a measure of sustainability assessment. Figure B-14 provides the combined results of last stage of AHP, in which three alternatives are compared. The assignment of relative importance involves human subjectivity. To counter this bias, a sensitivity analysis was conducted by decision makers, in which different weighting schemes were applied to re-evaluate SI for each alternative. Accordingly, the analysis was repeated in three trials. In the first trial, environmental concern was given priority and was assumed two times more important than other criteria. The second trial represents the case when economic concern was assumed two times more important than two other criteria. Finally in the third trial, both environmental and economic concerns are given same importance but both were assumed two times more important than socio-political concerns.

To sum up, results prove that, while flooring system with concrete block represents the lowest environmental loading, there is no significant different in this case between alternatives. EPS block is more economic and social acceptable option, although it represents less environmentally friendly option between the 3 alternatives. Moreover, clay block delineates a balance between TBL sustainability criteria. Alternatives SI were evaluated, by aggregating TBL sustainability criteria. As a result, flooring system with EPS block ranked the first alternative based on SI which is followed by alternatives 1 and 2.

Although the results of the case study shows that the EPS block is the most sustainable option among the three alternatives, it may not be the best option under the environmental impacts. Therefore, the material selection could be more justifiable if decision makers could invent new strategies and practices to reduce environmental impacts (e.g. some studies are under way to reduce toxic emission during EPS incineration). In addition, it is necessary in future to barter traditional flooring systems with more sustainable option such as, unbaked earthen blocks whose production gives off 0.2 percent of the pollution that traditional block making does (Roodman and Lenssen 1994).

During the development of AHP-based LCA model, authors found some challenges and limitations. In some cases, decision-making based on AHP technique can cause confusion and does not deal effectively with redundancy of selected criteria. For example, a criterion like injury potential and building weight can duplicate one issue (say, block weight). To remove this defect authors suggested more advanced MCDM techniques like ANP (Analytic Network Process) for future studies. Moreover, during this study it was realized that there is no sufficient data for environmental impacts of building material. Many conflicts were noted in databases which proposed environmental impacts of building materials.

On the other hand, it was also noted that making a comparison between different criteria was the most controversial challenge. There is no widely agreed method to determine the relative importance of different impacts. For example, whether or not the impact of 1 ton of concrete goes to landfill is equal to the emission of 1 ton CO_2? Therefore, in some cases, authors used qualitative comparisons and apply their own weighting criteria based on personal experiences. Certainly, in some cases the results are depended on construction practices on material use, geographical location, and other uncertainties. Therefore, uncertainty analysis with the use of probabilistic and fuzzy based methods is preferable (Sadiq and Tesfamariam 2008). Accordingly, authors recommend the use of advanced quantitative techniques like *emergy synthesis* that may reduce the multi-criteria dilemma to a single criterion model.

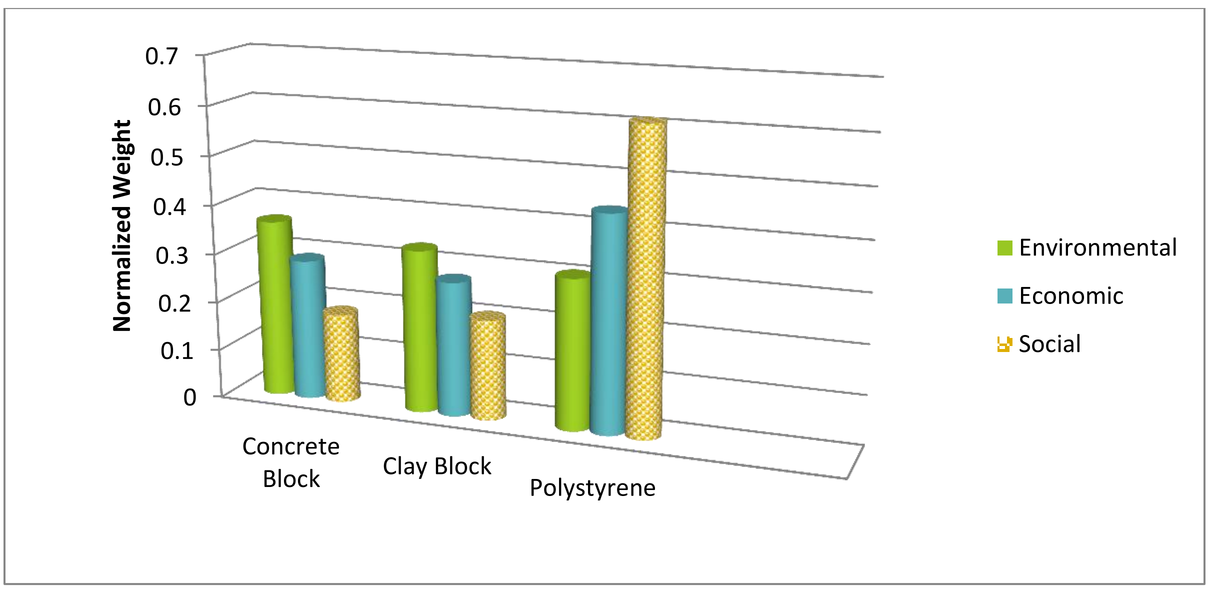


Figure B-12 Relative weights based on TBL sustainability criteria

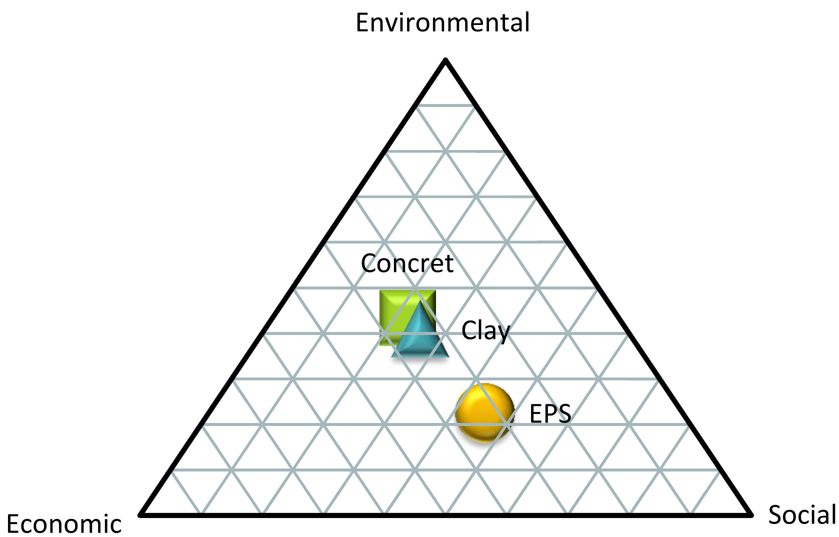


Figure B-13 TBL ternary plot

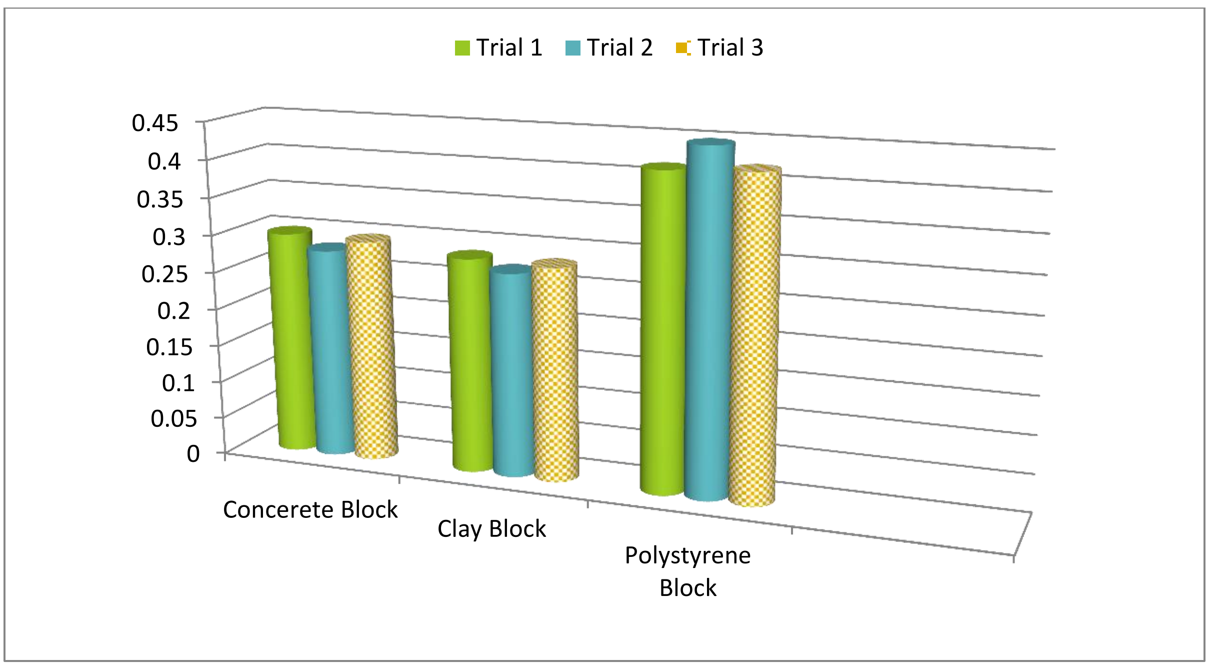


Figure B-14 Weights based on sustainability index (SI) in different trials