10-30-2020

Life Cycle Thinking-based Evaluation Framework for Road Infrastructure: A BIM-based Approach

Kartik Rajendrakumar Patel
University of Windsor

Recommended Citation

Patel, Kartik Rajendrakumar, "Life Cycle Thinking-based Evaluation Framework for Road Infrastructure: A BIM-based Approach" (2020). *Electronic Theses and Dissertations*. 8466.
https://scholar.uwindsor.ca/etd/8466

Life Cycle Thinking-based Evaluation Framework for Road Infrastructure: A BIM-based Approach

By

Kartik Patel

A Thesis

Submitted to the Faculty of Graduate Studies

through the Department of Civil and Environmental Engineering in Partial

Fulfillment of the Requirements for

the Degree of Master of Applied Science at

the University of Windsor

Windsor, Ontario, Canada

2020

Life Cycle Thinking-based Evaluation Framework for Road Infrastructure: A BIM-based Approach

By

Kartik Patel

APPROVED BY:

A. Emadi
Department of Electrical and Computer Engineering

T. Bolisetti
Department of Civil and Environmental Engineering

R. Ruparathna, Advisor
Department of Civil and Environmental Engineering

August 07, 2020

DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is the result of joint research, as follows:

This thesis was completed under the supervision of my advisor, Dr. Rajeev Ruparathna. In all cases, the key ideas, primary contributions, data analysis, and writing were carried out by the author. The contribution of the co-authors (advisor) was primarily through the provision of the broad research idea, review of results, participation in scientific discussion, literature review, and subsequently, in editing the presentation material.

I am aware of the University of Windsor Senate Policy on Authorship, and I certify that I have properly acknowledged the contribution of other researchers to my thesis and have obtained written permission from each of the co-authors to include the above material(s) in my thesis.

I certify that, with the above qualification, this thesis and the research to which it refers is the product of my own work.

II. Previous Publications

This thesis includes two original papers that have been previously published/ submitted for publication in peer-reviewed journal/ Conference, as follows:

Thesis Chapter	**Title**	**Publication Status**
1 and 2	Patel K. and Ruparathna R., (2020). “Rethinking Greener Road Infrastructure Planning with Building Information Modeling (BIM),” Clean Technologies and Environmental Policy (Manuscript ID: CTEP-D-20-00631)	Submitted

3 and 4	Patel K. and Ruparathna R., (2020). “Life cycle sustainability assessment of road infrastructure,” Sustainable Cities and Society	Completed
3	Patel, K., Ruparathna, R. (2019) “Life Cycle Thinking-Based Evaluation Framework for Road Infrastructure: A BIM-Based Approach,” International Conference on Structural Engineering and Construction Management (ICSECM-10), Kandy, Sri Lanka.	Published

I certify that I have obtained written permission from the copyright owner(s) to include the above-published material(s) in my thesis. I certify that the above material describes work completed during my registration as a graduate student at the University of Windsor.

III. General

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone’s copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

Environmental, social, and economic impacts of the construction industry have been a major concern for sustainable development. Consequently, green construction has been a popular focus of construction management academics during the recent past. A significant share of federal and regional infrastructure budgets is spent on constructing, maintaining, repairing, and replacing road infrastructure. Due to its magnitude, sustainable road construction practices support transformation towards a greener construction sector. However, the quest for sustainable road construction practices has been hindered by a lack of expertise, information, and resources. The advent of Building Information Modelling (BIM) provides more extensive access to functional and physical data of construction material. Published literature has overlooked BIM-based methods that facilitate the life cycle sustainability performance evaluation of road construction projects.

The vision of this research is to incorporate life cycle sustainability assessment into road infrastructure planning decision making. This research developed a methodological framework for life cycle thinking-based road infrastructure evaluation. This framework uses BIM to obtain material data of alternative road construction techniques. The developed framework was used to compare the life cycle sustainability performance of alternative road pavement construction methods by using the triple-bottom-line of sustainability. SimaPro software and published literature were used to develop the life cycle impact database. The proposed methodological framework was developed as a user-friendly Green Road tool. The BIM model was converted to an XML file and was linked with the Green Road tool and the life cycle sustainability impact database. Three road pavement types were compared using the proposed tool. Based on the evaluations, the geo-membrane road was identified as the preferable option. The above result was verified using emergy accounting. The ability to link with a BIM file enables the wider implementation of the proposed method. This tool will assist municipal infrastructure managers and civil engineers in selecting the most sustainable road construction and replacement method.

DEDICATION

This thesis is dedicated to my parents and sisters for their unconditional love and encouragement throughout all my endeavors. Without them none of this would be possible and I thank them for all that they do for me.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to Dr. Rajeev Ruparathna for his unfailing support throughout my master's degree at the University of Windsor. His tremendous support, wisdom, and recommendations have guided me to complete my studies effectively. I am always grateful for the inspiration, motivation, and energy he showed, which influenced me in many ways to pursue my master's studies and beyond.

I would like to thank my committee members, Dr. Tirupati Bolisetti and Dr. Arezoo Emadi. The advice and encouragement I received from them have helped me to improve the quality of this thesis.

I would like to thank the faculty of Engineering and the administrative staff of the University of Windsor for their support. I would especially like to recognize the support of Miss Suneeta Singh.

I would like to express my special thanks to my friends Saeed Parsa, Pranita Shinde, and Zahara Mokhtari for their help in carrying out the LCA and BIM modeling work.

I would like to thank my parents and sisters for the support and faith they have given me. Their support and guidance have made me into the person I am.

Last but not least, I would like to thank my friends Dorcas Appiah, Hemali Patel, Ravi Savaliya, Hemal Kanani, and Jemish Dhola for their support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CIS : Civil Infrastructure System
LCA : Life Cycle Assessment
GDP : Gross Domestic Product
GHG : Green House Gases
BIM : Building Information Modeling
U.S. : United States
IEA : International Energy Agency
OECD : Organization for Economic Co-operation and Development Countries
WBM : Water Bound Macadam
AC : Asphalt Concrete
PCC : Portland Cement Concrete
FHWA : Federal Highway Administration
INVEST : Infrastructure Voluntary Evaluation Sustainability Tool
KPI : Key Performance Indicators
LDPE : Low-density polyethylene
HDPE : High-density polyethylene
DST : Decision Supporting Tool
BEES : Building for Economic and Environmental Sustainability
YYL : Years of Life Lost
YLD : Years Lost due to Disabilities
DALY : Disability Adjusted Life Years
QALY : Quality Adjusted Life Years
GRTET : Green Road TBL Evaluation Tool

1 INTRODUCTION

1.1 Background Information

The civil infrastructure systems (CISs) at municipal, provincial, and federal levels are pivotal for the socio-economic development of a country. Road infrastructure is a key portion of CIS in a country. As an example, the road infrastructure in Canada accounts for more than 33% of the extrapolated replacement value of municipal infrastructure (Canadian Infrastructure Report Card, 2014). Rising population, urban sprawl, and the need to maintain physical conditions have been increasing the demand for road construction to reduce high congestion, reduce the frequency of accidents, and minimize transportation costs, energy usage, and pollution (Muench et al, 2011; Simpson et al., 2014). Significant investments are on the horizon for the road infrastructure construction and management worldwide (Infrastructure Canada, 2018).

Canada spends over $13 Billion annually to construct, repair, maintain, and replace highways, roads, and streets (Statistics Canada, 2019). Environmental and socio-economic impacts of road construction have been frequently highlighted in the published literature (Umer, 2015). Greener road infrastructure will support the national sustainable development goals as it is a crucial component of community infrastructure.

The long service life and spatial variations in road construction projects can generate a multitude of adverse impacts that are difficult to manage (OECD, 2015). As an example, an evaluation of 17 construction and rehabilitation projects in British Columbia revealed that an estimated 370,000 tonnes CO_2 of GHG emissions were emitted during construction, rehabilitation, and maintenance of road infrastructure (BCMoTI and BCRBHCA, 2011). Moreover, the construction phase has a significant effect on the sustainability performance of pavement through fuel consumption (for logistics and operations), emissions of particulate matter, traffic congestion, and noise pollution (Van Dam et al., 2015). Physical conditions of road pavement surface impact the friction coefficient, which consequently reduces vehicle fuel efficiency. The construction quality impacts the service life and the physical condition of the road infrastructure (Van Dam et al. 2015). Moreover, road infrastructure is exposed to aging effects, obsolescence, usage changes, and natural disasters (e.g., floods and earthquakes) that may lead to early replacement (Reza et al., 2014). Additionally, deteriorated pavement surfaces can create risks to the public, such as fatalities, injuries, and long-term health impacts. Hence, it is important to ensure the sustainability of road infrastructure from a life cycle perspective.

While there is a growing demand for sustainable road infrastructure (International Monetary Fund, 2016), there is also increasing pressure to enhance the sustainability of road construction. Canada is committed to UN 2030 sustainable development goals. Innovation and infrastructure (goal # 9), climate action (goal #13), and sustainable cities and communities (goal #11) are priority goals under the UN 2030 agenda (Government of Canada, 2017). Due to the above complexities, monetary and sectoral decision-makers demand better resources for planning and management of infrastructure (IDB Invest, 2018). Research and development on novel road construction methods have enhanced the physical quality and construction efficiency of road pavement. In order to address the external demands on sustainability, road construction methods should be selected by considering the life cycle impacts (Lepech, 2009).

Life cycle assessment (LCA) is a useful methodology that supports eco-friendly decision making (Glass et al., 2013). Recent LCA research on road infrastructure is focused on the methodological choices, allocation, and comparison of design options (Galatioto et al., 2015). LCA is heavily dependent on the quality of data, and traditional construction planning mechanisms (i.e., use of 2D drawings) have been hindering the effectiveness of the LCA. Building Information Modelling (BIM) is a potential solution here as it comprises physical and functional data of a construction project from initiation to decommissioning (Vanlande et al., 2008). BIM has been successfully implemented to enhance the sustainability performance of civil infrastructure (Kreiner et al., 2015). To the best of the author's knowledge, BIM is yet to be used for ‘cradle-to-grave’ sustainability evaluation of road infrastructure (Kreiner et al., 2015). Even though BIM has been gaining traction in the construction industry in the last decade, the application of BIM in road infrastructure has been slow (Chong et al., 2016). BIM adaptation can help deliver a safer, reliable, and sustainable infrastructure (Costin et al., 2018). Given the potential of BIM and LCA for road infrastructure planning, it is important to develop resources for implementation.

1.2 Knowledge Gap

The premise for this research was established based on the following knowledge gaps identified in the literature:

i. **Lack of research on BIM-based life cycle management of horizontal infrastructure:** BIM has been primarily used for vertical infrastructure planning (Tawelian and Mickovski, 2016). According to Tawelian and Mickovski (2016), BIM integration was overlooked for horizontal infrastructure. The same study emphasized the importance of BIM adaptation for geotechnical engineering and transportation infrastructure development.

ii. **No standardized method for BIM-LCA integration:** BIM-LCA integration can support planning greener infrastructure (Antóna and Díaza, 2014). Currently, there is no standard method suggested in the published literature for the integration of BIM and LCA. Despite its popularity, BIM and LCA integration is still in the prenatal stage. Further research is needed to link life cycle performance indicators with BIM model properties. Antóna and Díaza (2014) stated that no comprehensive framework is available for the integration of BIM for road infrastructure with LCA. BIM-based LCA has not been used for road infrastructure planning by previous researchers.

iii. **Triple bottom line (TBL) based evaluation of road infrastructure:** According to a comprehensive review, no previous studies have considered the social, environmental, and economic criteria for road infrastructure planning. Primarily, published research on road infrastructure planning has focused on environmental and economic performance (Lammam and Maclntyre, 2017). It is important to incorporate the social impact into road infrastructure planning.

1.3 Motivation

The above knowledge gap prompted this research, which expects to assist in planning for environmentally friendly, socially acceptable, and economically feasible road infrastructure. This research expects to adopt promising methodologies for greener road infrastructure planning, such as LCA and BIM. Currently, the lack of resources and knowledge are the main challenges for the above. Hence, given the potential of BIM and LCA for road infrastructure planning, it is important to develop resources for its wider adaptation (Costin et al., 2018). The deliverables of this research will inform infrastructure managers in project planning and alternative construction technique selection. Additionally, this research will be promoting BIM and LCA in road construction planning and management.

1.4 Research Objectives

The overall objective of this research is to develop a methodological framework for BIM-based road infrastructure planning. Life cycle sustainability assessment was used as the basis of evaluation. The proposed methodological framework will be used to develop a user-friendly decision-making tool for infrastructure managers. The specific sub-objectives of this research are as follows:

i. Develop a methodological framework for road pavement construction method selection
ii. Compare popular road construction techniques using multi-criteria decision making (MCDM)
iii. Develop a BIM-based road construction technique comparison tool
iv. Suggest best management practices and implementation guidelines for greener road infrastructure.

The main users of this research will be infrastructure managers who construct and maintain road infrastructure. Deliverables of this research can be blended with the sustainability agendas of such institutions.

1.5 Research Methodology

This research was carried out in four interrelated phases (Figure 1-1). A literature review was used to obtain data for creating the BIM model and developing the methodological framework. Procedures followed in subsequent phases are presented below. A detailed explanation of specific methods is presented in the respective chapters.

Phase 1 was BIM modeling of road infrastructure. Alternative road pavements were designed for an urban road and modeled using CIVIL 3D. This model was used to estimate material quantities for construction and maintenance.

Phase 2 was the database development. In this phase, a life cycle social, environmental, and economic database of road construction material was developed. LCA was conducted to obtain environmental impact data. LCA was conducted by using SimaPro software, according to ISO 14040/14044. Social and economic data were obtained from online databases and project reports.

The methodological framework for comparison of road infrastructure construction techniques was developed in Phase 3. A literature review identified key performance indicators for the social, environmental, and economic performance of alternative construction techniques. The weighted sum method was used for the aggregation of indicators.

Phase 4 developed implementation tools for the proposed methodological framework. An Excel based tool (Green Road) was developed to assist infrastructure managers in this process. The Excel tool was linked with BIM for extracting project related data. Additionally, this phase provided the implementation roadmap and best management practices for wider adaptation of this research.

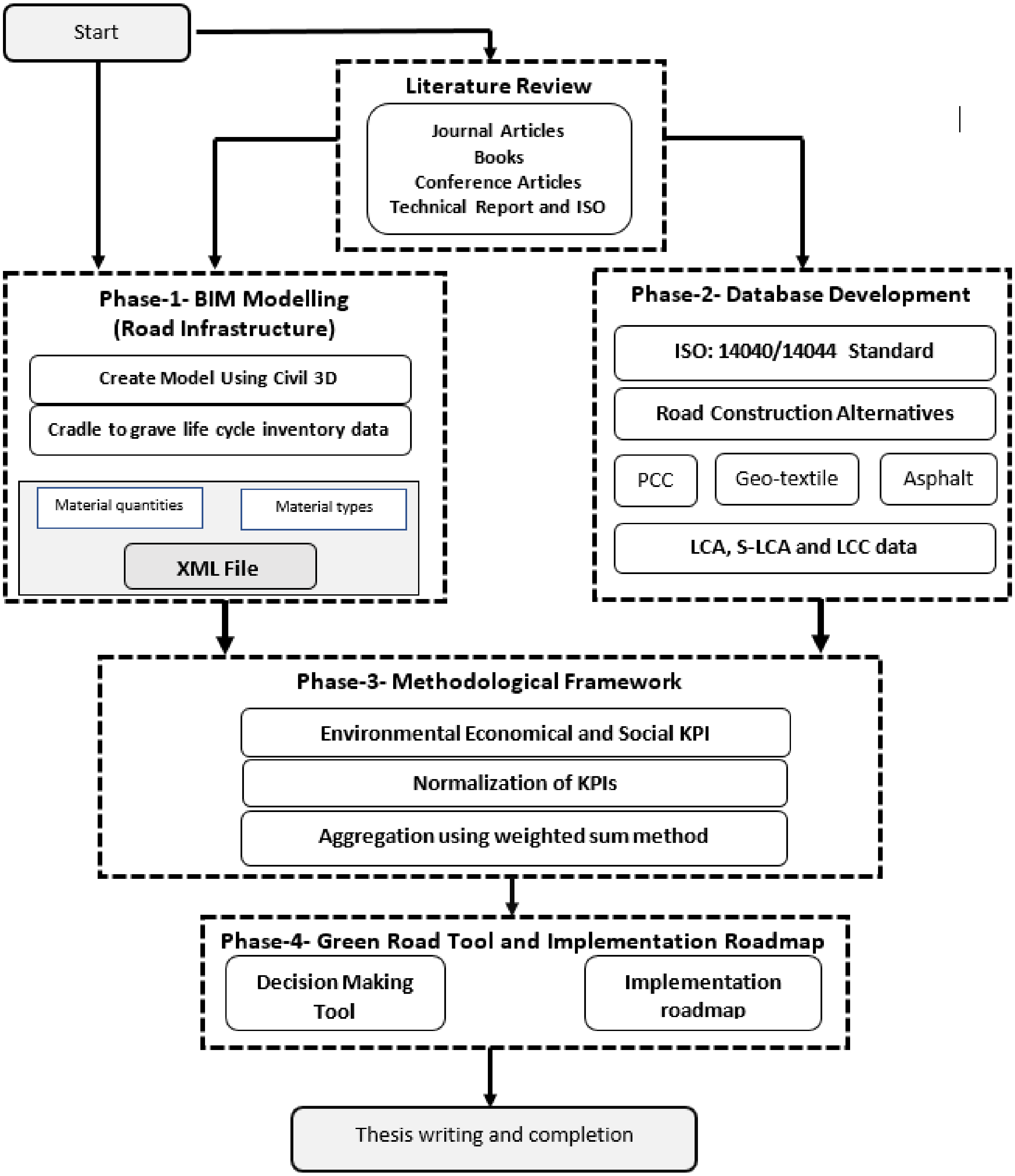


Figure 1-1 Research methodology

1.6 Thesis Organization

This thesis consists of six chapters with the following contents (Figure 1-2):

Chapter 1 (Introduction) of the thesis discusses the background of road infrastructure development in Canada and the impacts generated on environmental and economic aspects. Also, the research gaps present in the published literature are stated. It covers the objectives of this research work and motivation besides this research work.

Chapter 2 presents a comprehensive literature review on road infrastructure, BIM software, and LCA. Additionally, this chapter looks into published methods and databases used for LCA of road infrastructure.

Chapter 3 presents the methodological framework for comparative evaluation (Objective 1). This chapter explains the stepwise process of the evaluation algorithm.

Chapter 4 presents the life cycle sustainability assessment of different road construction methods (Objective 2). This chapter discusses the different road construction alternatives available, specifications for road construction, road material details, and specification for LCA. A comparative LCA was carried out for the three road construction techniques.

Chapter 5 presents the Green Road TBL Evaluation Tool (GRTET) (Objective 3). This chapter provides a stepwise explanation of the Green Road tool. A case study is used to demonstrate the implementation process.

Chapter 6 presents conclusions and recommendations for the implementation of the findings of this research (Objective 4). This chapter explains the contributions to research and limitations connected with it. A road map is proposed for achieving greener road infrastructure. Furthermore, recommendations are provided for extending the findings of this research.

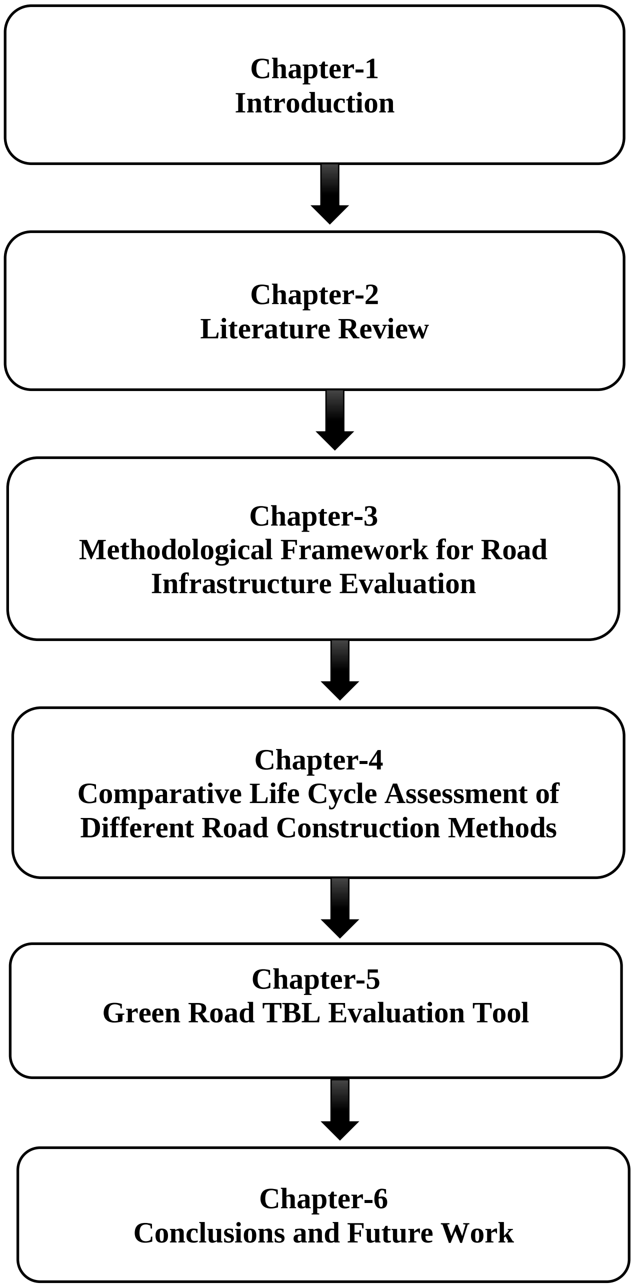


Figure 1-2 Thesis organization

References

Antóna, L. Á. and Díaza, J. (2014) ‘Integration of life cycle assessment in a BIM environment’, *Journal of the European Ceramic Society*, 17(2–3), pp. 233–238. doi: 10.1016/s0955-2219(96)00146-x.

BCMoTI and BCRBHCA (2011) ‘Reducing Greenhouse Gas Emissions in the B.C. Road Building and Maintenance Industry’, British Columbia Ministry of Transportation and B.C. Road Builders and Heavy Construction Association, (May). Available at: https://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/engineering-standards-and-guidelines/geotech/3348_roadbuilding_bp-v13-232ppi.pdf.

Canadian Infrastructure Report Card (2014) Canadian Infrastructure Report Card.

Chong, H., Lopez, R., Wang, J., Wang, X., and Zhao, Z. (2016) ‘Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects’, Journal of Management in Engineering, 32(6), p. 05016021. doi: 10.1061/(asce)me.1943-5479.0000460.

Costina, A., Adibfara, A., Hub, H., and Chen, S., (2018) ‘Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations’, Automation in Construction. Elsevier, 94(July), pp. 257–281. doi: 10.1016/j.autcon.2018.07.001.

Galatioto,F., Huang, Y., Parry, T., Bird, R.,and Bell, M., (2015) ‘Traffic modelling in system boundary expansion of road pavement life cycle assessment’, Transportation Research Part D: Transport and Environment. Elsevier Ltd, 36, pp. 65–75. doi: 10.1016/j.trd.2015.02.007.

Najjara, M., Figueiredob, K., Palumboc, M.,and, Haddad, A. (2013) ‘Future use of life-cycle assessment in civil engineering’, Proceedings of the Institution of Civil Engineers - Construction Materials, 166(4), pp. 204–212. doi: 10.1680/coma.12.00037.

Government of Canada (2017) The 2030 Agenda for Sustainable Development.

IDB Invest (2018) 'What is Sustainable Infrastructure A Framework to Guide Sustainability Across the Project Cycle', Inter American Development Bank.

Infrastructure Canada (2018) Investing In Canada, Ottawa, ON.

International Monetary Fund (2016) World Economic Outlook, October 2016, World Economic Outlook, October 2016. doi: 10.5089/9781513599540.081.

Kreiner, H., Passer, A. and Wallbaum, H. (2015) 'A new systemic approach to improve the sustainability performance of office buildings in the early design stage', Energy and Buildings, 109, pp. 385–396. doi: 10.1016/j.enbuild.2015.09.040.

Lammam, C. and Maclntyre, H. (2017) 'Myths of Infrastructure Spending in Canada', (March), p. 65. Available at: https://www.fraserinstitute.org/sites/default/files/myths-of-infrastructure-spending-in-canada.pdf.

Lepech, M. (2009) 'US - Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials Authors ':

Muench, S., Anderson, J., Hatfield, J., Koester, J., and Söderlund, M. (2011) '"Greenroads Manual v1. 5."'

OECD (2015) Green Finance and Investment Mapping Channels to Mobilise Institutional Investment in Sustainable Energy. Available at: http://www.oecd-ilibrary.org/docserver/download/9714581e.pdf?expires=1521715530&id=id&accname=ocid84004878&checksum=039F018EFCE32787DB4B20592691B38C.

Reza, B., Sadiq, R. and Hewage, K. (2014) 'Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: A case study on paved roads', Clean Technologies and Environmental Policy, 16(2), pp. 251–266. doi: 10.1007/s10098-013-0615-5.

Simpson, S., Ozbek, M., Clevenger, C., and Atadero, R., (2014) 'A Framework for Assessing Transportation Sustainability Rating Systems for Implementation in U . S . State Departments of Transportation', Transportation Research Board, 93rd Annual

Meeting, (May), pp. 1–19.

Tawelian, L. R. and Mickovski, S. B. (2016) ‘The Implementation of Geotechnical Data into the BIM Process’, Procedia Engineering. The Author(s), 143(Ictg), pp. 734–741. doi: 10.1016/j.proeng.2016.06.115.

Thomas J. Van Dam, John T. Harvey, Stephen T. Muench, K. D., Smith, Mark B. Snyder, Imad L. Al-Qadi, Hasan Ozer, J. M. and Prashant V. Ram, Jeffery R. Roesler, and A. K. (2015) ‘Chapter 5. Construction Considerations To Improve Pavement Sustainability’, in Towards Sustainable Pavement Systems: A Reference Document, p. 456. Available at: https://www.fhwa.dot.gov/pavement/sustainability/hif15002/chapters/hif15002_05.pdf.

Vanlande, R., Nicolle, C. and Cruz, C. (2008) ‘IFC and building lifecycle management’, Automation in Construction, 18(1), pp. 70–78. doi: 10.1016/j.autcon.2008.05.001.

2 LITERATURE REVIEW

2.1 Introduction to Road Infrastructure

The path over which automobiles and other traffic lawfully pass is known as a road (Ragab, 2016). It consists of a pathway, other associated constructions like culverts and bridges, and land required for future widening. The complete area required and reserved for a road alongside its alignment is known as the right of way (Ragab, 2016). Roads are classified based on usage (e.g., freeway, expressway, highways, arterial, local, and collector streets) as well as their paving material **(**e.g., asphalt, concrete, gravel ect.**)** (Ragab, 2016).

Pavement type is also a popular method for the classification of road infrastructure. Road infrastructure can be classified as surfaced and unsurfaced (Ragab, 2016). Surfaced roads are furnished with a bituminous or concrete surface. Unsurfaced roads are unpaved, with mud or gravel on the surface. Various types of pavement are discussed in the literature.

2.1.1 Flexible Pavement

Flexible pavement are constructed using bituminous material and aggregates. Any load gets transmitted down from the surface layer through successive layers, which gets distributed over an increasingly larger area at each layer (Mishra, 2016). A cross section of a flexible pavement is given in Figure 2-1. Examples for flexible pavmenets includes, water bound macadam roads and stabilized soil roads (Mishra, 2016).

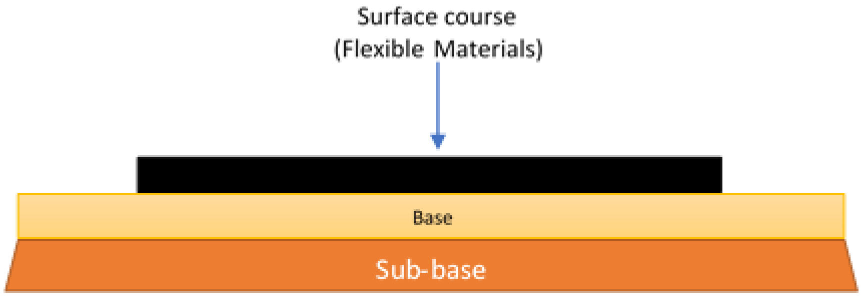


Figure 2-1 Flexible pavement components

2.1.2 Rigid Pavement

The rigid pavements are constructed using cement, concrete, or reinforced concrete slabs. Figure 2-2 presents the cross section of a rigid pavement. A regid pavement possess enough strength to resist the traffic loads and has both rigidity and high modulus of elasticity to distribute the loads over an large area of soil. Grouted concrete roads are categorized as semi-rigid pavements (Mishra, 2016).

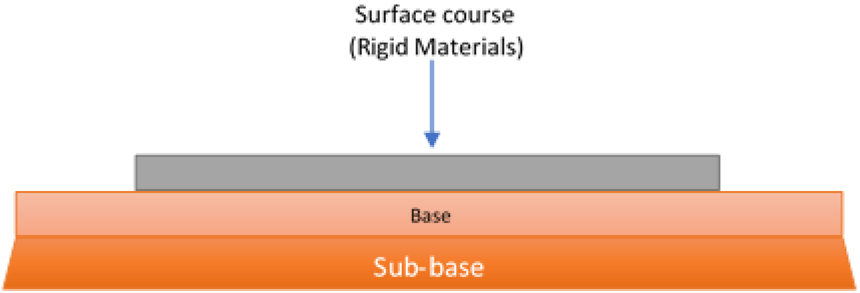


Figure 2-2 Rigid pavement components

2.2 Materials Used in Road Construction

Each pavement type is constructed with layers of different material, starting with the existing subgrade, with each overlaying layer utilizing higher quality material. Surface layers are the most durable and most expensive to construct (Tayabji and Smith, 2010). The conventional composition, by volume, of normal Asphalt Concrete (AC) is 6-8% asphalt binder, 85-90% aggregate (graded), 2-3% filler material, and 2-4% air. One lane-mile (1.6 km) of flexible pavement requires about 2,400 tonnes of AC for a 150 mm thick surface layer (Tayabji and Smith, 2010).

Standard PCC is 10-14% cementitious materials (Portland cement, fly ash, slag), 62-68% aggregate (coarse, intermediate, fine), 14-18% water, 4-8% air, and very small amounts of admixtures. A lane-mile of rigid pavement can require about 4,800 tonnes of concrete for a 300 mm thick surface layer. Also, a lane-mile of constantly strengthened concrete pavement (CRCP) requires about 100-120 tonnes of steel (Tayabji and Smith, 2010).

According to Tayabji and Smith (2010), pavement construction materials are classified as natural (raw) materials, manufactured materials, and composite manufactured materials. Natural materials include aggregates, lake asphalt, and natural resins. Metallic materials, ceramic-based materials, visco-elastic materials

(AC), industrial by-product materials (fly ash), other waste products (crumb rubber), chemical admixtures for concrete, fillers for AC, epoxies, and polymers, fibers, and synthetic aggregates (lightweight and slag aggregates) are manufactured materials. PCC, AC, and coated or clad steel are considered composite manufactured materials (Table 2-1).

Table 2-1: Green construction materials used in road construction (Tayabji and Smith, 2010; Kowalski et al., 2016; Das et al., 2017)

Classification	Materials	Benefits
Cementitious Materials	**Performance-specified cements**	Performance-specified cements will expand innovation in producing more environmentally benign cements, mainly linked to overall performance.
	Next-generation sustainable cements	Substantially minimize the carbon footprint of the constructed environment. Mitigate the long-term consequences of global climate change.
	Eco-friendly cements	Produced at lower kiln temperatures, and absorb and sequester CO_2, while also possessing rapid-hardening capabilities.
	Energetically modified cement	Reduced cement requirements, increased set times, increased strength, improved durability, improved workability, reduced shrinkage.
Concrete Materials	**Engineered cement composites**	Improved structural integrity, improved post-cracking behavior, and resistance to plastic shrinkage.
	Titanium dioxide-modified concrete	Conversion of noxious nitrogen oxides into greater environmentally friendly compounds.
	Pervious concrete	Serves as a retention pond, significantly

Classification	Materials	Benefits
		reducing surface water runoff, helps to recharge groundwater supplies, reduced hydroplaning potential (safer road), and absorbs noise emission.
	Self-consolidating concrete	Faster placement rate, save placement cost, ease of filling restricted sections, improved pumpability, and reduced construction period.
	Sulfur concrete	Rapid strength gain, dense matrix, resistance to acids and chemicals, and it is produced using by-product and waste materials.
	Autoclaved aerated concrete	Excellent noise-dampening properties, recyclable, lightweight, easily modified, and installed quickly and effectively.
	Geopolymer concrete	Excellent mechanical properties and is highly durable; increased longevity reduces the embodied energy and CO_2 associated with construction.
	Hydrophobic concrete	Waterproofed, fully recycled, and credit under the LEED program.
	Ductile concrete	Improved durability, Resistance to aggressive environments, and cost saving.
Asphalt Binder Materials	**Sulfur-extended asphalt**	Increases stiffness of the mixture increases the

Classification	**Materials**	**Benefits**
		Marshall Stability and deformation resistance.
	Bio-derived asphalt binders	Allow for partial replacement of the asphalt binders with the vegetable oils.
	High modified asphalt binders	Reduced rutting, reduced fatigue cracking, and reduced thermal cracking.
Asphalt Concrete Materials	**Warm asphalt mixtures**	Reduced energy consumption, reduced emissions from burning, cooler working environment for workers, use of higher percentages of recycled asphalt pavement, and earlier opening to traffic.
	Perpetual asphalt pavement systems	Provide a safe, durable, smooth, and long-lasting roadway without frequent expensive, time-consuming, traffic-disrupting reconstruction or major repair.
	Porous asphalt pavement	Improved safety, improved wet weather frictional properties, resistance to permanent deformation, reduced tire-pavement noise levels, and smoother pavements.
	Recycled asphalt shingles	Overall reduction in solid waste, savings in the cost of the mix, and reductions in the amount of energy.
Metallic and Polymer Materials	**Vitreous ceramic coatings for reinforcing**	Reduce corrosion, potentially increases the life

Classification	Materials	Benefits
	steel	of the concrete pavement, increased concrete-steel bonding.
	Fiber-reinforced polymer bars for CRCPs	Reduced corrosion, potentially increases the life of the concrete pavement, increased concrete-steel bonding, electromagnetic transparency of FRP bars makes them suitable for use at toll collection booths where electromagnetic vehicle detectors are used.
	Fiber-reinforced polymer dowel bars	Reduced corrosion, potentially increases the life of the concrete pavement, increased concrete–steel bonding, electromagnetic transparency of FRP bars makes them suitable for use at toll collection booths where electromagnetic vehicle detectors are used.
	Zinc-clad dowel bars	Superior resistance to corrosion, less susceptible to damage during transportation and construction operations.
	Micro-composite steel for dowels and tie bars	Superior corrosion resistance.
Aggregate Materials	**Synthetic aggregates**	Industrial waste products are productively used, serve as a replacement for more expensive aggregates or local aggregates of

Classification	Materials	Benefits
		marginal quality.
	Manufactured aggregate using captured CO_2	Availability of good quality aggregates at areas where sound aggregates may be in short supply and sequestering of CO_2 produced by coal-powered plant.
	Materials that allow internal concrete curing	Reduced early-age shrinkage, increased concrete strength, increased durability, and reduced permeability.
Geo-textiles	**Woven Geo-textiles**	Reduce material separation, increase soil stabilization, provide sufficient filtration in pavement layers, Reduce erosion of the other road materials, increase durability, reduce the thickness of road layers.
	Nonwoven Geo-textiles	
	Geo-synthetics (membrane)	
Other Materials	**Ultra-thin bonded wearing course**	Provide user safety and comfort, and excellent adhesion properties
	Advanced curing material	Eliminates surface restraint cracks, retains high internal moisture content, reduces permeability, increases long-term durability, promotes a more efficient hydration process.
	Workability-retaining admixture	Greater concrete workability minimizes re-dosing of high-range water-reducing admixture

Classification	Materials	Benefits
		and Provides consistent air contents.
	Concrete surface sealers	Reduce the ingress of deleterious substances that will reduce the service life of structures.

2.3 Planning for Green Road Infrastructure

In delivering a greener road project, it is important to include sustainability principals from the outset (Dvir and Lechler, 2004; Yu et al., 2018). LCA-based road infrastructure planning and decision making require quantification of TBL impacts (Umer, 2015). Despite that, road infrastructure planning has been going through a paradigm shift; cost has been considered the predominant decision criteria, while environmental degradation, climatic impacts, and societal trends have been given less emphasis (Heeres et al., 2012). Yet, there is an increasing demand to link environmental criteria and long-term sustainability goals with infrastructure planning (Vigar, 2001; Geerlings and Stead, 2002). The published literature highlights the importance of considering sustainability impacts on multi-stakeholder groups for road construction projects (Tillema et al., 2008). Currently, road construction planning strategies offer little towards the conflicts or complementarities among the social, economic, and environmental objectives of multiple stakeholders (Glasbergen and Driessen, 2005; Hull, 2008).

Environmental sustainability road standards have emerged to help assess the sustainability of road transportation projects such as INVEST (U.S. Federal Highway Administration), Envision (Institute for Sustainable Infrastructure), GreenLITES (New York State Department of Transportation), and CEEQUAL (UK Institution of Civil Engineers) (Montgomery, Hirsch, and Schirmer, 2015). Road infrastructure rating systems developed in recent years have distinct purposes and assessment processes (Armstrong et al., 2013). As an example, the Federal Highway Administration (FHWA) developed the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), which is an online tool (Armstrong et al., 2013). INVEST includes a collection of best practices to measure the sustainability of road infrastructure projects through development, operations, and maintenance phases. Here, the sustainability of road infrastructure is evaluated through life cycle cost analysis, habitat restoration, the safety of habitats, ecological connectivity, recycling and reuse of materials, contextual site vegetation, and others (Armstrong et al., 2013).

Table 2-2 Comparison of rating systems (Armstrong et al., 2013; Montgomery et al., 2015)

	INVEST	**ENVISION**	**GreenLITES**	**CEEQUAL**
Managing Body	Federal Highway Administration (FHWA)	Institute of Sustainable Infrastructure (ISI)	New York State Department of Transportation (NYSDOT)	Building Research Establishment (BRE)
Developed Year	2012	2012	2008	2003
Geography	United States	International	United States	International
Intended for	New Highways and Transportation Projects	New and Existing Civil Engineering Infrastructure and Buildings that are Primarily Process Focused	Transportation Infrastructure	New and Existing Civil Engineering Infrastructure, Landscaping
Project Phase Applicable	Planning, Design, Construction and Operation & Maintenance	Planning and Design	Planning, Design, Construction and Operation & Maintenance	Design and Construction
Sustainable Categories/Credits Accounted for	• System Planning for Region/ State • Project Development • Operations and Maintenance	• Quality of Life • Leadership • Resource Allocation • Natural World • Climate and Risk	• Water Quality • Materials and Resources • Energy and Atmosphere • Innovations	• Project Strategy • Project Management • People and Communication • Land Use • The Historic Environment • Ecology and Biodiversity • Water Environment • Physical Resources Use and Allocation • Transport
Rating Scale	• Bronze • Silver • Gold	• Bronze • Silver • Gold	• GreenLITES Certified	• Pass • Good • Very Good

	• Platinum	• Platinum	• GreenLITES Silver • GreenLITES Gold • GreenLITES Evergreen	• Excellent

Kassoff (2005) stated that “the purpose of sustainable highways may also at first sound like an oxymoron, that in actuality represents an opportunity whose time has come.” Every roadway design project is unique as designers must consider the character of the area, the values of the community, and the needs and opportunities of the highway users (Kassoff, 2005). The engineering design includes the resolution of routes, the diagram of the alignment, and the region of intersections to ensure access, capacity, level of service, safety, and journey time (Kassoff, 2005). The essence of a sustainable road is the mixture of functional requirements that enhance natural, built, and social environments. In ecological terms, a highway project can be planned, designed, built, and operated in such a way that when assessed on a general basis, it demonstrates the minimal effect on the environment (Kehagia, 2009).

The primary criteria of a sustainable roadway design are environmental stewardship, best practices and policies, measurement, and evaluation (Kehagia, 2009). The active participation of professionals would assist holistic strategies for planning, design, and development, adhering to appropriate environmental management strategies compliant with applicable environmental legislation and regulations (Kehagia, 2009). Sound policies and practices in the context of life cycle engineering practices are the keys to achieving sustainable road infrastructure. This process helps in the evaluation of the TBL performance during design as well as sound procedures and guidelines for monitoring and evaluating environmental performance throughout its life cycle (Kehagia, 2009).

Road infrastructure management has been a topic of focus among municipalities and in academia due to aging infrastructure, competing priorities, increasing renewal deficits, strict environmental regulations, and budget limitations (Curry, 2015). Moreover, Canadian municipalities are experiencing service inefficiencies and financial burdens due to underperforming infrastructure (Abu Samra et al., 2018). A comprehensive literature review revealed that there are three key knowledge gaps in municipal infrastructure management that should be addressed by academia. First, infrastructure management decision-making needs to be enhanced with scientific principals to arrive at optimized decisions (Halfawy, 2008; Ruparathna, 2017). Second, municipalities need to adopt performance-oriented infrastructure management strategies (Khan et al., 2015; Kabir et al., 2018). Third, pragmatic tools are needed to support municipal infrastructure management decision-making (Halfawy et al., 2008; Michele and Daniela, 2011; Ruparathna et al., 2018b).

A successful project delivery needs decision-making by the project manager, not only to manage the cost, schedule, and quality of the project but also to manage construction activities while the infrastructure is in operation. BIM includes physical and functional characteristics of civil infrastructure that support the ability to generate, represent, integrate, and optimize information and processes (Porwal, 2013; Porwal and Hewage, 2013). Recent advancements of BIM in construction management are waste minimization (Porwal and Hewage, 2013), sustainability management (Wong and Kuan, 2014), project partnering (Oraee et al., 2017), constructability analysis (Liu, van Nederveen and Hertogh, 2017), and facilities management (Becerik-Gerber et al., 2012; Wang et al., 2013). BIM could be the missing piece to support the successful delivery of road infrastructure projects.

2.4 Life Cycle Sustainability Assessment

Sustainability is a predominant concept in the modern era that affects and is affected by construction activities (Jones et al., 2010; Sev, 2009; Spence and Mulligan, 1995). According to the Brundtland Report, sustainable development is defined as "meeting the needs of today without compromising the needs of future generations" (World Commission on Environment and Development, 1987). Sustainable development constitutes achieving the balance among TBL of sustainability (i.e. environmental, social, and economic factors) (United Nations, 2005). Life cycle thinking allows improvements across the life cycle of construction and related activities (i.e. from raw material extraction and conversion to manufacture and distribution, through use, re-use, and recycling to ultimate disposal), while addressing

TBL issues (USEPA, 2014). LCSA is the evaluation of all environmental, social, and economic negative impacts and benefits throughout a product's life cycle (Kloepffer, 2008; United Nations Environment Program (UNEP), 2011). It has three components (Kloepffer, 2008; United Nations Environment Program (UNEP), 2011):

i. Life cycle assessment (LCA)
ii. Life cycle costing (LCC) and
iii. Social life cycle assessment (S-LCA).

Sustainability initiatives can effectively be adopted in preconstruction and construction stages rather than in later stages of building life cycle. Hence, LCSA for project planning is an important consideration for the future. Turk et al. (2016) suggested that LCSA is an essential part of road asset management and decision-making (Turk et al., 2016).

2.4.1 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a comprehensive instrument to evaluate the environmental impacts of a products,service or a processes. LCA evaluates the environmental impacts of a product or service over its life span. ISO 14040 and 14044 defines a standard framework for LCA (International Organization for Standardization, 2006). Section 2.5 further explains the LCA framework.

2.4.2 Life Cycle Costing (LCC)

Evaluating construction projects on the basis of the initial cost is recognized as a main drawback in the construction industry, as it does not consider the operating costs of the asset, which can be substantial along with the life of the constructed facility (iceberg effect) (Bull, 1993; Wübbenhorst, 1986). Lifecycle costing (LCC) is a recommended solution to overcome this concern (Bull, 1993; Hampton, 1994; National Audit Office, 2005). LCC is a feasible method of project evaluation that considers all costs related to the project over its life cycle, including initial cost, maintenance cost, financial cost, renewal cost, and disposal cost (Assaf et al., 2002). Further, LCC is identified as a central tenant of financial and procurement best practices (Warren, 2009). Lifecycle costing enables achieving cost savings (Warren, 2009).

2.4.3 Social Life Cycle Assessment (S-LCA)

S-LCA is a direct or potential social impact assessment technique that assesses the potential positive and negative social impacts along the life cycle of a product or a process encompassing extraction and processing of raw materials, manufacturing, distribution, use and re-use, maintenance, recycling, and final disposal (United Nations Environment Program (UNEP), 2011). Different S-LCA methods have been used in the literature, such as Norris's S-LCA, Dreyer et al.'s S-LCA, Hunkeler's S-LCA, and Weidema's S-LCA.

2.5 LCA Standards

The following section describes the LCA of road infrastructure, according to ISO 14040 (2006) (Trunzo et al., 2019). Life cycle assessment processes are combined by international standards for LCA to provide contributions between international companies and stakeholders (Lee and Inaba, 2004). Therefore, ISO (the International Organization for Standardization) 14040 and ISO 14044 are the standards for LCA (Lee and Inaba, 2004). Explanation principles and framework of LCA are provided by ISO 14040 so as to be readable and accessible for stakeholders and engineers (Lee and Inaba, 2004), while all technical requirements and guidelines are contained in ISO 14044 (ISO 14040, 2006b). ISO 14040 and ISO 14044 removed prior errors and inconsistencies, and technical and readable contents are added accordingly to clarify technical contents (Sato, 1977). The framework for LCA is presented in Figure 2-3.

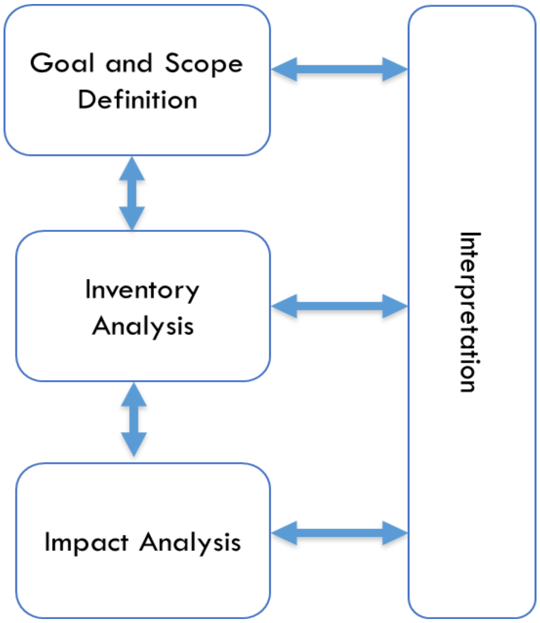


Figure 2-3 LCA phases (ISO 14040, 2006b)

- Goal and scope of the study: Establishing the objectives of the LCA study based on the requirements (i.e., design evaluation, design comparison, research).
- Life Cycle Inventory (LCI): Quantification of inputs and outputs of the road project (e.g., material, energy, water, equipment required for the pavement construction).
- Life Cycle Impact Assessment: Environmental impact assessment of the LCI using the life cycle database (e.g., Ecoinvent).
- Discussion and interpretation of results: Reporting the magnitude of environmental impacts created by pavement design and decision making.

A system boundary is an important aspect of LCA. Multiple system boundaries have been used in the literature for LCA.

Cradle to a grave is the whole life cycle assessment from supplier and resources step (cradle) to disposal step (grave) (Mehmet Ali Ilgin, no date). The perspective of cradle-to-grave is to recognize environmental impacts to reduce waste and costs. In addition, collection, assessment, and interpretation information is gathered by analyzing this system (*Cradle to Grave: Definition, Analysis & Approach*, no date).

Cradle to the gate is an assessment between raw material acquisition (cradle) and material processing (gate) before transporting and delivering to customers. In this phase, product use and disposal are removed. This step helps to gather all of the resource impacts to improve the quality of products (Franklin Assoc., 2010).

Gate to cradle life cycle assessment computation contains extraction materials and material processing phases when transportation and packaging are determined. These steps are monitored by consumers and are, therefore, important stages of LCA (Castro-Molinare and Korre, 2014).

Gate to gate is another important stage of LCA. Consequently, the product chain can link with gate-to-gate modules to complete the process of life cycle assessment (Jiménez-González, Kim and Overcash, 2000).

Cradle to cradle is a special kind of cradle-to-grave evaluation. This phase is the recycling process that occurs after the disposal of products to reduce environmental impacts by using sustainable production, operation, and disposal waste, demonstrating social responsibility (Bj and Hauschild, 2018).

2.6 Environmental Life Cycle Impact Assessment Methods

Life Cycle Impact Assessment (LCIA) methods quantify the environmental impact of the product or the process in focus. Various LCIA methods are used by practitioners. Table 2-3 presents popular LCIA methods.

Table 2-3 Life cycle impact assessment methods

Indicators	Explanation
Traci	• Chemical and other impacts on the environment are evaluated and reduced by this tool. • Assessing sustainability and life cycle, the ecology of industry, the procedure of design, and reducing contamination are the main goals of this tool. • Acidification, creation of smog, cancerous, and non-cancerous effects on human wellbeing, global warming, and the criteria of pollutions for human health are the

	main divisions of research. • It is a midpoint approach in which simple cause-effect chains are drawn to show the impacts (Bare, Norris, and Pennington, 2003).
ReCiPe	• It is integrated with two methods: CML as a midpoint indicator and Eco indicator as an endpoint indicator. • Midpoint and endpoint levels are determined indicators. • 18 midpoints illustrating the interpretation are difficult and uncertain, but it is used for acidification, eutrophication and climate change • 3 endpoint indicators show the interpretation is easy and uncertain, but it is utilized for determining the damage on human wellbeing, and ecosystem and resources are available (Goedkoop et al., no date).
Eco indicator 99	• It presents a comprehensive damage-oriented approach to life cycle assessment for description factors (Tukker, 2000). • Pre-consultants provide data about normalization factors of Eco indicator 99 (Siddiqui and Dincer, 2019).
CML 2001	• One of the methods commonly used for impact assessment is CML 2001. • It limits uncertainties by restricting quantitative modeling to early stages in the cause-effect chain. Moreover, CML 2001 groups the results in midpoint categories based on common mechanisms such as climate change, or commonly accepted groupings such as ecotoxicity. • It calculates the normalization factors via total substance emissions and Impact Assessment factors per substance • CML website provides Impact Assessment factors for more than 1700 different flows in the form of a Microsoft Excel spreadsheet. The Impact Assessment

	factors are updated once new knowledge of substance levels is available (Guinée et al., 2002).
Ecological footprint	• By EF, all data from an economy and population are converted into a land and water area. • Productions or services chain is supplied by EF (Wiedmann et al., 2006). • The land occupied in 6 separate occupation lands with different capacities is measured to absorb carbon. • The average capacity of bio productivity of land is based on hectares(Lee et al., 2015).
ILCD 1.0.8	• ILCD (International Reference Life Cycle Data System) completes information on the basis of the structure in the database and uses it in LCA software. • It explains the current limitations and resources to access data correctly. LCIA uses ILCD in mapping, checking extra qualifications in construction support projects, and it allows access to electronic data in LCA software. • LCIA contains all descriptive information and factors to represent reference unit, time, models' validation, ownership data, and calculating factors (European Commission, 2012).
IMPACT 2002+	• It offers a combination of midpoint damage approach and includes four damage categories in 14 midpoint indicators (Sato, 1977), such as human and ecotoxicity, carcinogens and non-carcinogens, food transfer of contaminations, agriculture, and livestock, and emission in indoor and outdoor air (Ilgin, no date). • Four main damage classes—human wellbeing, ecosystem qualification, sources, and climate change—are assessed by this (Pennington et al., 2002).

2.7 Midpoint and Endpoint Indicators for LCA

Various impact assessment approaches can be used to calculate the results of an LCA, and they are different in a number of aspects. However, the major distinction is midpoint and endpoint approaches. For calculating the impact, they look at diverse phases in the cause-effect chain. A midpoint method looks at the impact earlier along the cause-effect chain before the endpoint is reached. Endpoint approaches usually indicate the effects on human health, ecosystem quality, and resource depletion; therefore, extensive knowledge is not required for result interpretation. But a higher level of statistical uncertainties is a negative aspect of endpoint methods. Midpoint methods impact categories are tropospheric ozone formation, ionizing radiation, stratosphere ozone depletion, human toxicity, global warming, water use, freshwater ecotoxicity, freshwater eutrophication, terrestrial ecotoxicity, terrestrial acidification, marine ecotoxicity, mineral resources, and fossil resources. Although midpoint approaches need at least some knowledge for appropriate interpretation, they offer more detail in return and consider a large number of impacts as well as the lower level of statistical uncertainty than endpoint methods (Bare et al., 2012).

Ozone Depleting Potential (ODP):

During the life cycle of the product, this metric is used to quantify the ozone-depleting potential. There are two types of ozone, one of which is ground-level ozone. Ground-level ozone is a pollutant. However, the excessive amount of ultraviolet light is protected by a stratospheric ozone layer; therefore, this type of ozone is useful. Many man-made chemicals like chlorofluorocarbons (CFCs), which are used in the working fluid in refrigerator compressors and the blowing agent in aerosols, produce free radical catalysts that attack the stratospheric ozone layer. Therefore, this indicator—measured in kilograms of CFC-11 equivalents—adjusts all ozone-depleting chemicals associated with the UEL to the equivalent level of emissions of these harmful chemicals.

Global Warming Potential (GWP):

Through the build-up of greenhouse gases, a product converts the chemical composition of the atmosphere. Activities related to the life cycle of the product are measured by this indicator in kilograms of carbon dioxide (CO2) equivalent units.

When greenhouse gases such as methane, carbon dioxide, and nitrous oxide increase their concentration, the heat-trapping capability of the earth’s atmosphere will increase, and global climate change will occur.

Acidification Potential (AP):

This indicator measures air pollution, and specifically sulfur dioxide, ammonia, and nitrogen oxides (in kilograms of sulfur dioxide (SO2) equivalent units) resulting from the life cycle of the product, which contributes to the deposition of acidic materials. “Acid rain” is the most famous consequence, and it damages forests and lakes. Acid deposition also leads to increased environmental mobility of metals, leading to the source of water pollution and metal uptake.

Eutrophication Potential (EP):

This indicator measures the concentration of nitrates and phosphates in the water, in kilograms of phosphate (PO4) equivalent units. The excessive concentration of these substances in water can trigger excessive algae growth, decrease oxygen in the water, and damage ecosystems.

Photochemical Ozone Creation Potential (POCP) or Smog Formation:

During its life cycle, a product can generate photochemical smog. This indicator measures that smog in kilograms of ozone (O3) formed units. Fossil fuels used for heating, transportation, and industry and automobile internal combustion engines are the common sources. Emission of nitrogen oxides and volatile organic compounds (VOCs), which are two primary pollutants, are the consequences of these activities. The interaction of primary pollutants with sunlight leads to the conversion of pollutants into various hazardous chemicals known as secondary pollutants, which in turn cause ‘urban smog.’

Human Toxicity Potential (HTP):

This indicator has been introduced to quantify water, air, and soil emissions related to the life cycle of a product that may be hazardous to human health, in kilograms of 1,4-dichlorobenzene (DCB) equivalent units. Through scientific estimates of tolerable daily intake of toxic materials, the toxicological factors are measured. However, given the fact that this calculation is still at an early stage of development, it cannot be taken as an absolute measure of the toxicity potential.

Freshwater Aquatic Ecotoxicity Potential (FAETP):

This indicator, which is very similar to the HTP indicator, integrates maximum tolerable concentration of diverse toxic materials within the water by freshwater aquatic organism-related factors, and its measurement unit is kilograms of 1,4-dichlorobenzene (DCB) equivalent units.

Marine Aquatic Ecotoxicity Potential (MAETP):

This indicator integrates the maximum tolerable concentration of diverse toxic materials within the water by marine aquatic organism-related factors, and its measurement unit is kilograms of 1,4-dichlorobenzene (DCB) equivalent units.

2.8 Published Literature on BIM and LCA Use for Road Construction

Table 2-4 explores how BIM and LCA have been integrated into previous research, where LCA has been conducted for road infrastructure and the current status of using BIM for road infrastructure design and planning. This approach reveals how BIM can be adopted to enhance life cycle thinking-based road infrastructure planning and management.

Table 2-4 Summary of published research on road, BIM and LCA

Journal Articles	BIM, LCA		ROAD, LCA			BIM, ROAD			Integration of Road, BIM and LCA
	New work	Repair work	Planning	Construction	End of life	Pre-construction	During construction	Post Construction	
Umer (2015)	-	-	✓	✓	✓	-	-	-	✗
Häkkinen and Mäkelä (1996)	-	-	✓	✓	✓	-	-	-	✗
Piantanakulchai, Inamura and Takeyama (2011)	-	-	✓	✓	-	-	-	-	✗
Mroueh (2014)	-	-	✓	✓	✓	-	-	-	✗
Athena (2006)	-	-	✓	✓	-	-	-	-	✗
Santero, Masanet and Horvath, (a-2011)	-	-	✓	✓	✓	-	-	-	✗

Biswas (2014)	-	-	✓	✓	-	-	-	-	✗
Turk et al (2016)	-	-	✓	✓	-	-	-	-	✗
Park et al (2003)	-	-	✓	✓	✓	-	-	-	✗
B. Reza (2013)	-	-	✓	✓	✓	-	-	-	✗
Tezel *et al.* (2016)	-	-	-	-	-	-	✓	✓	✗
Skanska BIM brochure (2011)	-	-	-	-	-	-	-	✓	✗
Astour and Franz (2014)	-	-	-	-	-	✓	-	-	✗
Chong *et al.* (2016)	-	-	-	-	-	✓	✓	✓	✗
Soust-Verdaguer, Llatas and García-Martínez (2017)	✓	-	-	-	-	-	-	-	✗
Díaz and Antön (2014)	✓	✓	-	-	-	-	-	-	✗
Marzouk, El-zayat and Aboushady (2017)	✓	✓	-	-	-	-	-	-	✗
Azhar and Brown (2009)	✓	-	-	-	-	-	-	-	✗

2.9 Sustainability Evaluation of Road Infrastructure Using LCA

LCA research on road infrastructure has evolved from energy and material-based comparisons to methodological improvements. Multiple tools are available for conducting LCA of road pavement (e.g., DuboCalc, PaLATE, VTTI/UC, Gabi) (Galatioto et al., 2015). These tools focus on different phases of road pavement’s cycle and take different environmental impacts into account. The LCA databases available for road construction material have been developed for different purposes (e.g., consulting, research, and decision making). There is a distinct difference in the permitted flexibility allowed in these tools. LCA tools can be divided into two categories: i) black boxes that use default techniques and statistics, and ii) tools that permit customers to use their data and allow selecting the relevant database or modifying the existing data (dos Santos et al., 2017). Table 2-5 compares LCA tools used for road infrastructure.

Table 2-5 Comparison of LCA tools used for road infrastructure (Birgisdóttir, 2008; Santos et al., 2017; Soust-Verdaguer, Llatas and García-Martínez, 2017)

		DuboCalc	**PaLATE V2.2**	**VTTI/UC**	**ECORCE-M**	**GaBi**	**ROAD-RES**
Developed By		NRA Rijkswaterstaat	Green Design and Manufacturing from the University of California-Berkeley	Collaborative Effort Between the University of Coimbra, Portugal, and Virginia Tech.	IFSTTAR in collaboration with CEREMA of the French Ministry of Ecology, Sustainable Development and Energy (MEDDE)	PE International in collaboration with the University of Stuttgart	Harpa Birgisdóttir (Institute of Environment & Resources Technical University of Denmark)
Developed Year		2002	2003	2014	2008	2012	2005
Country		Netherlands	United States of America	United States of America	France	Germany	Denmark
LCA Phases Applicable		Planning, Design, Construction and End-of-Life	Planning, Design, Construction and End-of-Life	Material Extraction, Construction and Maintenance & Rehabilitation	Planning, Design, Construction and Maintenance	Planning, Design, Construction and End-of-Life	Design, Construction, Operation & Maintenance and Demolition
Intended for		Road and Water Works	Road LCA, specifically Environmental and Economic	Pavement work	Road Infrastructure	Road, Buildings, and other Civil Infrastructure	Road Infrastructure
Environmental Impact Category	**AD**	✓	-	-	-	-	-
	CC	✓	✓	✓	✓	✓	✓
	OD	✓	-	-		✓	✓
	POC	✓	-	✓	✓	✓	✓
	AC	✓	-	✓	✓	✓	✓
	EU	✓	-	✓	✓	✓	✓
	HT	✓	-	-	-	✓	✓
	FAE	✓	-	-	-	✓	✓
	MAE	✓	-	-	-	✓	✓
	TE	✓	-	-	-	✓	✓
	EC	-	✓	✓	✓	✓	✓
	HHCP	-	-	✓	-	-	-
	CE	-	-	-	✓	-	✓
	CT	-	-	-	✓	-	✓

AD: Abiotic Depletion; CC: Climate Change; OD: Ozone Depletion; POC: Photochemical Ozone Creation; AC: Acidification; EU: Eutrophication; HT: Human Toxicity; FAE: Freshwater Aquatic Ecotoxicity; MAE: Marine Aquatic Ecotoxicity; TE: Terrestrial Ecotoxicity; EC: Energy Consumption; HHCP: Human Health Criteria Pollutants; CE: Chronic Ecotoxicity; CT: Chronic Toxicity

The previous studies of LCA of road pavement have mainly used the system boundaries of cradle-to-grave, and cradle-to-cradle. Cradle-to-grave encompasses planning, design, construction, and maintenance and rehabilitation, while cradle-to-cradle includes recycling or reuse in addition to the phases considered in cradle-to-grave (Zhang et al., 2003; Bhise, 2014). Table 2-6 compares the LCA system boundaries used by previous researchers.

Table 2-6 LCA system boundaries used in literature

Journal Articles/ Reports	**Author**	**Year**	**Life Cycle Assessment**	
			Cradle to Cradle	**Cradle to Grave**
Sustainability Evaluation of Transportation Infrastructure Under Uncertainty.	Umer	2015	✗	✓
Environmental Impact of Concrete and Asphalt Pavements.	Häkkinen and Mäkelä	1996	✗	✓
a Life Cycle Inventory Analysis of Carbon Dioxide for a Highway Construction Project Using Input-Output Scheme a Case Study of the Tohoku Expressway Construction Works.	Piantanakulchai, Inamura and Takeyama	2011	✓	✗
Life Cycle Assessment of Road Construction.	Mroueh	2014	✗	✓
A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential.	Athena	2006	✓	✗
Life-cycle assessment of pavements Part I: Critical review & Life-cycle assessment of pavements Part II: Filling the research gaps.	Santero, Masanet and Horvath, (a), Santero, Masanet and Horvath, (b)	2011	✗	✓
Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia.	Biswas	2014	✓	✗
Environmental comparison of two alternative road pavement rehabilitation techniques: Cold-in-place-recycling versus traditional reconstruction.	Turk et al	2016	✓	✗
Quantitative Assessment of Environmental Impacts on Life Cycle of Highways.	Park et al	2003	✗	✓
Emergy-based life cycle assessment (EM-LCA) for sustainability appraisal of built environment,	Reza	2013	✗	✓

Life Cycle Analysis of Road Construction and Use	Trunzo, Moretti and D’Andrea	2019	✗	✓

Häkkinen and Mäkelä (1996) studied the cradle-to-grave life cycle impacts of asphalt and concrete pavement. This research considered the influence of pavement on gas consumption, as well as traffic, light requirements, and dust formation. This research revealed that the environmental impact of concrete depended on the cement content and the thickness of the concrete course. Raza (2013) and Reza et al. (2013) used energy accounting to quantify life cycle environmental burdens (e.g., pavement, concrete, buildings, gasoline production) of pavement construction (Reza, 2013; Reza et al. 2013). This research converted environmental impacts to *solar ampoules* that enabled aggregation of environmental impacts as an index, which is a unique feature of this approach. Piantanakulchai, Inamura, and Takeyama (2011) adopted a hybrid I-O (input-output) model to assess the life cycle impacts of an expressway construction project in Japan. The study, which was single impact-focused (i.e., carbon footprint), revealed that emissions from vehicles using the operation stage account for 90% of life cycle CO_2 emissions. The Athena Institute (2006) compared asphalt and concrete roadways in Canada considering a service life of 50 years (Athena Institute, 2006). This study used energy consumption and global warming potential, and its results revealed that life cycle energy consumption in concrete pavement is low compared to asphalt pavement. The differences in GWP of concrete pavement to asphalt pavement were less than 10%. Santero et al. (2011) recommended adopting a standardized functional unit and an evaluation framework that accounts for the function, location, and design of the pavement (Santero, et al. 2011a). They recommended the importance of using larger environmental impact categories to form a dependable decision basis.

Mroueh (2014) analyzed life cycle impacts when unique industrial by-products are used in road projects (Mroueh, 2014). This study compared the use of coal ash, crushed concrete waste, and granulated blast-furnace slag. The highest environmental impacts are created during the manufacturing of bitumen and cement. This study revealed that GHG emissions for each road construction alternative are 0.8 to 1.8% of the GHG emission from traffic on the road. Biswas (2014) analyzed the embodied energy and carbon in road construction materials and revealed that a recycling approach that uses 100% reused crushed rock base and recycled concrete rubble, and 15% Reclaimed Asphalt Pavement (RAP) could reduce the total carbon footprint of the road by 6%. Increasing the proportion of RAP in the wearing course is the major contributor to this improvement. This study further revealed that the use of recycled materials can reduce environmental impacts (i.e., acidification and abiotic depletion of fuels, and energy consumption) by 15% to 18% (Turk et al., 2016).

2.10 Building Information Modeling

BIM digitally represents the physical and functional characteristics of a building that aids forming a reliable basis for decisions during its life cycle from conseptual development to demolition (Department of Transport and Main Roads, 2017).Azhar (2011) mentioned the benefits of BIM for Architecture, Engineering, and Construction (AEC) industries in his research. BIM is a faster and more effective process, leads to better design, enables a better understanding of life cycle cost and environmental data, creates more flexible documentation output, and allows for the more accurate geometrical representation of the structural parts (Azhar, 2011).

2.11 BIM for Road Infrastructure

The published literature lacks a comprehensive review of BIM adaptation in transportation infrastructure (e.g., bridges, highways, and roads) (Costin et al., 2018). Benefits of BIM adaptation include 40% removal of unbudgeted changes, cost estimation accuracy (within 3%), 80% reduction of time in cost estimation, 10% financial savings of contract value due to conflict detections, 7% reduction in project durations, and a return on investment of 5 to 10 times for investing in BIM (CRC Construction Innovation, 2009). Hence BIM has been gradually gaining traction in the construction industry. Figure 2-4 illustrates how BIM adaptation was researched in academic papers and industrial cases from 2006-2016.

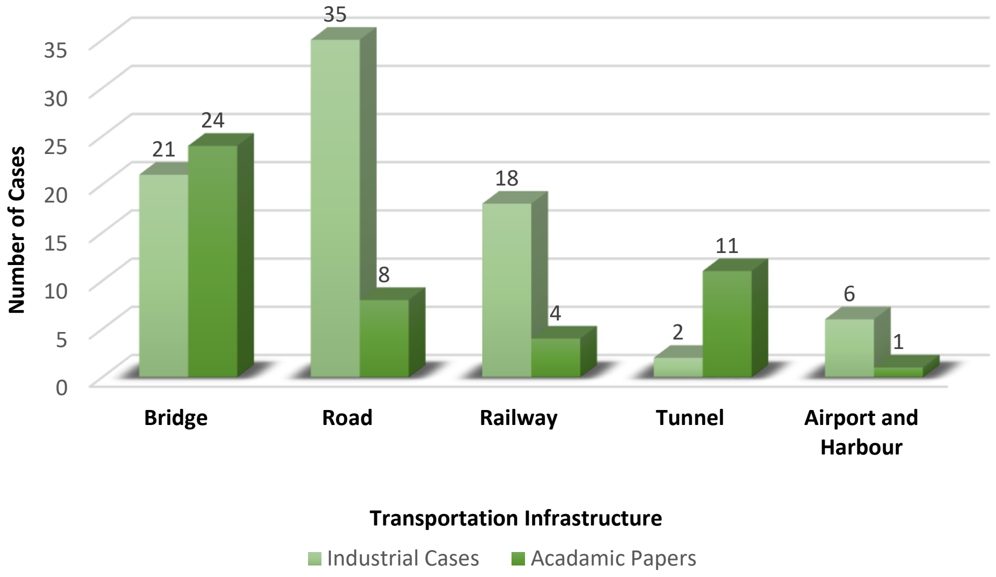


Figure 2-4 Nos. of cases and academic papers (2006-2016) BIM in transportation

Multiple BIM software tools are capable of modeling road infrastructure. Table 2-7 lists the number of projects that were observed for road infrastructure projects based on the information obtained from Cheng et al. (2016).

Table 2-7 Nos. of road construction projects that adopt BIM (Cheng, Lu and Deng, 2016)

Organization	Software tools	Nos. of Cases
Autodesk	Revit	3
	AutoCAD	2
	AutoCAD Map 3D	3
	AutoCAD Civil 3D	10
	Autodesk Infra-Works	3
	Autodesk 3Ds Max Design	6
	Navisworks	6
Bentley	RM Bridge, LEAP & LARS Bridge	2
	Power In roads, Power GEOPAK, MXROAD, and Power civil	16
	MicroStation	13

Tezel et al. (2016) explored the possibility of BIM implementation in motorway construction and maintenance. This study stated that BIM combined with the Internet of Things (IoT) and rapid laser scanning (e.g., LiDAR) for enhanced management of road infrastructure. Gerrish et al. (2017) stated that a BIM-based system provides pre-access to the end-user to make use of construction and operation data. Pappalardo et al. (2018) stated that information on design, construction, planning, operation and maintenance, budgets, and schedules enclosed in a BIM model will help in efficient construction and management of road infrastructure. Fanning et al. (2015) assessed bridge construction projects and revealed that BIM adaptation can achieve 5%-9% cost savings and reduce change orders and rework (Fanning et al., 2015). Chang and Lin (2016) proposed road information modeling (RIM) by using BIM as the basis (Chang and Lin, 2016). RIM is used to represent utilities such as electricity, potable water, gas, telecommunication, and storm and sewage infrastructure along the road (Chang and Lin, 2016).

BIM adaptation has achieved several successes in road infrastructure planning and management in the United Kingdom and North America. In the UK, a mandate was imposed to deliver public construction project data using BIM during procurement by 2016. Following the mandate, there have been many success stories. BIM adaptation in a M25 highway widening project around London enabled the project team to optimize the design and build the project safely, on time, and on a budget (Autodesk Inc., 2015). BIM-enabled virtual inspection before construction, allowing the project team to minimize rework due to clashes and improving data management (Guest Author, 2015). More importantly, BIM-based visualization enabled visual construction rehearsals that maximized the efficiency of construction. BIM was used in an A1 motorway upgrade between Leeming and Barton. This approach enabled improved stakeholder engagement, increased understanding of the project, improved safety and constructability, and a better-informed customer (Wilkhu, 2015). In the A556 improvement from Knutsford to Bowdon, BIM was used to illustrate and communicate safety risks and mitigation procedures (The Construction Index, 2016). The Department of Transportation in a number of states requires road designs to be delivered using BIM (Weiss, 2017). BIM-enabled the

Highway 78 Brawley Bypass project in California to be completed with minimum errors, highest efficiency, and reduced labor costs (McGraw Hill Construction, 2012). Despite the numerous benefits, however, BIM adaptation in the road construction sector is hindered by resistance to changing traditional practices by professionals (Blanco and Chen, 2014).

Astour and Franz (2014) developed a BIM-based method for project cost estimation that can be used in the pre-feasibility stage of a project. The suggested system offers numerous benefits over a traditional approach for feasibility studies. First, the proposed system supports assessing the cost by changing the route. Second, visualization enables enhanced communication with the client on the design. Third, this approach adopts a concrete technique that is independent of the evaluator. The suggested system minimizes the time and resources required for the feasibility study and provides a systematic decision aid system for selecting the best route.

Chong et al. (2016) examined and compared BIM adaptation in Australian and Chinese road projects. Even though BIM adaptation had been similar in the projects, managerial strategies had created several changes that have been rather distinctive to the cultural aspects of the two countries.

2.12 Integration of BIM and LCA

Soust-Verdaguer et al. (2017) stated that BIM-LCA is an effective and efficient solution in the preliminary stages of design to instruct builders, designers, and architects to address environmental problems (Soust-Verdaguer et al.,; CANARSLAN, 2007). BIM-LCA integration could be a starting point for the incorporation of environmental standards in the early design phases. There are various sustainability evaluation tools in the BIM platform (Azhar and Brown, 2009).

Ecotect is an Autodesk program that is capable of performing energy analysis, thermal analysis, solar analysis, and lighting/shading analyses (Autodesk Inc., 2008). Ecotech simultaneously allows alternative building performance assessment methods such as acoustic analysis (Azhar et al.,2009).

Green Building Studio and Insight are web-based energy and solar analysis service that analyzes environmental impact of buildings during the conceptual design. This software enables lighting and shading analysis, energy and thermal analysis, and value/cost analyses (Azhar et al., 2009).

Virtual Environment software package is a suite of integrated building performance analysis tool box. Developed by Integrated Environmental Solutions, this tool enables energy, costs, solar, and lighting analysis. The value/cost analysis functions encompass the lifecycle assessment and LCC (Azhar et al., 2009).

Tally is an application that enables quantification of the life cycle environmental impacts of constructed assets, allowing a comparative analysis of design options. The application of Tally is currently adapted to the United States (Soust-Verdaguer et al., 2017). The Tally plug-in only works with GaBi's database, and as a result, it fails to recognize selected materials in other LCA tools. This will compromise the accuracy of the results (Santos et al., 2016).

In order to assess the life cycle impacts of a constructed asset, it is important to consider the long-term performance. This process requires the integration of multiple software packages. Previous authors have combined different software with BIM to support specific analysis. As an example, Marzouk et al. (2017) computed life cycle cost, construction time, primary energy used, and environmental impacts with road construction processes by using multiple software programs, such as Revit 2015, Copert, and Athena Impact Estimator (Marzouk et al., 2017).

2.13 Interoperability and Integration

A major challenge for BIM-LCA integration is a lack of tools to integrate BIM and LCA (Tawelian and Mickovski, 2016). Because BIM software is not directly linked to popular LCA software, it is impossible to evaluate the real-time impacts of model changes. However, the modification should be reapplied in the LCA software to evaluate the impacts of design changes. Efficient data exchange supports work synchronization among architects, designers, contractors, and subcontractors. According to Eastman and Teicholz (2011), there are four approaches in which model data can be exchanged between different software tools:

The direct link between specific BIM tools: Direct links between commonly used BIM software include database, components, and interface connections (Eastman and Teicholz, 2011). The exchanged data is accessible for export, modification, and deletion through the BIM model (Jalaei, 2015).

Public Level Exchange Formats: Industry Foundation Classes (IFC) is the worldwide standard for data exchange in the construction industry (NBIMS, 2007). Most BIM tools such as Revit Architecture™, Bentley Architecture™, ArchiCAD™, etc. support IFC models. Specialized applications of IFC files include CIMsteel Integration Standard Version 2 (CIS/2) for structure and fabrication (Edwin, 2010; Eastman and Teicholz, 2011; Atlanta, 2016). Consistent standards must be followed in developing the IFC as the exchange format (Jalaei, 2015). IFC format can be used to model road pavement by representing the spatial and physical components (Lee and Kim, 2011).

Proprietary Exchange File Format: Proprietary exchange file format is a file-based information exchange method that is developed by an industrial corporation to support its own software product. Autodesk's Data Exchange Format (DXF) is one of the most favored forms of proprietary exchange file formats (Arayici et al., 2011; Eastman and Teicholz, 2011). Other proprietary exchange file formats such as SAT, ACIS, STL, and 3DS have been developed by institutions to suit their software and specific requirements.

XML-based Exchange Formats: Extendable Markup Language (XML) file format in the architectural engineering and construction (AEC) sector consists of a range of formats such as gbXML (green building data), aecXML, agcXML, and ifcXML (Jalaei, 2015).

The above file formats increase the interoperability of BIM tools, allowing users to pass complete models with fewer errors and omissions. Ultimately this can facilitate consistent data sharing at all levels of the infrastructure life cycle (Jalaei, 2015). There are several studies in the published literature that combine BIM and LCA, particularly focused on building information. Methods adopted to link BIM and LCA are presented in Table 2-8.

Table 2-8 BIM-LCA integration

Application	Methods used for BIM-LCA link	Reference

Evaluating Envelope Alternatives of Single-Family Houses in Uruguay	gbXML	(Soust-Verdaguer et al., 2018)
Evaluate and improve the life cycle performance of buildings in early design stages.	Grasshopper/ Dynamo	(Röck et al., 2018b)
LCA based omparative analysis of construction	Tally	(Bueno and Fabricio, 2018)
LCA and LCC analysis within a BIM-based environment.	IFC	(Santos et al., 2019)
To calculate total embodied impacts at the early design phase	Dynamo	(Röck et al., 2018a)
Building overhang design	EcoHestia	(Panteli et al., 2018)
LCA-based comparison of a modern Vernetztes Polyethylen water supply system	DDS-CAD/ GaBi	(Kylili et al., 2016)
Decision Making in building construction	IFC	(Kulahcioglu, Dang and Toklu, 2012)

2.14 Emergy Accounting

Solar energy is the foundation of all energy sources. Emergy is defined as the “available solar energy used up directly and indirectly to make a service or product” (Odum 1996). Emergy is measured using solar emjoules (Sej). Emergy flow (E_m) is calculated as (1):

$$E_m = \sum (Tr_i \text{ x } E_i)\ldots..(1)$$

Where, Tr_i is the transformity of type i input in a unit of sej/g or sej/J (for specific emergy), and E_i is available type i input in mass quantity (g) or energy quantity (J).

Emergy is an expression of all environmental supports, including ‘freely available’ ones, as well as cash and human services spent in the work process that produces a good or service in the unit of solar energy (Brown and Buranakarn, 2003).

Emergy is a plausible approach for sustainability evaluation of civil infrastructure. Ingwersen (2011) has recommended emergy as a beneficial measure for validating LCA. Recently, emergy-based evaluations have been used for economic and environmental evaluation of the construction projects (Reza, 2013). Brown and

Buranakarn (2003) performed an emergy analysis on the reuse of construction material. Reza (2013) evaluated road project proposals primarily based on emergy. Ruparathna (2013) used emergy for building project analysis. Hence, emergy can be used for validating LCA results.

2.15 Summary

This chapter reviewed the published literature on the life cycle thinking-based road infrastructure planning using BIM. BIM and LCA are emerging initiatives that support the green transformation of the construction sector. This review identified the research gaps in the current knowledge base.

References

Soliman, A., Mahmoud, A., Amin, H., and, Tarek, Z., (2018) ‘Multiobjective Framework for Managing Municipal Integrated Infrastructure’, Journal of Construction Engineering and Management, 144(1), p. 04017091. doi: 10.1061/(ASCE)CO.1943-7862.0001402.

Arayici, Y, Coates, SP, Koskela, LJ, Kagioglou, M, Usher, C and OReilly, K (2011) ‘BIM adoption and implementation for architectural practices’, Structural Survey, 29(1), pp. 7–25. doi: 10.1108/02630801111118377.

Armstrong, A., Sousa, L., Haggerty, C., Fischer C., and Wagenlander, W., (2013) An Integrated Approach to Sustainable Roadside Design and Restoration. Available at: https://www.fhwa.dot.gov/innovativeprograms/pdfs/centers/local_aid/IntegratedApproachtoSustainableRoadsideDesign.pdf.

Assaf, S.A., Al-Hammad, A., Jannadi, O.A.,and Saad, S.A. (2002) ‘Assessment of the problems of application of life cycle costing in construction projects’, Cost Engineering, 44(2), pp. 17–22.

Astour, H. and Franz, V. (2014) ‘Computing in Civil and Building Engineering’, The Sixth International Conference On Computing\Rin Civil And Building Engineering, pp. 1179–1184.

Athena Institute (2006) A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. Available at: http://s3.amazonaws.com/zanran_storage/www.athenasmi.ca/ContentPages/859479425.pdf.

Atlanta, G. (2016) Architecture Professor at Georgia Tech to Receive the 2016 Society Award of Excellence by ACADIA.

Autodesk Inc. (2008) Improving Building Industry Results through Integrated Project Delivery and Building Information Modeling., White Paper. Available at: www.autodesk.com.

Autodesk Inc. (2015) Atkins & Skanska Balfour Beatty widen London’s M25 motorway.

Azhar, S. (2011) ‘Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry’, Leadership and Management in Engineering, 11(3), pp. 241–252. doi: 10.1061/(ASCE)LM.1943-5630.0000127.

Azhar, S. and Brown, J. (2009) ‘Bim for sustainability analyses’, International Journal of Construction Education and Research, 5(4), pp. 276–292. doi: 10.1080/15578770903355657.

Azhar, S., Brown, J. and Farooqui, R. (2009) ‘BIM-based Sustainability Analysis : An Evaluation of Building Performance Analysis Software’, Proceedings of the 45th ASC Annual Conference, (August 2014), pp. 1–4.

Bare, J.C., G.A. Norris, D.W. Pennington, and T. M. (2003) ‘The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts’, Journal of Industrial Ecology, 6(3), pp. 49–78.

Bare, J., Hofstetter, P., Pennington, D., and Haes, H., (2012) ‘Midpoints Versus Endpoints : The Sacrifices and Benefits Midpoints versus Endpoints : The Sacrifices and Benefits’, Int. J. LCA, (June 2014). doi: 10.1007/BF02978665.

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G., (2012) ‘Application Areas and Data Requirements for BIM-Enabled Facilities Management’, Journal of Construction Engineering and Management, 138(3), pp. 431–442. doi: 10.1061/(ASCE)CO.1943-7862.0000433.

Birgisdóttir, H. (2008) Life cycle assessment model for road construction and use of residues from waste incineration, Volume 6: Turbomachinery, Parts A, B, and C. doi: 10.1115/GT2008-50898.

Biswas, W. K. (2014) ‘Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia’, International Journal of Life Cycle Assessment, 19(4), pp. 732–744. doi: 10.1007/s11367-013-0681-2.

Bj, A. and Hauschild, M. Z. (2018) ‘Cradle to Cradle and LCA’, pp. 605–631. doi: 10.1007/978-3-319-56475-3.

Blanco, F. G. B. and Chen, H. (2014) ‘The Implementation of Building Information Modelling in the United Kingdom by the Transport Industry’, Procedia - Social and Behavioral Sciences. Elsevier B.V., 138(0), pp. 510–520. doi: 10.1016/j.sbspro.2014.07.232.

Bueno, C. and Fabricio, M. M. (2018) ‘Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in’, Automation in Construction. Elsevier, 90(January 2016), pp. 188–200. doi: 10.1016/j.autcon.2018.02.028.

Bull, J. W. (1993) Life cycle costing for construction. London, UK: Spon press.

Canarslan, Ö. (2007) ‘Evaluation indicators for selection of sustainable building materials S’, (December).

Chang, J. and Lin, H. (2016) ‘Underground Pipeline Management Based on Road Information Modeling to Assist in Road Management’, Journal of Performance of Constructed Facilities, 30(1), pp. 1–14. doi: 10.1061/(ASCE)CF.1943-5509.

Cheng, J. C. P., Lu, Q. and Deng, Y. (2016) ‘Analytical review and evaluation of civil information modeling’, Automation in Construction. Elsevier B.V., 67, pp. 31–47. doi: 10.1016/j.autcon.2016.02.006.

Chong, H. Y., Lopez, R., Wang, J., Wang, X., and Zhao, Z.,‘Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects’, Journal of Management in Engineering, 32(6), p. 05016021. doi: 10.1061/(asce)me.1943-5479.0000460.

Costin, A., Adibfar, A., Hu, H., and Chen, S.S., (2018) ‘Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations’, Automation in Construction. Elsevier, 94(July), pp. 257–281. doi: 10.1016/j.autcon.2018.07.001.

CRC Construction Innovation (2009) National guidelines for digital modelling, Icon. Net Pty Ltd., Brisbane. doi: 978-0-9803503-0-2.

Curry, B. (2015) Municipalities not spending enough to maintain infrastructure: review.

Dan Campbell (2016) Emergy Accounting: A Unified, Comprehensive Triple Bottom Line. Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHEERL&dirEntryId=326034.

Das, S., Paul, D., Fahad, M., and Islam, T., (2017) 'Geotextiles-A Potential Technical Textile Product Available online www.jsaer.com Journal of Scientific and Engineering Research , 2017 , 4 (10): 337-350', Journal of Scientific and Engineering Research, 2017, 4(10):337-350, (November), pp. 1–15.

Department of Transport and Main Roads (2017) Building Information Modelling (BIM) for Transport and Main Roads: A guide to enabling BIM on Road Infrastructure Projects, Guideline, Transport and Main Roads.

Díaz, J. and Antön, L. Á. (2014) 'Sustainable Construction Approach through Integration of LCA and BIM Tools', 8(5), pp. 283–290. doi: 10.1061/9780784413616.036.

Dvir, D. and Lechler, T. (2004) 'Plans are nothing, changing plans is everything: The impact of changes on project success', Research Policy, 33(1), pp. 1–15. doi: 10.1016/j.respol.2003.04.001.

Eastman C., Teicholz P., S. R. and L. K. (2011) BIM handbook: A guide to building information modeling for owner, managers, designers, engineers, and contractors (2nd ed.). New York: Wiley., Appl. Phys. A.

Edwin T. (2010) 'Interoperability and the structural domain', Structures Congress 2010, pp. 1652–1659. doi: 10.1061/41130(369)150.

European Commission (2012) Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods: database and supporting information, European Commission. doi: 10.2788/60825.

Fanning, B.,

Clevenger, C.M., Ozbek, M., and Mahmoud, H., (2015) 'Implementing BIM on Infrastructure : Comparison of Two Bridge Construction Projects', Practice Periodical on StructuralDesign and Construction, 20(4), pp. 1–8. doi: 10.1061/(ASCE)SC.1943-5576.0000239.

Franklin Assoc. (2010) ‘LCI of nine plastic resins and four PU precursors’.

Galatioto, F., Huang, Y., Parry, T., Bird, R., and Bell, M., (2015) ‘Traffic modelling in system boundary expansion of road pavement life cycle assessment’, Transportation Research Part D: Transport and Environment. Elsevier Ltd, 36, pp. 65–75. doi: 10.1016/j.trd.2015.02.007.

Geerlings, H. and Stead, D. (2002) ‘Integrating transport, land use planning and environment policy in European countries’, European Journal of Transport and Infrastructure Research 2(3/4), 215-232. (2002).

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M., and Lowry, C., (2017) ‘BIM application to building energy performance visualisation and managementChallenges and potential’, Energy and Buildings. The Author(s), 144, pp. 218–228. doi: 10.1016/j.enbuild.2017.03.032.

Glasbergen, P. and Driessen, P. P. J. (2005) ‘Interactive planning of infrastructure : the changing role of Dutch project management’, 23, pp. 263–277. doi: 10.1068/c0441.

Guest Author (2015) BIM Level 2 for UK Motorways.

Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M. A. . (2002) Operational guide to the ISO standards. I: LCA in perspective.

Häkkinen, T. and Mäkelä, K. (1996) Environmental impact of concrete and asphalt pavements, Environmental Impact of Concrete and Asphalt Pavements, Technical Research Centre of Finland, Espoo.

Halfawy, M. R. (2008) ‘Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions’, Journal of Computing in Civil Engineering, 22(3), pp. 216–229. doi: 10.1061/(ASCE)0887-3801(2008)22:3(216).

Halfawy, M. R., Dridi, L. and Baker, S. (2008) ‘Integrated Decision Support System for Optimal Renewal Planning of Sewer Networks’, Journal of Computing in Civil Engineering, 22(6), pp. 360–372. doi: 10.1061/(ASCE)0887-3801(2008)22:6(360).

Hampton, D. (1994) ‘Procurement issues’, Journal of Management in Engineering, 10(6), p. 5. doi: 10.1061/(ASCE)9742-597X(1994)10.

Heeres, N., Tillema, T., Arts, J. (2012) Towards area-oriented approaches in infrastructure planning Nederlandse samenvatting.

Howard T. Odum (1996) Environmental accounting : EMERGY and environmental decision making.

Hull, A. (2008) ‘Policy integration : What will it take to achieve more sustainable transport solutions in cities ?’, Transport Policy. Elsevier, 15(2), pp. 94–103. doi: 10.1016/j.tranpol.2007.10.004.

Ingwersen, W. W. (2011) ‘Emergy as a Life Cycle Impact Assessment Indicator’, Journal of Industrial Ecology, 15(4), pp. 550–567.

International Organization for Standardization (2006) ISO 14040: Environmental management-- Life cycle assessment - Principles and framework. Geneva: International Organization for Standardization.

ISO (2006) ‘Environmental management - Life Cycle Assessment - Principles and Framework’, International organization for standardization, 3, p. 20. doi: 10.1016/j.ecolind.2011.01.007.

ISO 14040 (2006a) ‘14044: environmental management—life cycle assessment—requirements and guidelines’, International Organization for Standardization.

ISO 14040 (2006b) ‘Environmental management - Life Cycle Assessment - Principles and Framework ISO 14040: 2006’, International organization for standardization, 3(1), p. 20. doi: 10.1016/j.ecolind.2011.01.007.

Jalaei, F. (2015) Integrate building information modeling (bim) and sustainable design at the conceptual stage of building projects, PhD Thesis - University of Ottawa.

Jiménez-González, C., Kim, S. and Overcash, M. R. (2000) ‘Methodology for developing gate-to-gate Life Cycle Inventory information’, International Journal of Life Cycle Assessment, 5(3), pp. 153–159. doi: 10.1007/BF02978615.

Jones, T., Shan, Y. and Goodrum, P. M. (2010) ‘An investigation of corporate approaches to sustainability in the US engineering and construction industry’, Construction Management and Economics, 28(9), pp. 971–983. doi: 10.1080/01446191003789465.

Julio Castro-Molinare, Anna Korre, S. D. (2014) ‘Sustainability Analysis of Copper Extraction and Processing using Life Cycle Analysis Methods: a Case Study in the North of Chile’, 33, pp. 1861–1866.

Kabir, G., Balek, N. B. C. and Tesfamariam, S. (2018) ‘Consequence-based framework for buried infrastructure systems: A Bayesian belief network model’, Reliability Engineering and System Safety. Elsevier Ltd, 180(August), pp. 290–301. doi: 10.1016/j.ress.2018.07.037.

Kassoff, H. (2005) ‘Sustainable Highways – Oxymoron or Opportunity ?’, p. 2005.

Kehagia, F. (2009) ‘The implementation of sustainability in highway projects’, International Journal of Sustainable Development and Planning, 4(1), pp. 61–69. doi: 10.2495/SDP-V4-N1-61-69.

Khan, Z., Moselhi, O. and Zayed, T. (2015) ‘Identifying Rehabilitation Options for Optimum Improvement in Municipal Asset Condition’, Journal of Infrastructure Systems, 21(2), p. 04014037. doi: 10.1061/(ASCE)IS.1943-555X.0000220.

Kloepffer, W. (2008) ‘Life Cycle Sustainability Assessment of Products’, The International Journal of Life Cycle Assessment, 13(2), pp. 89–95. doi: 0.1065/lca2008.02.376.

Kowalski, K., Król, J., Radziszewski, P., Casado, R., Blanco, V., Pérez, D., Viñas, V., Brijsse, Y., Frosch, M., Le, D. M., and Wayman, M., (2016) ‘Eco-friendly Materials for a New Concept of Asphalt Pavement’, Transportation Research Procedia. The Author(s), 14, pp. 3582–3591. doi: 10.1016/j.trpro.2016.05.426.

Kulahcioglu, T., Dang, J. and Toklu, C. (2012) ‘A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole process of construction’, HVAC and R Research, 18(1–2), pp. 283–293. doi: 10.1080/10789669.2012.634264.

Kylili, A., Fokaides, P.A., Vaiciunas, J., and Seduikyte, L., (2016) ‘Integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for sustainable constructions’, Journal of Sustainable Architecture and Civil Engineering, 13(4), pp. 28–38. doi: 10.5755/j01.sace.13.4.12862.

Lee, K.-M. and Inaba, A. (2004) ‘Life Cycle Assessment: Best Practices of International Organization for Standardization (ISO) 14040 Series’, (February), p. 99.

Lee, S.J., Hawkins, T.R., Ingwersen, W.W., and Young, D.M., (2015) ‘Exploring the Use of Ecological Footprint in Life Cycle Impact Assessment: Findings from a Comparison of Transportation Fuels’, Journal of Industrial Ecology, 19(3), pp. 416–426. doi: 10.1111/jiec.12188.

Lee, S. and Kim, B. (2011) ‘IFC Extension for Road Structures and Digital Modeling’, Procedia Engineering. Elsevier B.V., 14, pp. 1037–1042. doi: 10.1016/j.proeng.2011.07.130.

Liu, Y., van Nederveen, S. and Hertogh, M. (2017) ‘Understanding effects of BIM on collaborative design and constructionAn empirical study in China’, International Journal of Project Management. Elsevier Ltd, APM and IPMA, 35(4), pp. 686–698. doi: 10.1016/j.ijproman.2016.06.007.

Mark Brown and Vorasun Buranakarn (2003) ‘Emergy indices and ratios for sustainable material cycles and recycle options’.

Mark Jacob GoedkoopReinout HeijungsReinout HeijungsMark A J HuijbregtsMark A J HuijbregtsR. Van Zelm (no date) ‘ReCiPE 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint leve’.

Marzouk, M., El-zayat, M. and Aboushady, A. (2017) ‘Assessing environmental impact indicators in road construction projects in developing countries’, Sustainability

(Switzerland), 9(5). doi: 10.3390/su9050843.

McGraw Hill Construction (2012) The Business Value of BIM for Infrastructure, McGraw Hill Construction.

Mehmet AliIlgin (2009) ‘Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art’, Journal of Environmental Management, 91(3), pp. 563–591.

Michele, D. S. and Daniela, L. (2011) ‘Decision-support tools for municipal infrastructure maintenance management’, Procedia Computer Science. Elsevier, 3, pp. 36–41. doi: 10.1016/j.procs.2010.12.007.

Mishra, G. (2016) ‘Types of Pavement - Flexible and Rigid Pavement’, The Constructor: Civil Engineering Home, pp. 1–11. Available at: http://qu.edu.iq/el/pluginfile.php/76422/mod_resource/content/1/Pavement design Lectures .pdf%0Ahttp://theconstructor.org/transportation/types-of-pavement-flexible-and-rigid-pavement/9570/.

Montgomery, R., Hirsch, A. and Schirmer, H. J. (2015) ‘Improving environmental sustainability in road projects’, (93903), pp. 1–102. Available at: http://documents.worldbank.org/curated/en/2015/02/23990347/improving-environmental-sustainability-road-projects.

Mroueh, U. (2014) Life cycle assessment of road construction.

Nagar, C. V. R. (no date) Highway Engineering.

National Audit Office (2005) Improving Public Services through better construction. London, UK.

NBIMS (2007) ‘The National Building Information Model Standard™ (NBIMS) V1’, Vasa. Available at: http://medcontent.metapress.com/index/A65RM03P4874243N.pdf.

Oraee, M., Hosseini, M. R., Papadonikolaki, E., Palliyaguru, R., and Arashpour, M., (2017) ‘Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review', International Journal of Project Management. Elsevier Ltd, APM and IPMA, 35(7), pp. 1288–1301. doi: 10.1016/j.ijproman.2017.07.001.

Osamah Siddiqui and Ibrahim Dincer (2019) 'A well to pump life cycle environmental impact assessment of some hydrogen production routes', International Journal of Hydrogen Energy, 44(12), pp. 5773–5786.

Panteli, C., Kylili, A., Stasiuliene, L., Seduikyte, L., and Fokaides, P.A., (2018) 'A framework for building overhang design using Building Information Modeling and Life Cycle Assessment', Journal of Building Engineering. Elsevier Ltd, 20(April), pp. 248–255. doi: 10.1016/j.jobe.2018.07.022.

Pappalardo, G., D'Agostino, C., Delfino, E., Cafiso, S., and Di Graziano, A., (2018) 'A new perspective in the road asset management with the use of advanced monitoring system & BIM', MATEC Web of Conferences, 231, p. 01007. doi: 10.1051/matecconf/201823101007.

Park, K., Hwang, Y., Seo, S., and Seo, H., (2003) 'Quantitative Assessment of Environmental Impacts on Life Cycle of Highways', Journal of Construction Engineering and Management, 129(1), pp. 25–31. doi: 10.1061/(asce)0733-9364(2003)129:1(25).

Pennington, D.W, Crettaz, P., Tauxe, A. and J. (2002) 'Assessing Human Health Response in Life Cycle Assessment using ED10s and DALYs: Non-Carcinogenic Effects', Journal of Risk Analysis, 22(5), pp. 945–961.

Piantanakulchai, M., Inamura, H. and Takeyama, Y. (2011) 'a Life Cycle Inventory Analysis of Carbon Dioxide for a Highway Construction Project Using Input-Output Scheme a Case Study of the Tohoku Expressway Construction Works', Infrastructure Planning Review, 16(January), pp. 411–418. doi: 10.2208/journalip.16.411.

Porwal, A. (2013) Construction waste management at source: A building information modelling based system dynamics approach. University of British Columbia.

Porwal, A. and Hewage, K. N. (2013) 'Building Information Modeling (BIM) partnering framework for public construction projects', Automation in Construction.

Elsevier B.V., 31, pp. 204–214. doi: 10.1016/j.autcon.2012.12.004.

Ragab, O. (2016) ‘Types Of Roads & Road Components’, (February 2016). doi: 10.13140/RG.2.1.1052.3925.

Reza, B. (2013) Emergy-based life cycle assessment (EM-LCA) for sustainability appraisal of built environment. The University of British Columbia (Okanagan).

Reza, B., Sadiq, R. and Hewage, K. (2013) ‘Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: a case study on paved roads’, Clean Technologies and Environmental Policy, 15(2). doi: 10.1007/s10098-013-0615-5.

Röck, M., Hollberg, A., Habert, G., and Passer, A., (2018a) ‘LCA and BIM: Integrated Assessment and Visualization of Building Elements’ Embodied Impacts for Design Guidance in Early Stages’, Procedia CIRP. The Author(s), 69(May), pp. 218–223. doi: 10.1016/j.procir.2017.11.087.

Röck, M., Hollberg, A., Habert, G., and Passer, A., (2018b) ‘LCA and BIM: Visualization of environmental potentials in building construction at early design stages’, Building and Environment. Elsevier, 140(May), pp. 153–161. doi: 10.1016/j.buildenv.2018.05.006.

Ruparathna, R. (2017) Climate-driven asset management of public buildings : a multi-period maintenance planning framework. University of British Columbia.

Ruparathna, R., Hewage, K. and Sadiq, R. (2018) ‘Multi-period maintenance planning for public buildings: A risk based approach for climate conscious operation’, Journal of Cleaner Production. Elsevier Ltd, 170, pp. 1338–1353. doi: 10.1016/j.jclepro.2017.09.178.

Santero, N. J., Masanet, E. and Horvath, A. (2011a) ‘Life-cycle assessment of pavements. Part I: Critical review’, Resources, Conservation and Recycling. Elsevier B.V., 55(9–10), pp. 801–809. doi: 10.1016/j.resconrec.2011.03.010.

Santero, N. J., Masanet, E. and Horvath, A. (2011b) ‘Life-cycle assessment of pavements Part II: Filling the research gaps’, Resources, Conservation and Recycling.

Elsevier B.V., 55(9–10), pp. 810–818. doi: 10.1016/j.resconrec.2011.03.009.

Santos, J., Thyagarajan, S., Keijzer, E., Flores, R., and Flintsch, G.. (2017) ‘Pavement life cycle assessment: A comparison of American and european tools’, Pavement Life-Cycle Assessment - Proceedings of the Pavement Life-cycle Assessment Symposium, 2017, pp. 1–10. doi: 10.1201/9781315159324-2.

Dos Santos, J.M.O., Thyagarajan, S., Keijzer, E., Flores, R.F., and Flintsch, G., (2017) ‘Comparison of Life-Cycle Assessment Tools for Road Pavement Infrastructure’, Transportation Research Record: Journal of the Transportation Research Board, 2646(1), pp. 28–38. doi: 10.3141/2646-04.

Santos, R., Costa, A.A., and Pais, A.R., (2016) ‘BIM in LCA / LCEA Analysis : Comparative analysis of Multi-family House and Single-family’, Bim, (Commission 2015), pp. 212–223.

Santos, R., Costa, A.A., Silvestre, J.D., and Pyl, L., (2019) ‘Integration of LCA and LCC analysis within a BIM-based environment’, Automation in Construction. Elsevier, 103(September 2018), pp. 127–149. doi: 10.1016/j.autcon.2019.02.011.

Sato, N. (1977) ‘Observational studies of 12 DD Lacertae - II. Radial velocity and the variation of line profile’, Astrophysics and Space Science, 48(2), pp. 453–470. doi: 10.1007/BF00648130.

Sev, A. (2009) ‘How Can the Construction Industry Contribute to Sustainable Development? A Conceptual Framework’, 17(3), pp. 161–173. doi: 10.1002/sd.

Shiraz Tayabji, Kurt D. Smith, T. V. D. (2010) ‘Advanced high-performance materials for highway applications a report on the state of technology’, Report No. Fhwa-Hif-10-002, (October).

Skanska BIM brochure (2011) ‘BIM- Building Quality’, Change: The Magazine of Higher Learning, 18(4), pp. 57–66. doi: 10.1080/00091383.1986.9937083.

Soust-Verdaguer, B., Llatas, C. and García-Martínez, A. (2018) ‘BIM-Based LCA Method to Analyze Envelope Alternatives of Single-Family Houses: Case Study in Uruguay’, Journal of Architectural Engineering, 24(3), pp. 1–15. doi:

10.1061/(ASCE)AE.1943-5568.0000303.

Soust-Verdaguer, B., Llatas, C. and García-Martínez, A. (2017) 'Critical review of bim-based LCA method to buildings', Energy and Buildings, 136(February), pp. 110–120. doi: 10.1016/j.enbuild.2016.12.009.

Spence, R. and Mulligan, H. (1995) 'Sustainable development and the construction industry', Habitat International, 19(1), pp. 279-292. doi: 10.1016/0197-3975(94)00071-9.

Tawelian, L. R. and Mickovski, S. B. (2016) 'The Implementation of Geotechnical Data into the BIM Process', Procedia Engineering. The Author(s), 143(Ictg), pp. 734–741. doi: 10.1016/j.proeng.2016.06.115.

Tezel, A., Aziz, Z., Koskela, L., and Tzortzopoulos, P., (2016) 'Visual Management Condition in Highways Construction Projects in', 24th Annual Conference of the International Group for Lean Construction, pp. 133–142. Available at: http://www.iglc.net/papers/details/1357.

The Construction Index (2016) Road builders turn to Google Earth.

Tillema, T., Hague, T. and Arts, J. (2008) 'Space for mobility : towards a paradigm shift in Dutch transport infrastructure planning ?', (January).

Trunzo, G., Moretti, L. and D'Andrea, A. (2019) 'Life cycle analysis of road construction and use', Sustainability (Switzerland), 11(2). doi: 10.3390/su11020377.

Tukker, A. (2000) 'Life cycle assessment as a tool in environmental impact assessment', Environmental Impact Assessment Review, 20(4), pp. 435–456. doi: 10.1016/S0195-9255(99)00045-1.

Urk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., and Jurjavčič, P., (2016) 'Environmental comparison of two alternative road pavement rehabilitation techniques: Cold-in-place-recycling versus traditional reconstruction', Journal of Cleaner Production, 121, pp. 45–55. doi: 10.1016/j.jclepro.2016.02.040.

Umer, A. (2015) Sustainability Evaluation Of Transportation Infrastructure Under

Uncertainty: A Fuzzy-Based Approach. The University Of British Columbia.

United Nations (2005) Resolution adopted by the General Assembly.

United Nations Environment Program (UNEP) (2011) Towards a Life Cycle Sustainability Assessment: Making informed choices on products. Nirobi: United Nations Environment Programme,.

USEPA (2014) Risk Management Sustainable Technology.

Vigar, G. (2001) ‘Implementing transport ’ s ’ new The dissemination of demand-’, 72(4), pp. 423–443.

Vishal Yashwant Bhise, A. K. (2014) ‘the Cradle To Cradle Life Cycle Assessment: a Case Study’, International Journal of Technical Research and Applications, Volume 2(Issue 4), pp. 84–89.

Wang, Y., Wang, X., Wang, J., Yung, P., and Jun, G., (2013) ‘Engagement of facilities management in design stage through BIM: Framework and a case study’, Advances in Civil Engineering, 2013(30836). doi: 10.1155/2013/189105.

Warren, M. (2009) ‘Whole life cycle costing’, Financial Management, November, pp. 31–32.

Weiss, K. (2017) BIM for roads & highways, DOT standards and more.

Wiedmann, T., J. Minx, J. Barrett, and M. W. (2006) ‘Allocating ecological footprints to final consumption categories with input-output analysis. Ecological Economics’, 56(1), pp. 28– 48.

Wilkhu, R. (2015) BIM on the A1(M) Leeming to Barton.

Wong, J. K. W. and Kuan, K. L. (2014) ‘Implementing “BEAM Plus” for BIM-based sustainability analysis’, Automation in Construction. Elsevier B.V., 44, pp. 163–175. doi: 10.1016/j.autcon.2014.04.003.

World Commission on Environment and Development (1987) Our Common Future. 1st edn. London: Oxford University Press.

Wübbenhorst, K. L. (1986) ‘Life cycle costing for construction projects’, Long range planning, 19(4), pp. 87–97. doi: 10.1016/0024-6301.

Yu, M., Zhu, F., Yang, X., Wang, L., and Sun, X., (2018) ‘Integrating sustainability into construction engineering projects: Perspective of sustainable project planning’, Sustainability (Switzerland), 10(3). doi: 10.3390/su10030784.

Zhang, Z., Machemehl, R. B. and Ahson, I. (2003) ‘Definition of the “ Cradle-to-Grave ” Pavement Management Process’, pp. 1–8.

3 METHODOLOGICAL FRAMEWORK FOR ROAD INFRASTRUCTURE EVALUATION

3.1 Introduction

Life cycle thinking allows improvements across the life cycle of products and processes (i.e., from raw material extraction and conversion; to manufacture and distribution; through use, re-use, and recycling; to ultimate disposal) while addressing triple bottom line issues (USEPA, 2014). LCA follows the product system from the processing of raw materials to the manufacturing, distribution, use, reuse, maintenance, recycling stages, and then to final disposal, including all transportation involved (Lindfors, 1995). Quantitative or qualitative information on emissions, material, and energy used in all phases is gathered and processed so that an assessment can be made on various impact categories: climate change, resource depletion, human health, and ecological considerations (International Organization for Standardization, 2006).

Building information modeling (BIM) is a versatile technique that can be used to mitigate the above-mentioned challenges. BIM digitally represents the physical and functional characteristics of a constructed asset. Hence, a BIM model can be used as a reliable basis for construction management decision making (Porwal, 2013). BIM has been gaining popularity in the construction industry due to its ability to facilitate sustainable development (USGBC, 2010). Altaf et al. (2014) stated that BIM could be used to cut down project durations by 7% while improving cost accuracy by 3%, decreasing the cost estimation time by 80%, and mitigating unbudgeted changes up to 40%.

A majority of published research on BIM has focused on vertical infrastructure. Moreover, LCSA is yet to be integrated with BIM. Even though industry adaptation has been piecemeal, BIM is expected to play a crucial role in green construction. The proposed approach combines BIM and LCSA in evaluating road construction designs. The outcomes of this research will inform and guide engineers in green road construction and will extend the utilization of BIM in horizontal infrastructure planning.

3.2 Overview of the Framework

This research proposes a BIM integrated evaluation framework to compare the life cycle sustainability performance of road construction methods. The framework encompasses four key steps in evaluating the triple bottom line (TBL) performance of alternatives. Figure 3-1 illustrates the methodological framework for road infrastructure planning.

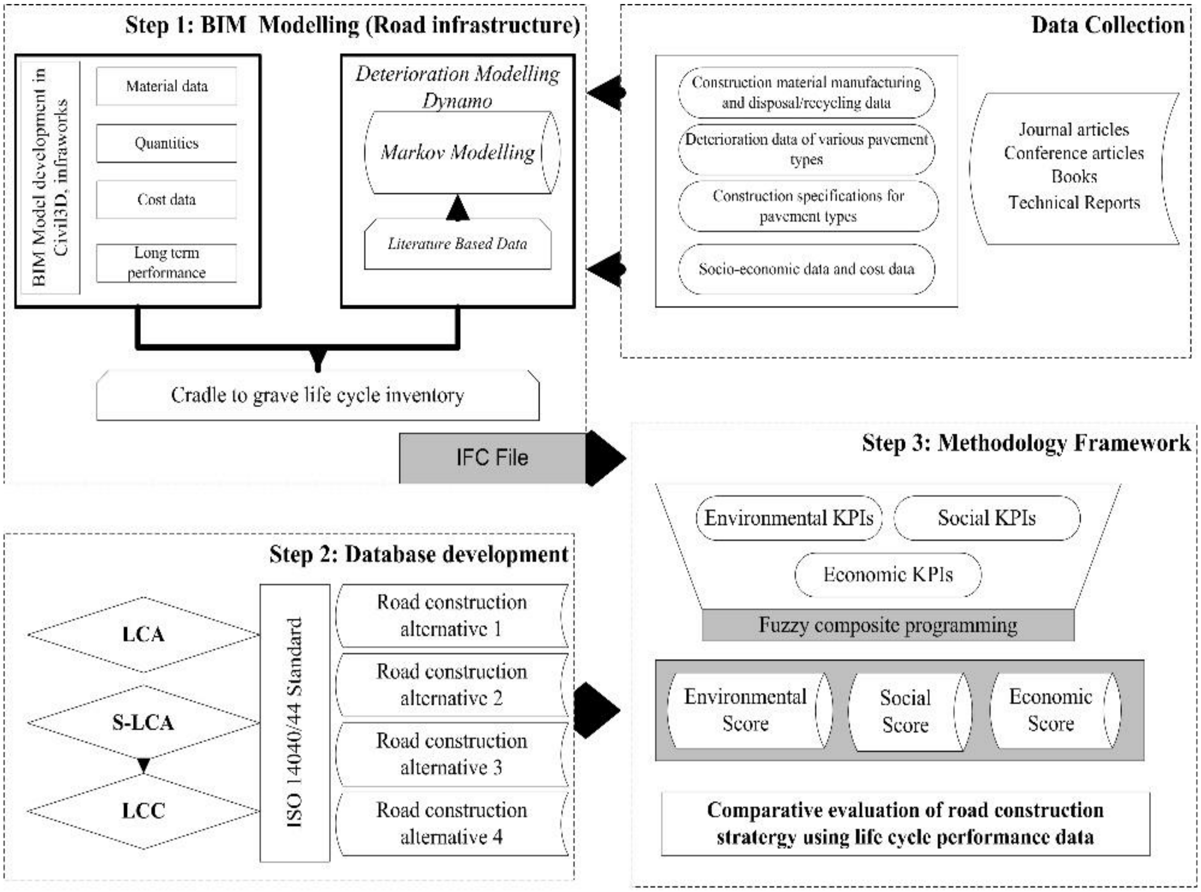


Figure 3-1 Methodological framework

3.3 Phase 1: BIM model of the road infrastructure model

A regular BIM model includes construction material information and quantities. Markov modeling was used to model the life cycle material requirement for repair and renovation. Eastman and Teicholz (2011) stated that there are four approaches in which model data can be exchanged between different software tools (i.e. Direct link between specific BIM tools, Public level exchange format, Proprietary exchange file format and XML-based exchange format). According to NBIMS (2007), the IFC information model is the worldwide standard for data exchange in the construction industry. These formats improve interoperability between various software tools (Autodesk Infraworks, Revit) and integrate the BIM model standard. The challenge is that the BIM model must follow the same standards as the exchange format (Jalaei, 2015). Road pavement can be modeled as an IFC file by representing the spatial and physical characteristics (Lee and Kim, 2011). Figure 3-2 illustrates a 3D model of a road.

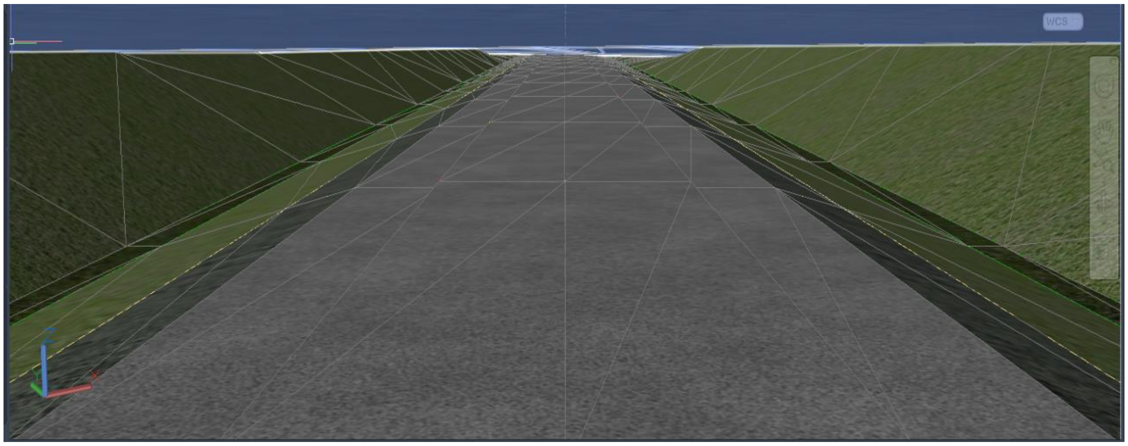


Figure 3-2: BIM road model

3.4 Phase 2: LCSA Database

LCSA was conducted for popular road pavement types according to ISO14044. Life cycle inventory data was obtained from published literature. The database contains life cycle performance data for alternative pavement types. The life cycle sustainability performance database was developed in the Microsoft Excel platform as an .xlsx file.

3.5 Phase 3: Framework Development

The proposed framework evaluates the LCSA performance of the road infrastructure model. INVEST is the most popular rating system that encompasses all life cycle phases for the environment and economic indicators. The social performance criteria had been set up using the UNEP information on social impact assessment. The framework developed by UNEP/SETAC defines the social effect through focusing on five stakeholder groups (i.e., worker, consumer, society, local community, and value chain actors). Key performance indicators for every stakeholder team are available in "The Methodological Sheets for Subcategories in S-LCA." Life cycle costing is the most comprehensive economic evaluation method. Content analysis was used for identifying the TBL KPIs. Table 3-1 lists key performance indicators (KPIs) for TBL performance.

Table 3-1: Summary of triple bottom line indicators (Lippiatt, 2007; UNEP, 2013)

Impact Categories	Triple Bottom Line Indicators (KPIs)
Environmental	Global warming
	Acidification
	HH cancer
	HH noncancer
	HH criteria air pollutants
	Eutrophication
	Ecotoxicity
	Smog
	Natural resource depletion
	Indoor air quality
	Habitat alteration
	Water intake
Economic	Initial Cost
	Repair and Maintenance Cost
Social	Well Being for Life Cycle

3.5.1 Aggregation and interpretation

The phased aggregation procedure is explained in Figure 3-3. First, sustainability category-level performance is assessed by aggregating KPIs. The sustainability index will be arrived at by aggregating the performance related to sustainability categories. Weighted sum method is a solution approach in multi-objective optimization where the objective functions or KPIs are aggregated by multiplying them to weights (importance level) and summing them over (Vasant and Alparslan-Gok, 2017).

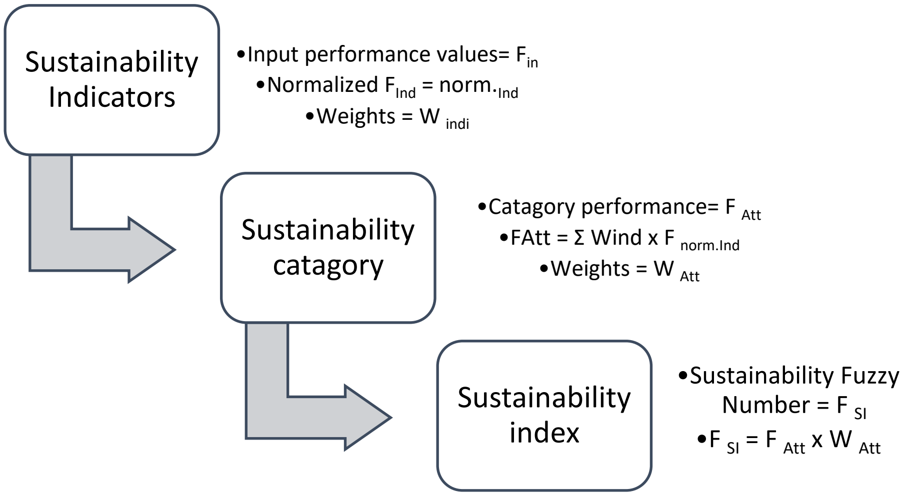


Figure 3-3: Aggregation procedure

Several KPIs in the evaluation framework has to be evaluated using linguistic identifiers, which will be converted to quantitative values using the Likert scale. Performance values for KPIs will be normalized to assist aggregation by using equations (1) and (2).

If the decrease of the KPI is desirable:

$$Normalized\ KPI\ value = \frac{\overline{KPI}_{High\ (Regional)} - \overline{KPI}}{\overline{KPI}_{High(Regional)} - \overline{KPI}_{Low\ (Regional)}} \quad \text{…..(2)}$$

If the increase of the KPI is desirable:

$$Normalized\ KPI\ value = \frac{\overline{KPI} - \overline{KPI}_{Low\ (Regional)}}{\overline{KPI}_{High\ (Regional)} - \overline{KPI}_{Low(Regional)}} \quad \text{…..(3)}$$

BEES weights will be used for aggregating KPI to the category score. Category scores will be aggregated to determine the sustainability index. Weights for social, environmental, and economic categories will be determined based on the priorities of local governments.

3.6 Phase 4: Decision Support Tool

A decision support tool that integrates the Phase 1 database and Phase 2 is a viable resource for planners. The proposed tool helps to carry out a TBL-based comparative evaluation of road construction methods. Score-based results of the different alternatives provide the easy way to select the appropriate road construction method. The details of the tool and evaluation methods are provided in Section 4.4, 4.5, and Chapter 5. The BIM road model materials quantity data are integrated with a decision support tool via an XML file. The BIM data integration flow diagram is shown in Figure 3-4.

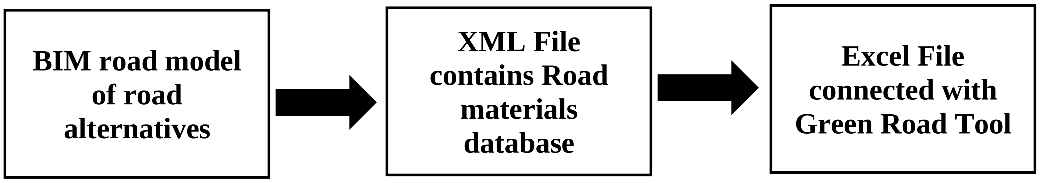


Figure 3-4 Flow diagram of BIM data integration with a decision support tool

3.7 Summary

This chapter presents the greener road planning methodological framework for local governments. The proposed method encompasses social, environmental, and economic dimensions into construction technique evaluation. Additionally, life cycle thinking is incorporated into the decision. This methodological framework offers a comprehensive insight into road infrastructure selection decision making.

References

Eastman C., Teicholz P., S. R. and L. K. (2011) BIM handbook: A guide to building information modeling for owner, managers, designers, engineers, and contractors (2nd ed.). New York: Wiley., Appl. Phys. A.

International Organization for Standardization (2006) ISO 14040: Environmental management-- Life cycle assessment - Principles and framework. Geneva: International Organization for Standardization.

Jalaei, F. (2015) Integrate building information modeling (bim) and sustainable design at the conceptual stage of building projects, PhD Thesis - University of Ottawa.

Lee, S. and Kim, B. (2011) 'IFC Extension for Road Structures and Digital Modeling', Procedia Engineering. Elsevier B.V., 14, pp. 1037–1042. doi: 10.1016/j.proeng.2011.07.130.

Lindfors, L.-G. (1995) Nordic guidelines on life-cycle assessment. Indiana University: Nordic Council of Ministers.

Lippiatt, B. (2007) 'BEES 4.0: Building for Environmental and Economic Sustainability, Technical Manual and User Guide', Director, p. 307. doi: 860108.

NBIMS (2007) 'The National Building Information Model Standard^{TM} (NBIMS) V1', Vasa. Available at: http://medcontent.metapress.com/index/A65RM03P4874243N.pdf.

Pandian Vasant, Sirma Zeynep Alparslan-Gok, G.-W. W. (2017) Handbook of Research on Emergent Applications of Optimization Algorithms.

UNEP (2013) Guidelines for social life cycle assessment of products.

USEPA (2014) Risk Management Sustainable Technology.

4 COMPARATIVE LIFE CYCLE ASSESSMENT OF DIFFERENT ROAD CONSTRUCTION METHODS

4.1 Introduction

In this chapter, the proposed section of the road was analyzed for different construction alternatives. The life cycle phases considered for this analysis were raw material extraction, construction, and the end-of-life scenario. The analysis period is different from the design period. The design period represents the time to attain terminal serviceability without any maintenance. The analysis period represents a span of time throughout which pavement design alternatives must function above a minimum level of service (Umer, 2015).

For LCA, this study establishes a 20-year evaluation period for a collector street (AASHTO, 2018). Guven at al. (2008) conducted LCCA practices for US states and Canadian provinces and advocated a 40-year LCCA duration instead of the 30-year period mostly referenced in their findings. AASHTO (1993) endorsed analysis duration in the range of 30-50 years for high volume urban roads and recommended a shorter evaluation period for low-volume road cases. Therefore, for the roadway scenarios included in this study, a 20-year evaluation was deemed the best time period to align with the recommendation of standard guidelines.

4.2 Designing Road Pavement Alternatives

Flexible pavements, also referred to as asphaltic concrete or hot mix asphalt (HMA) pavements, are a basic element associated with the construction of highway amenities Other fundamental pavement types include rigid or Portland cement concrete (PCC) pavements, and composite pavements consisting of a PCC pavement overlaid with an HMA pavement (Huang, 1993). Increasing traffic loads, diverse environmental conditions, and inadequate maintenance inhibit the serviceable life of these pavements (Ballari, 2019). Some modern techniques include incorporating geosynthetic products, such as grids, fabrics, or composites, into the pavement structure. This system is usually achieved by attaching the geosynthetic product to the current pavement (e.g., flexible or rigid) with an asphalt tack coat and then covering it with a particular thickness of HMA pavement (Ballari, 2019).

This study considered three different types of road construction methods for collector roads. Based on published literature, asphalt road, plain cement concrete (PCC), and geo-membrane road were considered for LCA analysis of collector streets. Table 4-1 materials desity used for this study and figure 4-1 elabroates general cross-section of road.

Table 4-1 Material inventory (AASHTO, 2018; Ballari, 2019)

Road Layers	*Materials Used and Density (kg/m^3)*		
	Asphalt Road	**PCC Road**	**Geo-membrane Road**
Paving	Asphalt (721)	Plain cement concrete (2400)	Asphalt (721)
Base course	Sand and Gravel (1550)	Sand and Gravel (1550)	Sand and Gravel (1550)
Sub-base course	Limestone (2720)	Limestone (2720)	Limestone (2720) and Heavy-duty polypropylene (940)

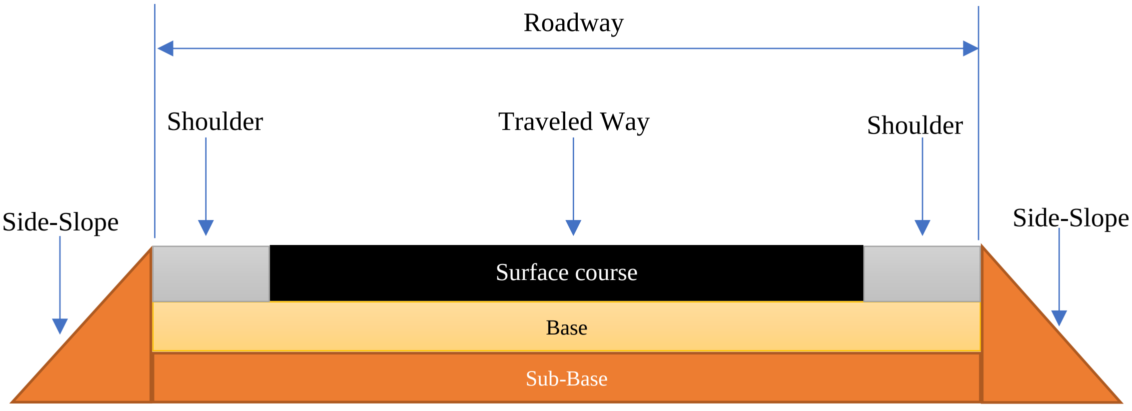


Figure 4-1 Cross-section of road

Travel way: Travel lanes/way are those lanes intended for vehicular use and are designed to provide the suitable lane width, surface type, and cross slope to serve the preferred characteristics and vehicle composition (MDT, 2016).

Shoulder: Shoulders are contiguous with the traveled way and, depending on width, can provide many advantages to a cross-section. They are used for the following functions (MDT, 2016):

- Structural support to the traveled way
- Improved operation and increased roadway capacity
- Improved safety through improved clear recovery location
- Increased sight distance for horizontal curves
- Space for emergency and discretionary stops
- A sense of openness and roadway aesthetics; and
- Space for pedestrian and bicycle use, on-street parking, or both.

Roadway: The element of a road, including shoulders and roadway, for vehicular use (MDT, 2016).

This study considered cross-section dimensions of road profiles based on the AASTHO guideline of collector roads. The road surface is considered level and the design speed of the road used for this study is 80km/h. The traffic volume of the level road is considered as 2000 and more vehicles per day for this road.

Table 4-2 Design speed and design volume of collector road (AASHTO, 2018)

Type of terrain	**Design Speed (km/h) for specific design volume (veh/day)**		
	0 to 400	**400 to 2000**	**Over 2000**
Level	60	80	100
Rolling	50	60	80
Mountainous	30	50	60

Based on the design speed and volume of the vehicles, carriageway of the proposed cross-section of the road is 3.6 m per lane. The two-lane collector road is considered to have a travel way 7.2m wide, with a 2.4m wide shoulder on each side. Therefore, the total width of the roadway is 12m.

Table 4-3 Carriageway and shoulder minimum width (AASHTO, 2018)

Design Speed (km/h)	Minimum Width of travel way for specific design volume (veh/day)			
	Under 400	**400 to 1500**	**1500 to 2000**	**Over 2000**
30	6	6	6.6	7.2
40	6	6	6.6	7.2
50	6	6	6.6	7.2
60	6	6.6	6.6	7.2
70	6	6.6	6.6	7.2
80	6	6.6	6.6	7.2
90	6.6	6.6	7.2	7.2
100	6.6	6.6	7.2	7.2
All Speed	**Width of shoulders on each side of Road (m)**			
	0.6	1.5	1.8	2.4

The thickness of the pavement is affected by a number of variables, including the type of soil, the function of the road, and environmental elements like precipitation and temperature (Mathew and Rao, 2007). Therefore, the thickness considered for different cross-sections of pavement is based on published literature. The thickness of different layers of pavement is shown in Table 4-4 below.

Table 4-4 Road layers thickness (Mathew, 2009; Ghafoori and Sharbaf, 2016)

Road Layers	Layer Thickness (mm)		
	Asphalt Road	**PCC Road**	**Geo-membrane Road**
Paving	150	100	100
Base course	200	200	150
Sub-base course	300	300	200

4.3 LCSA of Road Alternatives

LCSA was conducted for the previously developed road pavement alternatives.

4.3.1 Functional Unit and Boundary Condition

A 2 km length of the road is considered as the functional unit for a comparative lifecycle assessment of the different road construction methods. Figure 4-2 elaborates the different boundary conditions for conducting LCA. Cradle-to-grave impacts were selected as the system boundary.

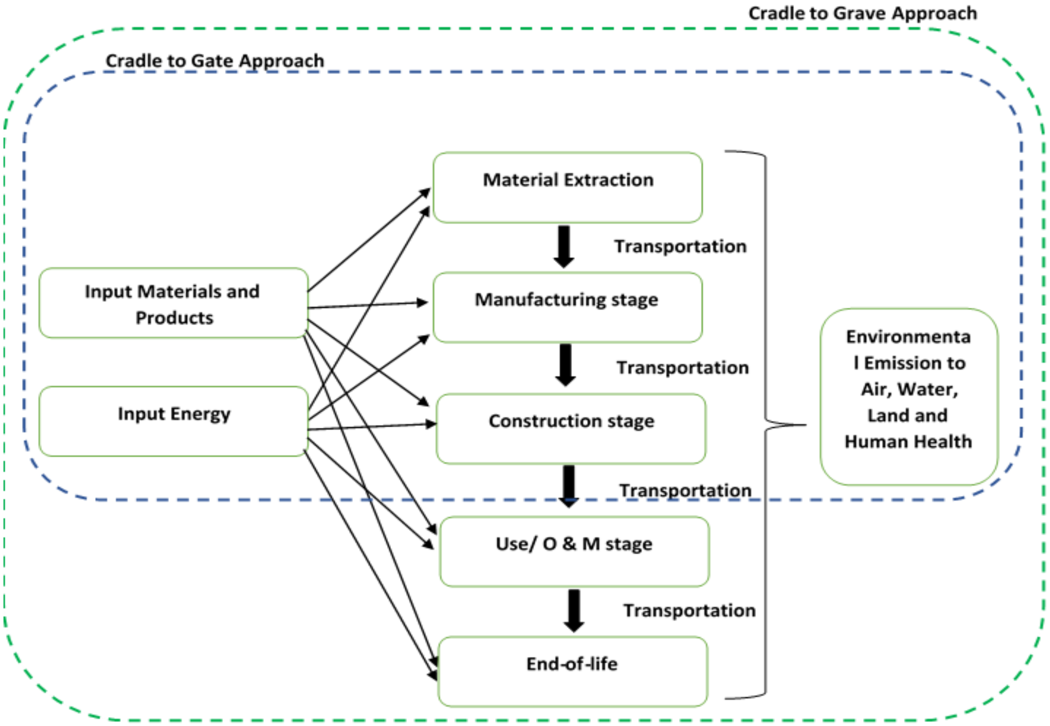


Figure 4-2 System boundary (ISO 14040, 2006b)

The following assumptions were considered in conducting this study:

- LCA was carried out for a 2 km length.
- 20-year service life was considered

4.3.2 Analyzing Environmental Impacts

The Life Cycle Assessment can be significantly simplified with the use of dedicated computer software, such as SimaPro, designed by PRe Consultants (Zarębska, 2013). SimaPro is one of the most sophisticated LCA software products on the market. SimaPro is equipped with the Ecoinvent database, which is the most up-to-date database available in the industry. The comparative LCA of road alternatives was carried out using SimaPro software. BEES environmental impact assessment was used for comparison of three road construction methods.

4.4 Building for Economic and Environmental Sustainability (BEES) Rating System

Being developed by the National Institute of Standards and Technology (NIST), The Building for Economic and Environmental Sustainability (BEES) is a life cycle thinking-based evaluation method developed for construction products (BEES, no date). BEES contains economic and environmental evaluation criteria that have been developed using guidelines published by ISO (Lippiatt, 2007). This study considered only environmental assessment factors of the different road construction methods: global warming, acidification, human health (HH) cancer, HH noncancer, HH criteria, air pollutants, eutrophication, ecotoxicity, smog, natural resource depletion, indoor air quality, habitat alteration, water intake, and ozone depletion. BEES provides normalization and a weighting score in eco indicator points. An eco point (Pt) expresses a value representing one-thousandth of a yearly environmental impact of one inhabitant (Dzikuć, 2014).

Cradle-to-grave LCA results are shown in Table 4-5. The results indicate that the PCC road creates around 20% and 71% more environmental impacts than asphalt road and geo-membrane road, respectively. Hence, for a cradle-to-grave system boundary, the geo-membrane road has a proven greener road construction method than the asphalt road and PCC road.

Table 4-5 Impact assessment result

Impact category	Unit	Asphalt Road	PCC Road	Geo-Membrane Road
Global warming	g CO_2 eq	1.67E+08	5.50E+08	1.22E+08
Acidification	H+ mmole eq	1.12E+08	1.38E+08	7.47E+07
HH cancer	g C6H6 eq	1.09E+06	1.89E+06	8.54E+05
HH noncancer	g C7H7 eq	1.02E+10	1.22E+10	6.87E+09
HH criteria air pollutants	microDALYs	2.61E+05	2.79E+05	1.69E+05
Eutrophication	g N eq	6.06E+05	8.04E+05	4.98E+05
Ecotoxicity	g 2,4-D eq	1.15E+06	2.89E+06	9.45E+05
Smog	g NOx eq	2.24E+06	3.02E+06	1.48E+06
Natural resource depletion	MJ surplus	1.03E+06	4.44E+05	6.95E+05
Indoor air quality	g TVOC eq	0.00E+00	0.00E+00	0.00E+00

Habitat alteration	T&E count	1.47E-09	4.92E-09	1.13E-09
Water intake	liters	1.49E+07	1.64E+07	1.08E+07
Ozone depletion	g CFC-11 eq	9.79E+01	2.72E+01	6.56E+01

4.4.1 Analyzing Economic Impacts

For this study, economic impacts were divided into initial cost, and repair and maintenance cost of the material required for each layer of the different road alternatives. The unit cost value of the materials considered was based on the published literature described in Chapter 5. The following equations are used for the calculation:

$$\text{Initial Cost}_{\text{ALT 1}} = \sum Q_m \text{ x } C_{i\ \text{unit}} \ldots..(4)$$

Where Q_m is the quantity of material used, and C_i unit is the unit cost of the material. The repair and maintenance cost of the asphalt paved road is considered as 16%, and the concrete paved road is considered as 8% of the initial cost of the specific type of road (Holt et al., 2011). The Repair and Maintenance (R & M) cost includes the amount of material cost required to maintain the damage sustained on road layers due to wear, tear, and weather effects during its life cycle. Therefore, the total LCC of the road materials is calculated as follows:

$$\text{Total LCC of materials} = \text{Initial Cost}_{\text{ALT 1}} + \text{R \& M Cost}_{\text{ALT 1}} \ldots..(5)$$

For instance, the Initial cost of the Asphalt road is,

Initial Cost = [(1,540.21 x 120) + (7,358.07 x 18) + (24,748.41 x 30)] = $ 1,059,722.38

The repair and maintenance cost of materials for the asphalt road is 16% of the initial cost of materials, which is $ 169,555.58. Therefore, the total LCC of the asphalt road is,

Total LCC = $1,059,722.38 + $169,555.58 = $ 1,229,277.96

4.5 Analyzing Social Impacts

The previously developed S-LCA method, Weidema's S-LCA, is used for analyzing the social impact in this study. In this method, the social impact is quantified as the human life lost during the product life cycle. It also focuses on the affected stakeholders. The damage category is identified in many ways, for instance, anxiety, unequal opportunities, etc. (Muthu, 2015). The overall well-being of the road infrastructure life cycle is calculated as follows:

$$\text{Overall Well-being for life cycle} = \text{QALY}/\ [\text{Life Expectancy x Total Stakeholders}] \ldots..(6)$$

$$\text{QALY} = \text{DALY x N} - \sum \text{YL}_i \text{ x N}_i \ldots..(7)$$

Where QALY is Quality Adjusted Life Years, N is the total number of stakeholders related to the product in its life cycle. YL_i is the Life years lost due to damage i and N_i is the number of stakeholders affected by damage i. DALY is calculated as follows:

$$\text{DALY} = \text{Life Expectancy} - \text{YLL} - \text{YLD} \ldots..(8)$$

Where YLL is the Years of life lost, and YLD is the Years lost due to Disabilities. Life expectancy, YLL, and YLD data is provided by the WHO (World Health Organization).

For instance, according to the WHO, the average life expectancy in Canada was 82.5 years in 2019, YLL is ten years, and YHD is 21 years.

So, the DALY is 51.5 years (82.5-10-21 = 51.5 years).

Also, if the number of internal stakeholders is 15 and the total number of stakeholders affected by unequal opportunities is 20 for a 5 year period, then QALY is 672.5 years

(51.5 x 15-20 x 5 = 672.5 years).

Hence, overall well being is,

$$\frac{672.5}{(82.5 \text{ X } 15)} \text{ X } 100 = 54.34\%$$

4.6 Comparison of road construction alternatives

The results of this study illustrate the comparative LCA results of three road construction methods (i.e., Asphalt road, PCC road, and Geo-membrane road) (Table 4-6). The BEES Standard was considered for the analysis of the inventory data for normalization and weighting of the characterized value. In the following results, smaller scores indicate the minimum impacts, and higher scores indicate higher environmental impact. The results of the LCA study for the "cradle to grave" system boundary are as follows. Also, the weightage of environmental, economic, and social categories was considered as 40, 50, and 10. The comparative result gives the result in a score value out of 100.

Table 4-6: LCA comparison of road alternatives

Impact Categories	**Unit**	**Asphalt Road**	**PCC Road**	**Geo-Membrane Road**
Environment				
Global warming	g CO2 eq	1.67E+08	5.50E+08	1.22E+08
Acidification	H+ mmole eq	1.12E+08	1.38E+08	7.47E+07
HH cancer	g C6H6 eq	1.09E+06	1.89E+06	8.54E+05
HH noncancer	g C7H7 eq	1.02E+10	1.22E+10	6.87E+09
HH criteria air pollutants	microDALYs	2.61E+05	2.79E+05	1.69E+05
Eutrophication	g N eq	6.06E+05	8.04E+05	4.98E+05
Ecotoxicity	g 2,4-D eq	1.15E+06	2.89E+06	9.45E+05
Smog	g NOx eq	2.24E+06	3.02E+06	1.48E+06
Natural resource depletion	MJ surplus	1.03E+06	4.44E+05	6.95E+05
Indoor air quality	g TVOC eq	0.00E+00	0.00E+00	0.00E+00
Habitat alteration	T&E count	1.47E-09	4.92E-09	1.13E-09
Water intake	liters	1.49E+07	1.64E+07	1.08E+07
Ozone depletion	g CFC-11 eq	9.79E+01	2.72E+01	6.56E+01
Economic				
Initial Cost	CAD $	1059722.38	1181087.59	722929.98
Repair and Maintenance Cost	CAD $	169555.58	94487.01	115668.80
Social				
Overall Well-being for LCA	% age	54.34	52.32	55.45

Equation (9) was used for calculating the green roads score.

$$\text{Green Road Score}_{ALT} = [W_{EN} * \text{Score}_{EN}] + [W_{EC} * \text{Score}_{EC}] + [W_S * \text{Score}_S] \ldots..(9)$$

Where, $W_{EN,}$ $W_{EC,}$ and Ws are the weightage of Environmental, Economic, and Social categories. The above weights can be selected based on institutional priorities. TBL evaluation scores, final score, and rank are presented in Table 4-7.

Table 4-7: Score base comparison of road alternatives

Impact Categories	**Asphalt Road**	**PCC Road**	**Geo-Membrane Road**
Environmental	19.02	29.51	5.73
Economic	32.47	35.16	9.75
Social	4.94	5.76	4.49
Total Score	**56**	**70**	**20**
Rank	**2nd**	**3rd**	**1st**

4.7 Life cycle impact database

The above procedure was used to develop the economic and environmental impact database for road construction materials identified in Chapter 2. Table 4-8 lists the life cycle impacts of the materials identified.

Table 4-8: LCSA data of road materials

Impact category	**Unit**	**Asphalt**	**PCC**	**Sand and Gravel**	**Limestone**	**Geo-membrane**	**Sand**	**Gravel**	**Dolomite**	**Bentonite**	**Basalt**	**Diesel**	**LDPE**	**Waste Polythylene**
Environmental														
Global warming	g CO2 eq	6.4E+01	3.4E+05	2.3E+00	2.1E+00	4.9E+02	1.2E+01	1.0E+01	3.9E+01	4.0E+01	9.2E+00	5.0E+02	1.8E+03	5.4E+01
Acidification	H+ mmole eq	2.8E+01	4.9E+04	1.0E+00	2.5E+00	9.1E+01	4.4E+00	3.1E+00	1.3E+01	1.6E+01	4.8E+00	2.6E+02	3.0E+02	1.0E+01
HH cancer	g C6H6 eq	5.3E-01	1.1E+03	1.7E-02	6.0E-03	5.6E+00	4.8E-02	6.2E-02	1.8E-01	2.4E-01	3.1E-02	2.8E+00	5.5E-01	3.3E-01
HH noncancer	g C7H7 eq	7.0E+02	2.2E+06	2.5E+01	3.6E+02	1.7E+04	8.3E+01	1.0E+02	6.7E+02	4.8E+02	4.1E+02	1.7E+03	1.1E+03	2.0E+03
HH criteria air pollutants	microDALYs	1.4E-02	2.8E+01	4.0E-04	9.6E-03	1.5E-01	2.2E-03	2.4E-03	2.0E-02	6.5E-03	1.1E-02	8.9E-02	1.4E-01	1.0E-02
Eutrophication	g N eq	2.8E-01	4.5E+02	7.3E-03	4.7E-03	4.2E+00	2.6E-02	3.9E-02	1.4E-01	1.0E-01	2.8E-02	1.6E+00	3.8E-01	2.9E-01
Ecotoxicity	g 2,4-D eq	5.2E-01	1.8E+03	2.6E-02	6.9E-03	7.5E+00	7.0E-02	9.3E-02	2.3E-01	3.5E-01	4.1E-02	2.4E+00	5.6E-01	8.9E-01
Smog	g NOx eq	3.5E-01	9.2E+02	2.3E-02	6.2E-02	1.3E+00	8.7E-02	4.6E-02	1.7E-01	3.1E-01	1.1E-01	2.2E+00	3.7E+00	1.3E-01
Natural resource depletion	MJ surplus	5.9E-01	2.3E+02	3.8E-03	3.8E-03	5.1E-01	2.0E-02	1.1E-02	3.1E-02	6.4E-02	1.3E-02	7.5E+00	1.0E+01	5.9E-02
Indoor air quality	g TVOC eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Habitat alteration	T&E count	7.2E-16	3.2E-12	2.2E-17	7.8E-18	6.5E-15	2.3E-16	2.2E-16	8.4E-16	5.4E-16	1.2E-16	2.3E-15	6.3E-16	1.2E-15
Water intake	liters	2.4E+00	3.6E+03	1.4E+00	2.9E-02	2.0E+00	1.4E+00	3.7E-01	1.9E-01	4.3E-01	4.4E-02	5.9E+00	4.4E+01	2.8E-01
Ozone depletion	g CFC-11 eq	5.8E-05	1.3E-02	2.7E-07	2.7E-07	2.0E-05	1.4E-06	4.2E-07	9.1E-07	4.5E-06	7.0E-07	5.7E-04	1.3E-06	2.5E-06
Economical														
Unit Cost	CAD $	$120	$215	$18	$30	$1.50	$15	$52	$0.65	$15	$44	$1.41	$1.45	$-
* $ Amount Calculated for, Asphalt, Sand and Gravel, Sand, Gravel, Limestone, and Ballast per Ton, PCC per Cubic Meter and Geo-membrane, Dolomite, Bentonite, and LDPE per Kilogram														

4.8 Summary

Based on the LCA, the following conclusions have been derived. The “cradle to grave” analysis on different road construction methods indicates that,

- The PCC road creates more environmental, social, and economic impacts than the asphalt and geo-membrane roads. It has 20% and 71% more impact than the asphalt and geo-membrane roads, respectively.
- The geo-membrane road generates minimum impacts on all three major categories of the LCA.
- The geo-membrane road is a greener construction method than the asphalt road and PCC road, based on a cradle to grave system boundary score base evaluation.

References

AASHTO (2018) A policy on Geometric Design of Highways and Streets, The Green Book.

Ballari, S. O. (2019) ‘Application Of Geosynthetics For Strengthening Of Flexible Issn No : 2236-6124 Application Of Geosynthetics For Strengthening of Page No : 2150’, (May).

Barbara C. Lippiatt (2007) NISTIR 7423 Building for Environmental and Economic S ustainability Technical Manual and User Guide.

BEES (no date) National Institute of Standards and Technology. Available at: https://www.nist.gov/services-resources/software/bees (Accessed: 17 February 2020).

Dzikuć, M. (2014) ‘Applying the life cycle assessment method to an analysis of the environmental impact of heat generation’, International Journal of Applied Mechanics and Engineering, 18(4), pp. 1275–1281. doi: 10.2478/ijame-2013-0078.

Guven, Z., Rao Rangaraju, P. and Amirkhanian, S. (2008) Life Cycle Cost Analysis in pavement type selection, Life-Cycle Civil Engineering. doi: 10.1201/9780203885307.ch125.

Holt, A., Sullivan, S. and Hein, D. K. (2011) ‘Life cycle cost analysis of municipal pavements in Southern and Eastern Ontario’, 2011 Conference and Exhibition of the Transportation Association of Canada - Transportation Successes: Let’s Build on Them, TAC/ATC 2011, (September).

ISO 14040 (2006) ‘Environmental management - Life Cycle Assessment - Principles and Framework ISO 14040: 2006’, International organization for standardization, 3(1), p. 20. doi: 10.1016/j.ecolind.2011.01.007.

Mathew, T. V and Rao, K. V. K. (2007) ‘Factors affecting pavement design’, in Introduction to Transportation Engineering, pp. 3–5.

Mcgee, H. W., Nabors, D. and Baughman, T. (2009) ‘Maintenance of Drainage Features for Safety, A Guide for Local Street and Highway Maintenance Personnel 5.

Report Date’, (July).

MDT (2016) ‘Montana Department Of Transportation Road Design Manual’, In, Pp. 5–1 To 5–32.

Nader Ghafoori and Sharbaf, M. (2016) ‘Use of Geogrid for Strengthening and Reducing the Roadway Structural Sections’, (327), p. 119. Available at: https://www.nevadadot.com/home/showdocument?id=9121.

Subramanian Senthilkannan Muthu (2015) Social Life Cycle Assessment: An Insight.

T. Mathew (2009) ‘Introduction to pavement design’, in Highways, pp. 225–266. doi: 10.1016/b978-075065090-8/50011-9.

Umer, A. (2015) Sustainability Evaluation Of Transportation Infrastructure Under Uncertainty: A Fuzzy-Based Approach. The University Of British Columbia.

Yang H. Huang (1993) Pavement Analysis and Design.

Zarębska J. (2013) Ecological and economic aspects management of packaging waste in Lubuskie.

5 GREEN ROAD TBL EVALUATION TOOL (GRTET)

In this chapter, the proposed GRTET is outlined, and the development process is represented.

5.1 Overview

Proposed GRTET is designed to assist TBL based decision making in road infrastructure planning for local governments and road designers to select the most sustainable road construction method. This tool is integrated with BIM and LCSA database for TBL evaluation of road construction alternatives.

5.2 Green Road TBL Evaluation Tool

The Green Road TBL Evaluation Tool (GRTET) follows a sequential process. The road materials information for the tool is extracted from a BIM file, and the LCA database. The GRTET can be divided into the following six parts:

1) Project Information
2) Road Materials Information
3) Social Impact Data
4) Category Weights
5) Score Result
6) Detailed Report

5.3 Project Information

The first page of the tool is used to obtain background information on the project. General project information includes Project name, Project location, Province, Country, and Project date. This will be important information for the detailed report. Figure 5-1 presents the project information page of the GRTET.

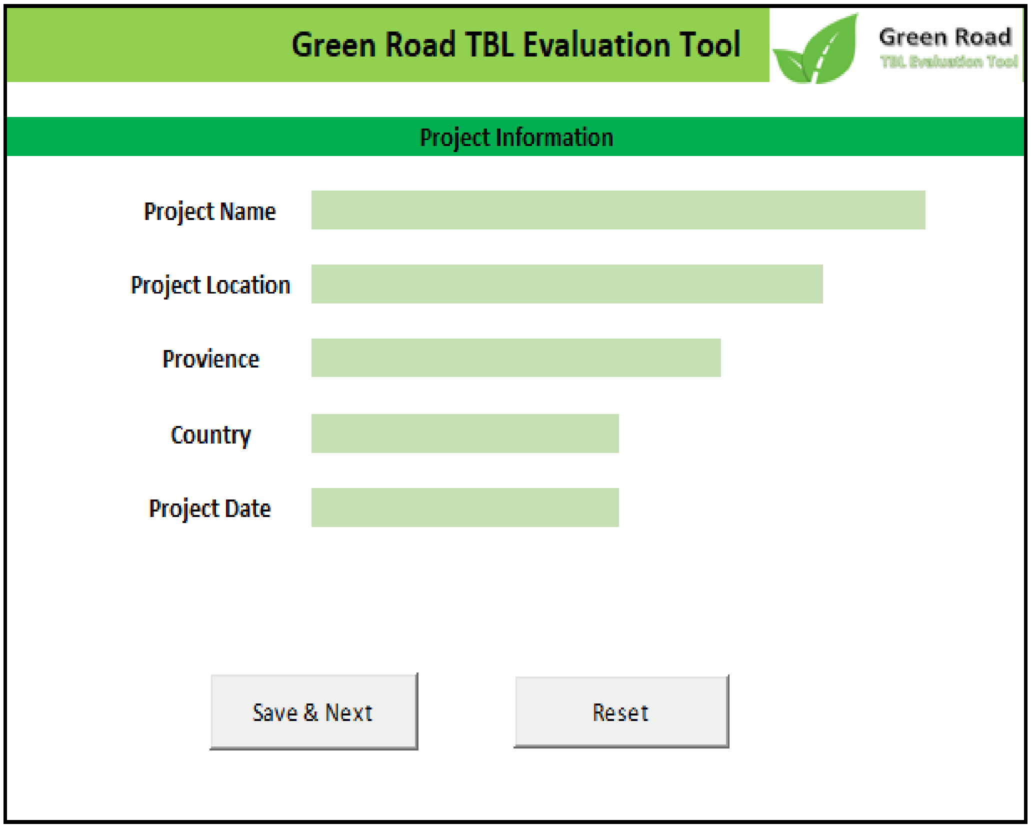
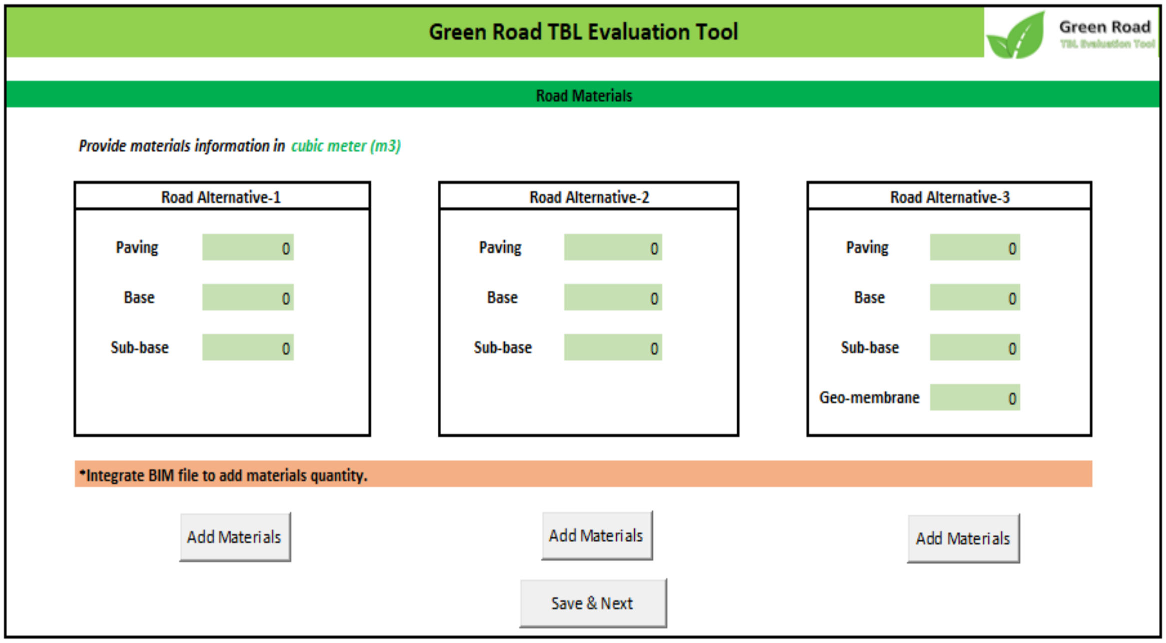


Figure 5-1 Project information page

5.4 Road Materials Information

“Road Materials” page links Green Road with the BIM model. The BIM file generates the material volume schedule in an XML file that will be integrated into the tool. The XML report of the material volume is added by using “add materials” and selecting relevant XML files. This tool can use a text file for adding material data as well. Users need to select relevant XML files. The GRTET extracts the material volume data from the integrated XML file and calculates the TBL impacts of the considered road alternatives. Figure 5-2 illustrates the road materials information page of the tool:



Green Road TBL Evaluation Tool

Road Materials

Provide materials information in cubic meter (m3)

	Road Alternative-1	Road Alternative-2	Road Alternative-3
Paving	0	0	0
Base	0	0	0
Sub-base	0	0	0
Geo-membrane			0

*Integrate BIM file to add materials quantity.

Figure 5-2 Road materials information page

5.5 Social Impact Data

The ‘Social Impact Data’ page of the tool primarily collects details required for S-LCA. Data required here include life expectancy, YLL, YLD, numbers of stakeholders (internal), and numbers of stakeholders affected by damages (i.e., unequal opportunities). The data for life expectancy, YLL, and YLD are obtained from WHO website and will be automatically added to the tool when selecting the country. The number of stakeholders affected should be entered by the user. The analytic formula used for S-LCA is mentioned in Section 4.5 of this thesis. Figure 5-3 illustrates the other information page of the GRTET.

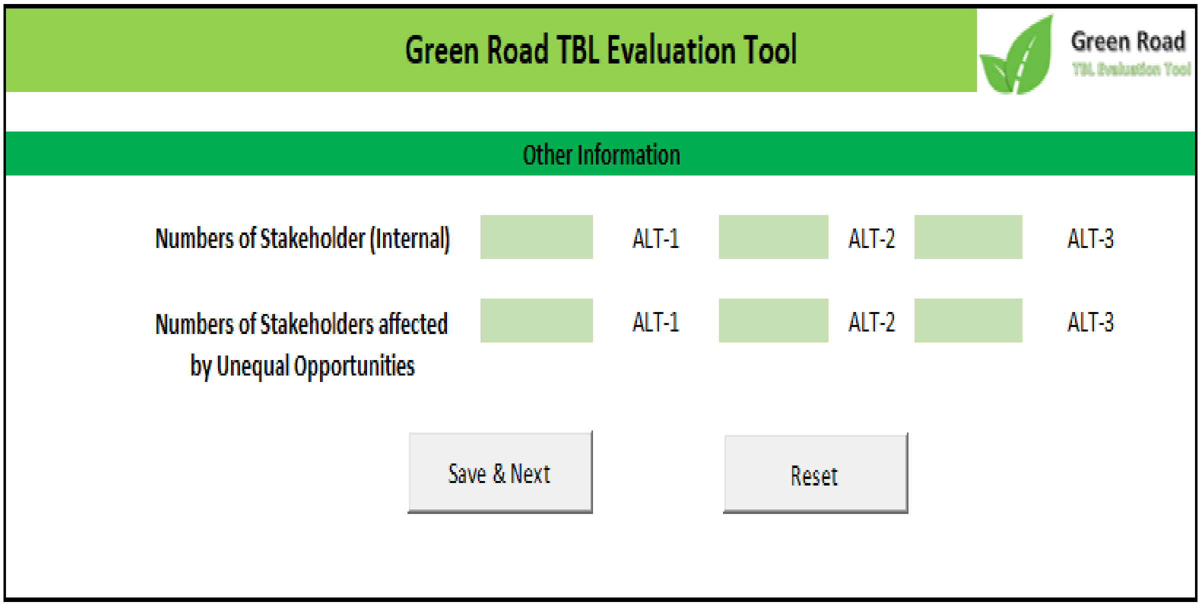


Figure 5-3 Other information page

5.6 Category Weights and Score Result

The Green TBL Evaluation tool generates a score based on the comparative evaluation of environmental, economic, and social categories. Apart from the KPI, these three broad categories are also categorized for comparison of the road alternatives. The weight of each category is decided by the users based on institutional priorities (Figure 5-4). According to the defined weight, the results will be calculated as an index score (Figure 5-5). Higher score values indicate more impacts, and lower score values indicate a more suitable alternative for road construction. The lower score value in Figure 5-5 indicates that the geo-membrane road is the preferable road construction alternative.

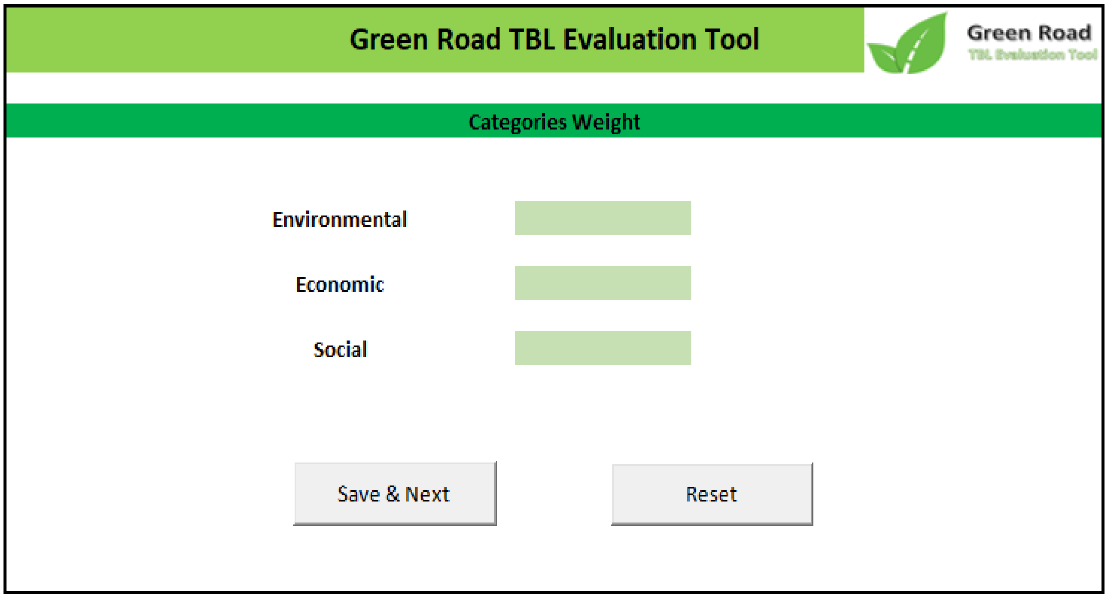
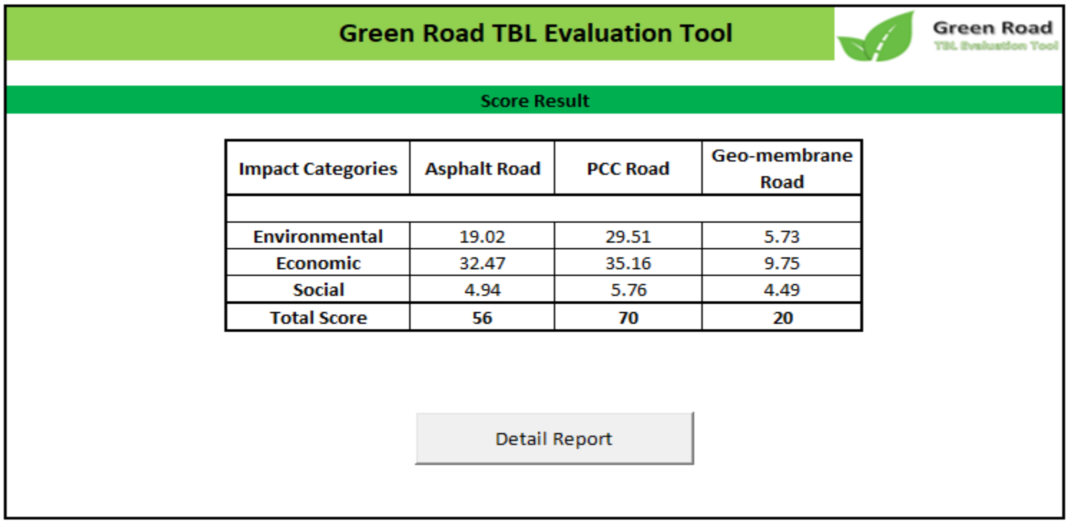


Figure 5-4 Category weights page



Impact Categories	Asphalt Road	PCC Road	Geo-membrane Road
Environmental	19.02	29.51	5.73
Economic	32.47	35.16	9.75
Social	4.94	5.76	4.49
Total Score	56	70	20

Figure 5-5 Score result page

5.7 Evaluation Process of the GRTET and Detail Report

5.7.1 Environmental Evaluation

The environmental evaluation follows the BEES specification, as mentioned in section 4.4. The characterized value of each indicator is normalized by the equation provided in section 3.5. Then the normalized value of KPIs is multiplied by the weighted factors and converted into a final score. The BEES weighting factors are widely used in construction industries. However, some of the KPIs for this study do not impact by its weightage factor values (e.g., indoor air quality). In Table 5-1 indicates each KPI with its weighted factor (Lippiatt, 2007):

Table 5-1 Weighted factors of environmental KPIs

Environmental KPIs	Weight (%)
Global Warming	16
Acidification	5
Eutrophication	5
Fossil Fuel Depletion	5
Indoor Air Quality	11
Habitat Alteration	16
Water Intake	3
Criteria Air Pollutants	6
Smog	6
Ecological Toxicity	11
Ozone Depletion	5
Human Health	11

5.7.2 Economic Evaluation

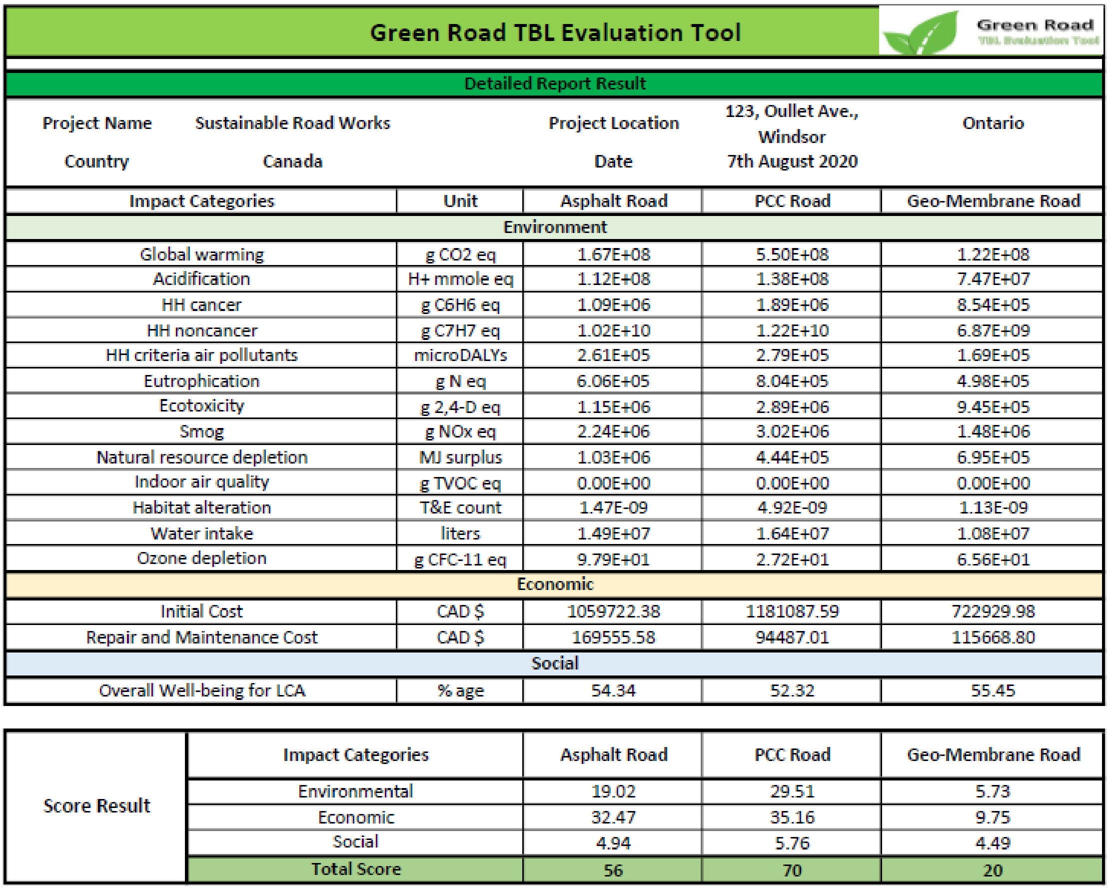
The economic evaluation also follows the BEES specification. For the economic evaluation, the initial cost of the materials and the repair and maintenance cost of the material is considered as a KPI. For the initial cost of the materials, different construction material cost data were used, as indicated in Table 4-8. Also, the calculation formulas used for economic evaluation are indicated in section 4.4.1. Material cost data and calculation algorithm is embedded in the tool.

5.7.3 Social Evaluation

S-LCA was carried out using Weideman's method. Overall, well-being for the life cycle is considered as the KPI of the social evaluation. The result is given in percentage form. The detailed evaluation formulas are defined in section 4.5 of this thesis. The calculation algorithm is embedded in the tool.

5.7.4 Detailed Report

The final page of the GRTET is the detailed report. The detailed report provides the score-based result of the three main categories of the TBL evaluation. Figure 5-6 illustrates the detailed report of the GRTET. As mentioned in the previous section, the lowest total score of the road alternative is the more suitable alternative among all three road alternatives.



Green Road TBL Evaluation Tool

Detailed Report Result

Project Name	Sustainable Road Works	Project Location	123, Oullet Ave., Windsor	Ontario
Country	Canada	Date	7th August 2020	

Impact Categories	Unit	Asphalt Road	PCC Road	Geo-Membrane Road
Environment				
Global warming	g CO2 eq	1.67E+08	5.50E+08	1.22E+08
Acidification	H+ mmole eq	1.12E+08	1.38E+08	7.47E+07
HH cancer	g C6H6 eq	1.09E+06	1.89E+06	8.54E+05
HH noncancer	g C7H7 eq	1.02E+10	1.22E+10	6.87E+09
HH criteria air pollutants	microDALYs	2.61E+05	2.79E+05	1.69E+05
Eutrophication	g N eq	6.06E+05	8.04E+05	4.98E+05
Ecotoxicity	g 2,4-D eq	1.15E+06	2.89E+06	9.45E+05
Smog	g NOx eq	2.24E+06	3.02E+06	1.48E+06
Natural resource depletion	MJ surplus	1.03E+06	4.44E+05	6.95E+05
Indoor air quality	g TVOC eq	0.00E+00	0.00E+00	0.00E+00
Habitat alteration	T&E count	1.47E-09	4.92E-09	1.13E-09
Water intake	liters	1.49E+07	1.64E+07	1.08E+07
Ozone depletion	g CFC-11 eq	9.79E+01	2.72E+01	6.56E+01
Economic				
Initial Cost	CAD $	1059722.38	1181087.59	722929.98
Repair and Maintenance Cost	CAD $	169555.58	94487.01	115668.80
Social				
Overall Well-being for LCA	% age	54.34	52.32	55.45

	Impact Categories	Asphalt Road	PCC Road	Geo-Membrane Road
Score Result	Environmental	19.02	29.51	5.73
	Economic	32.47	35.16	9.75
	Social	4.94	5.76	4.49
	Total Score	56	70	20

Figure 5-6 Detailed report

5.8 Validation

Emergy evaluation was used to validate the findings of this research. The Emergy conversion values were obtained from published literature (Table 5-2). The calculation of the total emergy for road alternatives is presented in Table 5-3.

Table 5-2 Emergy values of road materials (Pulselli et al., 2007; Reza, 2013; Ruparathna, 2013)

Materials	Quantity	Unit	Unit Emergy Value (sej/Unit)	Total Emergy (sej)
Asphalt	1.54E+06	kg	1.33E+12	2.05E+18
Sand and gravel	7.36E+06	kg	1.69E+12	1.24E+19
Limestone	2.47E+07	kg	1.69E+12	4.18E+19
PCC	3.42E+06	kg	1.17E+12	4.00E+18
Geo-membrane	2.23E+04	kg	8.85E+09	1.97E+14

Table 5-3 Road alternatives emergy evaluation result

Road Alternatives	Emergy Values (sej)	Rank
Asphalt Road	5.63E+19	2nd
PCC Road	5.83E+19	3rd
Geo-membrane Road	3.70E+19	1st

The emergy evaluation of the three road alternatives indicates that the geo-membrane road is a more suitable alternative than the asphalt and PCC roads. Therefore, this confirms the result obtained from the Green Roads TBL Evaluation Tool.

5.9 Generalizability and scalability of Green Roads tool

The GRTET contains impact data for popular road materials. Therefore, a user can easily compare traditional road construction methods by using Green Roads TBL Evaluation Tool. Currently, new green construction materials are invented for sustainable road construction. A user can easily update the tool database with LCSA details of new material from:

1) SimaPro (Environmental impact generated from a unit mass of material)
2) Cost of different road materials (Construction Bills, RS Means, and literature)
3) The service life of road (AASTHO Standards)

Green Roads TBL Evaluation Tool can incorporate more alternatives to the evaluation. The proposed tool provides flexibility to add more construction alternatives. Cost data and social impact data changes over the years. Updated cost data and social impact data can be directly be added to this tool.

5.10 Summary

The GRTET uses a holistic approach to evaluate environmental, economic, and social criteria of road construction alternatives. This tool contains a life cycle sustainability impact database for popular road construction materials, and a number of new materials can easily be added. The tool evaluation provides the user with the flexibility to select weights for environmental, economic, and social categories based on institutional priorities. The final report outlines the scoring of each alternative and rationale for the result. The tool is flexible to change the category weight according to the changes in federal and provincial policies (e.g., more weight on environment category when strict climate action regulations are in place). The validation of the GRTET results is carried out using emergy accounting method, and the result verifies that the geo-membrane is a more suitable alternative.

References

Lippiatt, B. (2007) ‘BEES 4.0: Building for Environmental and Economic Sustainability, Technical Manual and User Guide’, Director, p. 307. doi: 860108.

Pulselli, R. M., Simoncini, E., Pulselli, F. M., and Bastianoni, S., (2007) ‘Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability’, Energy and Buildings, 39(5), pp. 620–628. doi: 10.1016/j.enbuild.2006.10.004.

Reza, B. (2013) ‘Emergy-Based Life Cycle Assessment (EM-LCA) For Sustainability Appraisal of Built Environment’, Civil Engineering, (April). Available at: http://circle.ubc.ca/handle/2429/44444.

Ruparathna, R. and Hewage, K. (2015) ‘“Em-procure”: A sustainable procurement tool for building construction’, Proceedings, Annual Conference - Canadian Society for Civil Engineering, 2(August), pp. 675–684.

6 CONCLUSIONS AND FUTURE WORK

6.1 Implementation guide for greener road infrastructure

The proposed BIM-LCA integration framework provides an implementation guide for greener road infrastructure. Figure 6-1 illustrates the process of the integration of BIM, LCA, and road infrastructure and who is responsible for the specific task in the whole process. By creating a road model in BIM software (e.g., Autodesk Civil 3D, Autodesk infraworks), an IFC/ XML file can be created for data exchange. The long-term maintenance requirements of road infrastructure can be predicted using stochastic modeling techniques such as Markov modeling or published literature (Ruparathna et al. 2018). Such methods have been used by previous researchers to long-term model maintenance, repair, and renovation requirements. This approach would create a data file in the BIM platform (Ruparathna et al. 2018).

The client of the project is responsible for obtaining land use data, numbers of stakeholders connected with that road project, and BIM software training required for the employees. BIM model data generation is concentrated by the road designer of the project. LCA of the different road construction materials and transfer of the LCA data and BIM road model data are concerned by the academic expert of the field. Also, academic experts analyze the road construction alternatives by client preference weightage of the TBL categories and prepare the final report of the more suitable road construction option for the project.

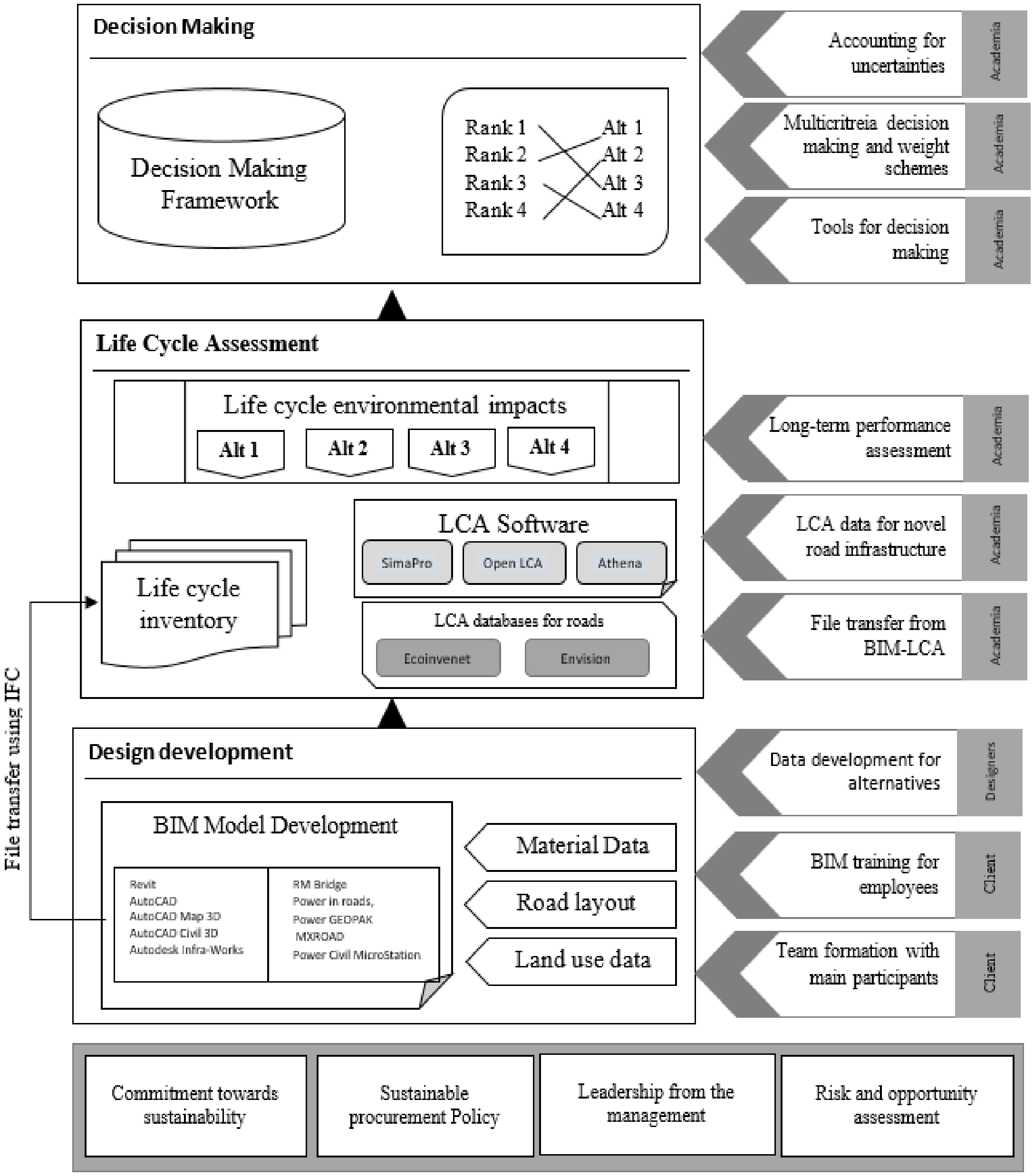


Figure 6-1: BIM-LCA road map for greener road infrastructure

6.2 Conclusions

The comparative evaluation of the road construction suggested that the geomembrane road is the perform well in all three TBL categories, the asphalt road is the second-best alternative, and the PCC road performs poorly in terms of environment, economic, and social impacts. Therefore, the comparative TBL analysis carried out using the Green Road tool and its emergy accounting-based validation recommends that the geo-membrane road is a more sustainable alternative than the asphalt and PCC roads.

This research revealed that there are several key research gaps that need the attention of academia. The lack of knowledge has been preventing constructing industry adoption of BIM and LCA in road construction projects. First, research on BIM implementation has focused mainly on buildings, primarily because of a lack of research and awareness. There is an opportunity to enhance infrastructure construction using BIM. Second, BIM and LCA integration for road infrastructure planning has not received enough attention in academia. Similarly, more attention on BIM-based LCA in other infrastructure classes would provide much-needed information, primarily for construction industry decision making. LCA-BIM would act as a decision aid mechanism for engineers and infrastructure management personnel with limited expert knowledge on niche areas such as LCA. Currently, there is no standard method suggested in the literature for the integration of BIM and LCA, and with the popularity of these concepts, there should be standardized direct methods to support this course.

This IFC/XML data file effectively transfers infrastructure data with LCA tools (e.g., One-click LCA, Open LCA) for LCA. File transfer using IFC/XML will avoid manual re-entry of project data, which will reduce the time for decision making during the planning stage. One major challenge for BIM-LCA integration is the inability for real-time synchronization. Currently, an XML file is used for transferring BIM data to the Green road tool. Also, the integration of BIM with road infrastructure is still a new concept under research, and it requires informing the construction industry of its benefits.

The findings of this research can be directly transferred to the construction industry, contributing to evidence-based policy-making for road construction and infrastructure management. Implementation of BIM and LCA integration can be facilitated through green procurement, which would support the wider implementation of green procurement in the construction industry. Future research should look into implementation challenges for proposed initiatives. Developing green procurement guidelines to support the Green Roads tool will promote the implementation of life cycle thinking-based road construction method selection.

6.3 Contributions

The following are key contributions of this research.

TBL based evaluation of road infrastructure: This research integrated TBL of sustainability for road construction method evaluation. Although previous studies have used life cycle assessment for road infrastructure evaluation, social impacts have been overlooked. TBL of sustainability provides a more comprehensive evaluation of construction decision making.

BIM and LCSA integration for horizontal infrastructure: Integrating BIM and life cycle thinking for road infrastructure planning provides decision support resources to local governing bodies and designers. Proposed is an external method for BIM and LCSA integration. A use can efficiently decide on the most suitable road alternative based on the designed road model data with the proposed integration.

A user friendly tool for implementation support: GRTET is a user-friendly decision support tool for infrastructure managers in road construction alternative selection. There is a lack LCA knowledge in the construction industry that hinders LCSA based decision making. This tool allows non-experts of LCA to perform an LCSA-based comparison of alternative road construction methods. The excel-based platform ensures a wider adaptation of this tool. The tool is flexible to add new materials into the database and adjust weights for TBL based on institutional priorities.

6.4 Limitations and Future Research Recommendations

The following are the limitations of this research as recommendations for extending the findings.

Extending the Database: The above research was carried out based on popular materials used in road construction. The tool contains a limited list of road construction materials. However, the flexibility of GRTET material database can be easily expanded.

LCA Scope: Impacts created by road transportation are neglected in this study. The main focus of this tool is the life cycle impact based on materials used. Additional material and energy flows are neglected. The LCA is carried out only for construction and repair and maintenance of the road alternatives. One end-of-life scenario (landfilling) is considered while alternative end-of-life scenarios are neglected

Uncertanity: The proposed evaluation framework is a crisp evaluation and ignored data and the model uncertainties. A comprehensive uncertainty evaluation by using a suitable method such as fuzzy logic could improve the reliability of results..

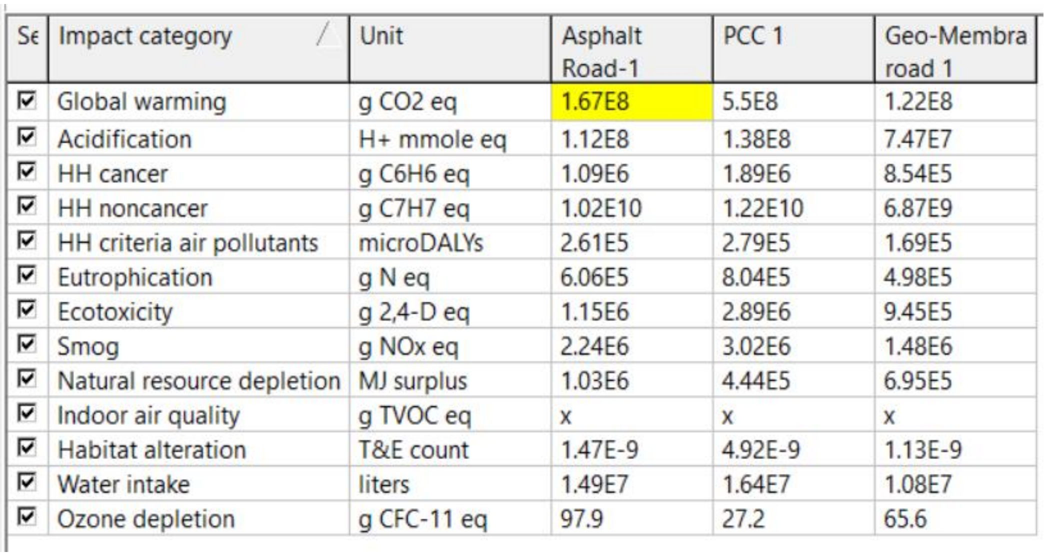
This project initiates unique approaches for road infrastructure sustainability evaluation and advancements in BIM. The proposed approach would be improved by using regional benchmarks in categorization, which enables identifying the most suitable construction method based on regional characteristics. Regional impact benchmark values can be defined for each KPI. A database of best and worst KPI performance values for regions should be developed. The weight schemes for TBL criteria could be improved based on regional and institutional priorities, which would provide a base level for TBL criteria. Finally, the implications of this study heavily depend on provincial and federal highway construction specifications, which should be studied in detail and be incorporated into this tool.

References

Ruparathna, R., Hewage, K. and Sadiq, R. (2018) ‘Multi-period maintenance planning for public buildings : A risk based approach for climate conscious operation’, Journal of Cleaner Production. Elsevier Ltd, 170, pp. 1338–1353. doi: 10.1016/j.jclepro.2017.09.178.

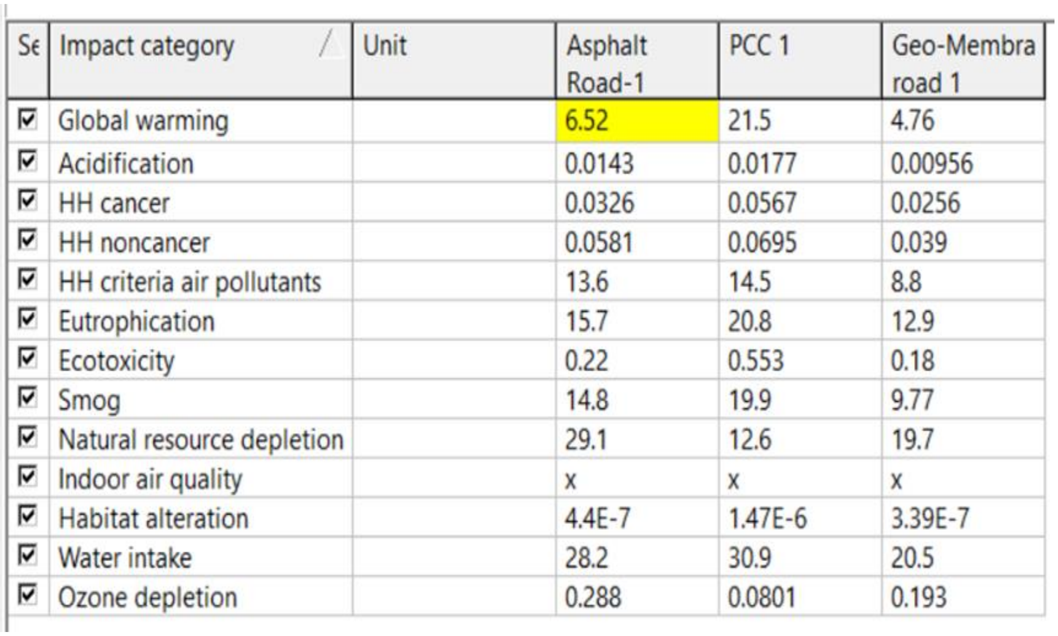
APPENDIX A: SIMAPRO ROAD ALTERNATIVES LCA RESULTS

A1: Charactarization result



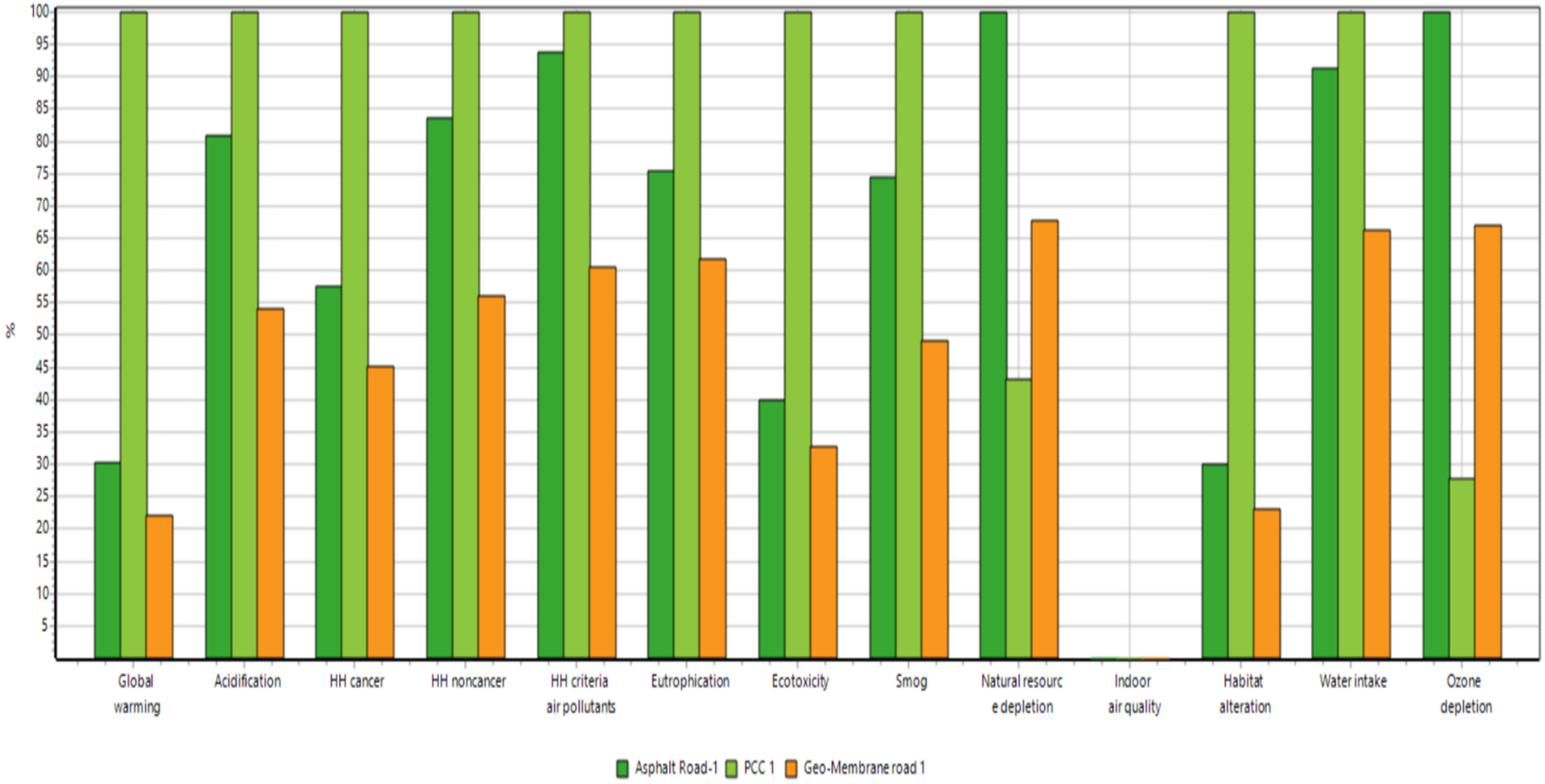
Se	Impact category	Unit	Asphalt Road-1	PCC 1	Geo-Membra road 1
☑	Global warming	g CO2 eq	1.67E8	5.5E8	1.22E8
☑	Acidification	H+ mmole eq	1.12E8	1.38E8	7.47E7
☑	HH cancer	g C6H6 eq	1.09E6	1.89E6	8.54E5
☑	HH noncancer	g C7H7 eq	1.02E10	1.22E10	6.87E9
☑	HH criteria air pollutants	microDALYs	2.61E5	2.79E5	1.69E5
☑	Eutrophication	g N eq	6.06E5	8.04E5	4.98E5
☑	Ecotoxicity	g 2,4-D eq	1.15E6	2.89E6	9.45E5
☑	Smog	g NOx eq	2.24E6	3.02E6	1.48E6
☑	Natural resource depletion	MJ surplus	1.03E6	4.44E5	6.95E5
☑	Indoor air quality	g TVOC eq	x	x	x
☑	Habitat alteration	T&E count	1.47E-9	4.92E-9	1.13E-9
☑	Water intake	liters	1.49E7	1.64E7	1.08E7
☑	Ozone depletion	g CFC-11 eq	97.9	27.2	65.6

A2: Normalization result



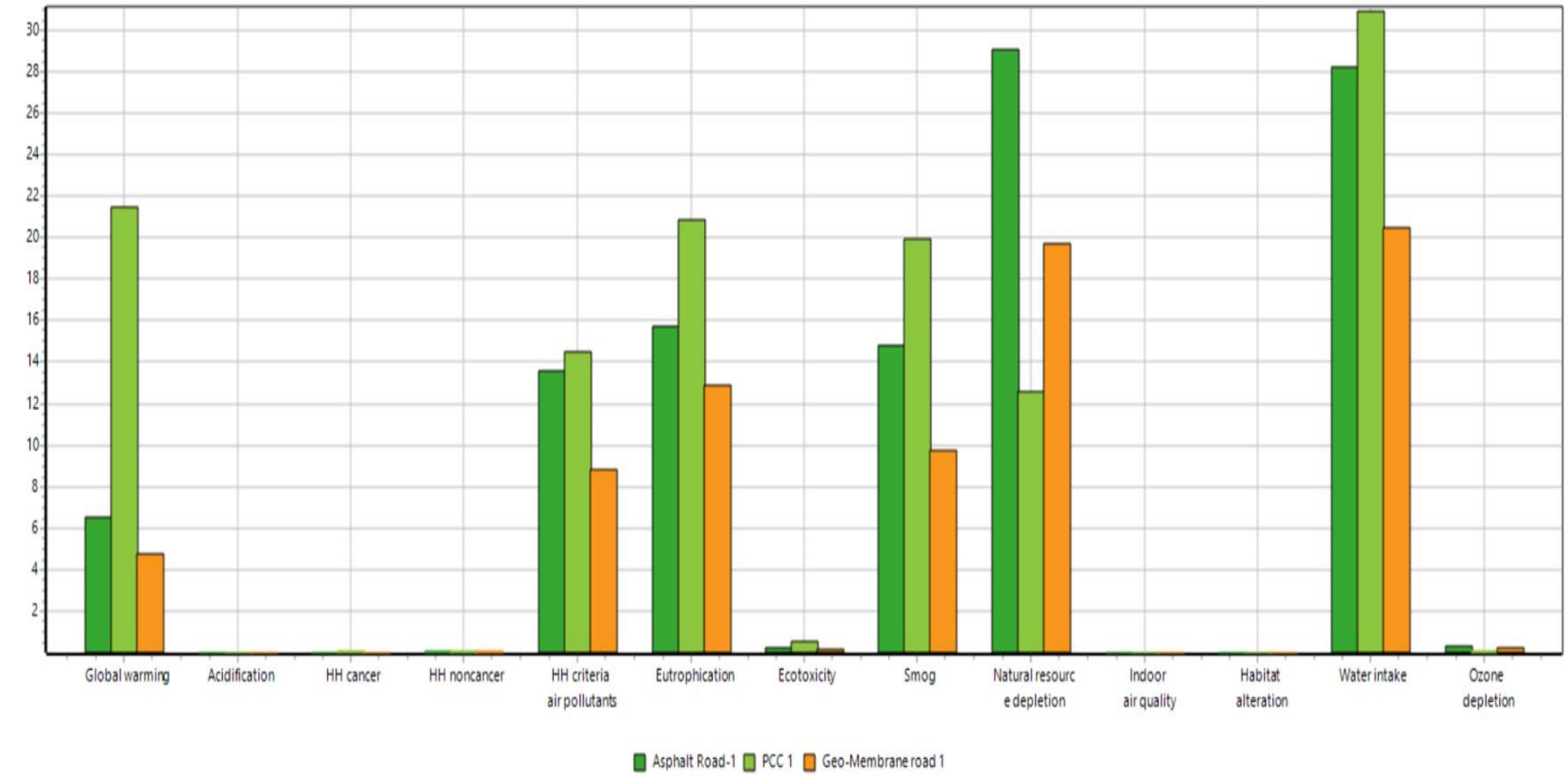
Se	Impact category	Unit	Asphalt Road-1	PCC 1	Geo-Membra road 1
☑	Global warming		6.52	21.5	4.76
☑	Acidification		0.0143	0.0177	0.00956
☑	HH cancer		0.0326	0.0567	0.0256
☑	HH noncancer		0.0581	0.0695	0.039
☑	HH criteria air pollutants		13.6	14.5	8.8
☑	Eutrophication		15.7	20.8	12.9
☑	Ecotoxicity		0.22	0.553	0.18
☑	Smog		14.8	19.9	9.77
☑	Natural resource depletion		29.1	12.6	19.7
☑	Indoor air quality		x	x	x
☑	Habitat alteration		4.4E-7	1.47E-6	3.39E-7
☑	Water intake		28.2	30.9	20.5
☑	Ozone depletion		0.288	0.0801	0.193

A3: Charactarization graph



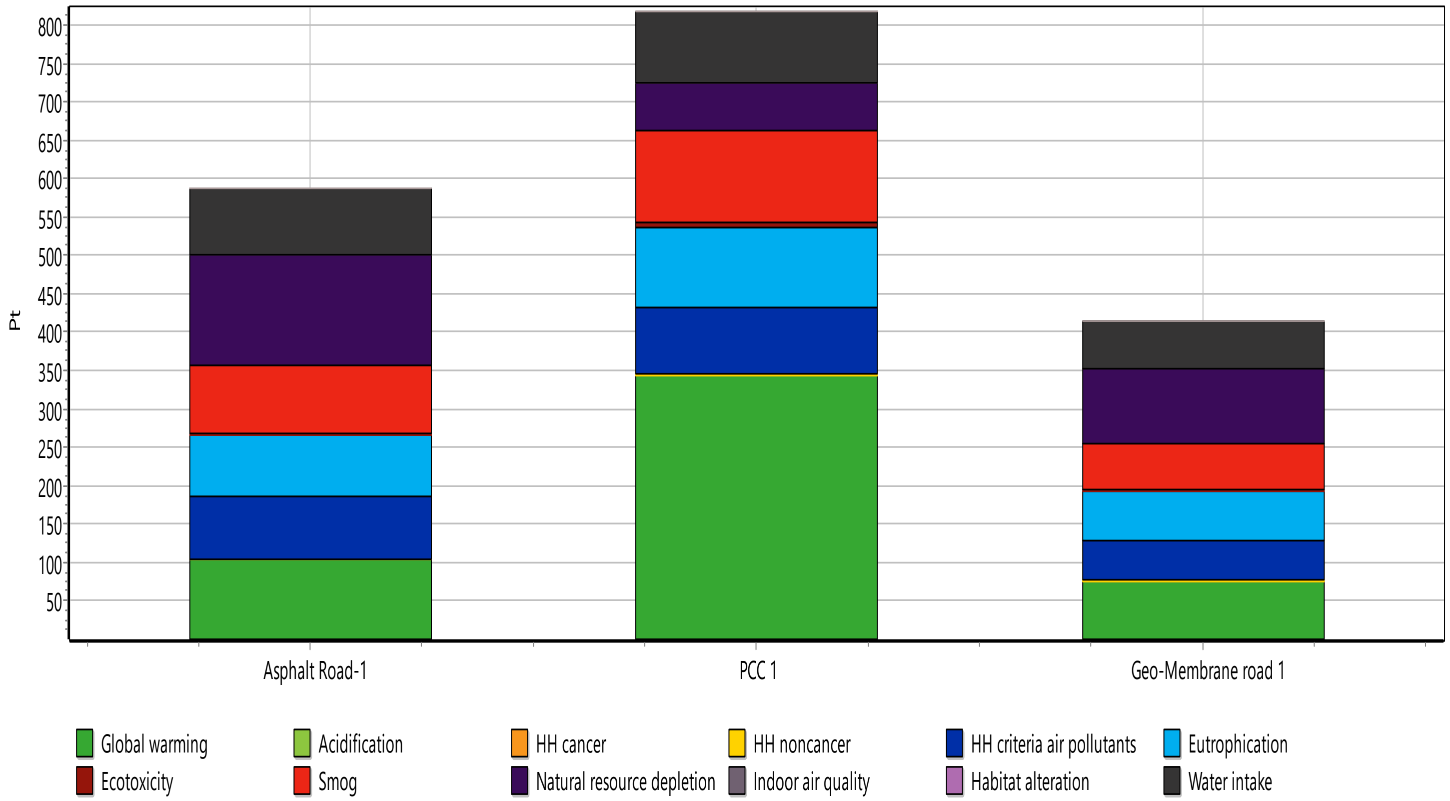
Method: BEES+ V4.08 / USA per cap '97-EPA Weighting / Characterization
Comparing 1.98 km 'Asphalt Road-1', 1.98 km 'PCC 1' and 1.98 km 'Geo-Membrane road 1';

A4: Normalization graph



Method: BEES+ V4.08 / USA per cap '97-EPA Weighting / Normalization
Comparing 1.98 km 'Asphalt Road-1', 1.98 km 'PCC 1' and 1.98 km 'Geo-Membrane road 1';

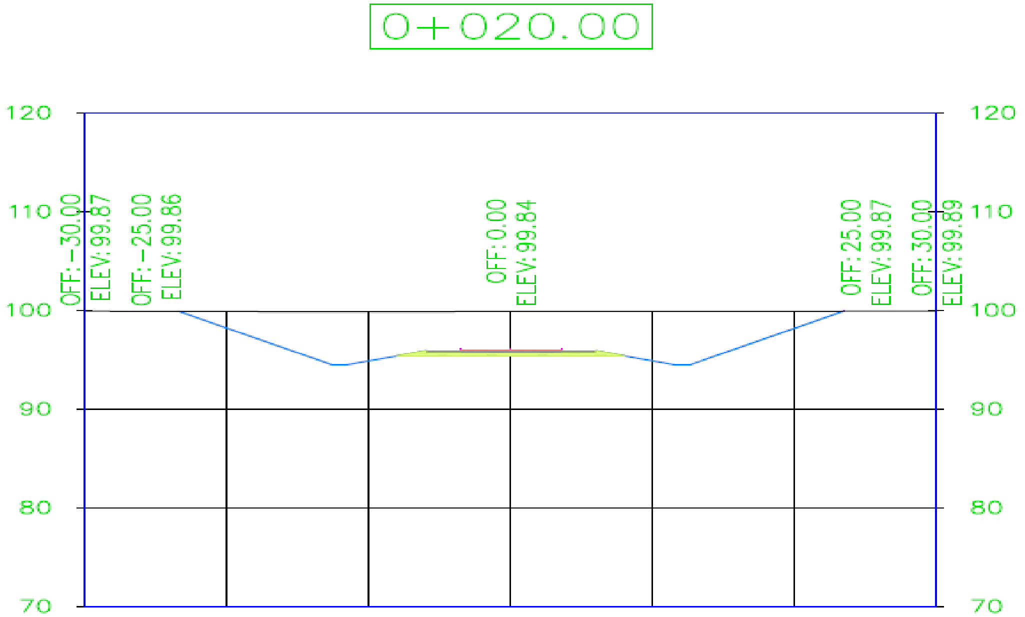
A5: Single score result

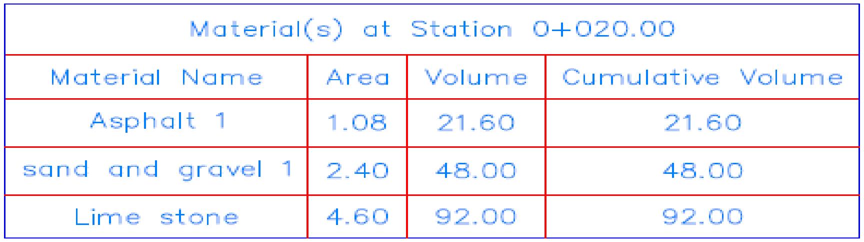


Method: BEES+ V4.08 / USA per cap '97-EPA Weighting / Single score

Comparing 1.98 km 'Asphalt Road-1', 1.98 km 'PCC 1' and 1.98 km 'Geo-Membrane road 1';

APPENDIX B: AUTODESK CIVIL 3D ROAD CROSS SECTION





Material(s) at Station 0+020.00			
Material Name	Area	Volume	Cumulative Volume
Asphalt 1	1.08	21.60	21.60
sand and gravel 1	2.40	48.00	48.00
Lime stone	4.60	92.00	92.00

VITA AUCTORIS

NAME:	Kartik Rajendrakumar Patel
PLACE OF BIRTH:	Surat, Gujarat, India
YEAR OF BIRTH:	1994
EDUCATION:	Dr. S. & S.S. Ghandhy College of Engineering and Technology, Diploma Civil, Surat, Gujarat, 2013 Sarvajanik College of Engineering & Technology, B.E. Civil, Surat, Gujarat, 2016 University of Windsor, M.A.Sc., Windsor, ON, 2020
PROFESSIONAL EXPERIENCE	Research Assistant, Dept. of Civil & Environmental Engineering, University of Windsor, May 2019 – Aug 2020. Lecturer (Department of Civil Engineering), C.K. Pithawalla College of Engineering & Technology, Surat, Gujarat, Aug 2016- Aug 2018.