INTEGRATING BRIDGE INFORMATION MODELING (BRIM), BRIDGE SUSTAINABILITY RATING SYSTEM (BRSRS), BRIDGE ENVIRONMENTAL PERFORMANCE STRATEGY MAPPING (BREPSM) AND COST ESTIMATING AT THE CONCEPTUAL DESIGN STAGE

By

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Acknowledgment

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Abstract

Bridges are crucial infrastructure for urban development as cities rely heavily on various modes of transportation for access and mobility. In an effort to fill the gap in the knowledge and methodology used in the construction of sustainable bridges, a model is developed using the concept of BrIM having the capabilities to develop bridges at the conceptual design stage, which offers ample versatility to influence stakeholders' decisions towards sustainable bridge design. The model incorporates a knowledge-based decision support system and four modules namely: BrIM module; the first ever Bridge Sustainability Rating System (BrSRS) module; Bridge Environmental Performance Strategy Map (BrEPSM) module; and a conceptual cost estimating module. The model takes fundamental data input and processes it through the knowledge-based system established based on MTO's Highway Geometric Design and the Navigational Waterways Clearance guidelines. The sustainability capabilities of the model are broken into two sub-modules; a BrSRS was developed by using the amalgamation of various existent highways and roads sustainability rating systems and by considering the introduction of bridge design. The system mimics the style of LEED as users can select from a weighted list of sustainable construction activities and materials to accumulate credits towards a sustainability classification. The second includes a BrEPSM that the forecasts footprints levels of bridge projects based on 5 footprint indicators namely; carbon; water; energy; emissions; and work environment with data obtained from Statistics Canada pertaining to each footprint illustrated on a radar graph. The third module takes the knowledge-based output and presents it in 3D mode via AutoCAD allowing users to alter the drawing's dimensions and accordingly the model reiterates the calculations based on

the changes made in the 3D CAD model. The final module generates an approximate cost estimate of the conceptually designed bridge, which is ideal for the feasibility study of the project.

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Glossary

2D	Two Dimensions
3D	Three Dimensions
AHP	Analytic Hierarchy Process
BIM	Building Information Modeling
BrIM	Bridge Information Modeling
BrSRS	Bridge Sustainability Rating System
CAD	Computer-Aided Design
CF	Carbon Footprint
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
EMF	Emission Footprint
ENF	Energy Footprint
BrEPSM	Bridge Environmental Performance Strategy Mapping
GDL	Graphics.DrawLine
GHG	Green House Gases
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
MTO	Ministry of Transportation of Ontario
SEPI	Sustainable Environmental Performance Indicator
SO_2	Sulfur Dioxide
SPI	Sustainable Process Index

WEF	Work Environment Footprint
WF	Water Footprint
VB.NET	Visual Basic.Net

Chapter One

Introduction

1.1 General

Building Information Modeling (BIM) has been one of the most prominent technological advances in the construction industry. However, its applications have been limited to building project types and it has not been adapted to apply to all the various types of construction projects. Bridges are a type of infrastructure project that is equally as complex as the building project type, but the new technological developments have not been integrated into bridge construction and project management. Thus, the adaptation of BIM concept toward the characteristics of bridge projects to perform Bridge Information Modeling (BrIM) has great potential benefit to the industry and could fill in the gap between conventional construction methods and the era of technological advances (Shirole et al., 2009). BrIM methodology is capable of establishing a tool that can simplify the design and construction stages of a bridge project. BrIM achieves this by taking large amounts of complex information related to a bridge project and breaking that information down using techniques such as visualization, information management and detailing (Katz, 2008). Similarly, the concept of sustainable infrastructure development is gaining momentum in the industry, but no technological advancements have been integrated into this concept. To maximize efficiency, sustainable development should be considered at the earliest possible stage of a project's life cycle. Considering sustainability requirements in the project's design will add excess information that requires to be managed. BrIM can integrate the management of those sustainability considerations into the general bridge design (Chen and Shirole, 2006; Barrella, 2012).

1.2 Research Objectives

Managing the multitude of information generated by a project is difficult. Traditional methods incur high levels of information loss due to ineffective communications protocols and information management administration. Adding sustainability concepts to a project's design complicates things further as more information needs to be managed. BrIM has the capabilities to manage all the information related to a project in an automatic and organized manner as well as strengthening the transmission and communication of information among project's stakeholders. Therefore, the main research objectives of this thesis are as follows:

- Search and understand BrIM characteristics for model development,
- Identify the existing gaps in bridges' sustainable development methodologies,
- Identify and outline the techniques that evaluate a project's sustainability level,
- Identify the relationship between the conceptual design of infrastructure projects and sustainable development,
- Develop and integrate a novel Bridge Sustainability Rating System (BrSRS), a bridge project sustainability evaluation tool, and 3D CAD modeling along with cost estimates at the conceptual design stage.

1.3 Research Methodology

The research followed a series of steps that outline the methodology to achieve the set list of objectives. The procedure is as follows:

1.3.1 Literature Review

A comprehensive literature review is conducted to identify the recent advancements and gaps in BrIM and sustainable infrastructure development studies. This step is critical as it ultimately refined the research objectives and methodology.

1.3.2 Data Collection

One of the modules requires a database to be established in order to carry out forecasting models and the evaluation technique. The collected data pertains to infrastructure projects' factors that contribute to a project's environmental impact through the analysis of five footprints. The variables required for each of the five footprints are identified and an adequate sample of historical data is compiled. The reliability of the historical data is imperative for the forecasting of future estimates. Thus, the data is acquired from reliable public database sources such as the governmental database of Statistics Canada.

1.3.3 Modules Implementation and Integration

From the literature review, the implementation methodologies for each of the three newly developed modules are clearly outlined and followed. The three modules are 1) a Bridge Sustainability Rating System (BrSRS), 2) a Bridge Environmental Performance Strategy Map (BrEPSM) and 3) 3D CAD modeling. The BrSRS and the BrEPSM methodologies requires independent development before their integration into the model due to their need for compiled databases; however, the 3D CAD module is a direct implementation of Visual Basic coding. Once each module is developed, they are integrated with the existing model following a logical design sequence to enhance the model's overall capabilities. This is done with regard to the model's step by step structure so that the model continues to provide a user-friendly interface.

1.4 Thesis Organization

This thesis is broken-down into a total of six chapters. The titles and a brief description of each chapter are as follows:

Chapter Two: Literature Review

Covers the extensive literature review conducted that defines the terms and concepts related to sustainability and BrIM. Advancements in the industry are noted and the gaps that remain in the literature are identified. The lack of a dedicated BrSRS is the first identified gap in literature. Infrastructure sustainability rating systems exist; however, their regard for bridge projects lacks depth. This also shed light on the lack of methodologies for bridge projects' environmental impact evaluation techniques identifying a dire need for emphasis on sustainable bridge design. Literature indicated that a project's sustainability is significantly influenced the earlier sustainable concepts are introduced in its lifecycle. Thus, the conceptual design stage is identified as the optimal phase for critical sustainable design decisions.

Chapter Three: Research Methodology

Clearly outlines the developmental methodologies of the three modules, namely being 1) the BrSRS, 2) the BrEPSM and 3) the 3D CAD modeling. Each module's methodology outlines its developmental process, any data that is compiled and the sources, any intermediate techniques involved in the development of the module and, the most critical step, each module's integration into the existing model. Furthermore, the overall model components and dataflow developmental methodologies are covered.

Chapter Four: Model Development

Illustrates the process that is followed in developing the model and the integration of the modules and how they interrelate.

Chapter Five: Model Validation

Demonstrates the full capabilities of the model by simulating a conceptual bridge project.

Chapter Six: Conclusion and Future Work

Presents the conclusions of the research by identifying how the BrSRS, BrEPSM, and the 3D CAD modeling modules enhance the existing model by introducing sustainability design features and BIM capabilities as early as the conceptual design stage. Similarly, the chapter identifies the enhanced model's contributions to the conceptual sustainable bridge design methodology. Moreover, the current model's limitations are covered and recommendations for further model development in future research are mentioned.

1.5 Summary

This chapter covered the outline of the research problem and the inferred research objectives designated to solving the problem. A brief description of the research methodology that is followed to fulfill the research objectives is explained and the thesis organization is broken-down with brief elaboration on what each chapter encompasses.

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Chapter Two

Literature Review

2.1 Introduction

Extensive literature review is a crucial step in the conduction of any research. By reviewing previous published literature, the research problem is properly defined, gaps in the literature can be identified and the research objectives are solidified. Bridges are vital part of infrastructure as they affect society's economy and mobility. Bridge projects design and construction are expensive and complex; thus, the application of BrIM concepts can potentially have positive impacts such as introduce sustainable design, reduce costs, improve quality and expedite construction. This chapter will define pertinent concepts and outlines methodologies to BrIM, sustainable bridge design and bridge environmental impact evaluation.

2.2 Bridge Information Modeling (BrIM)

BrIM is a concept similar to Building Information Modeling (BIM), but with applications to bridge projects. BIM is one of the most promising developments in architectural and engineering technology. It is defined to be "a digital representation of physical and functional characteristics of a facility" offering a "shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition" (NBIM, 2013). The advantage of BIM is the accurate digital/virtual rendering of building models that aids decision-making and activities in the design and construction phases of a project. In literature, the definition of BrIM as well as its applicability to various project life cycle phases seem to converge towards commonality between building and bridge projects.

2.2.1 Definition and Applications

Shah and Dawood (2008) compared the complexity levels of both bridge and building projects and found that both project types have similar degrees of complexity associated with them. However, bridge projects are perceived to have a higher degree of complexity due to the crucial environmental management process involved. Thus, BrIM is a shared information resource that supports the capability of 3D visualization of bridge project design. This is a holistic approach dealing with a bridge project's overwhelming information management and augmentation in terms of specifications, design, planning, construction, and operation (Katz, 2008; Shirole et al., 2009). BrIM has been applied in the production of prefabricated concrete bridges, where a 3D developed model illustrates the specific construction method guiding the prefabrication process of bridge components. The use of the 3D model eliminated design errors; reduced/optimized the overall material used, reduced the cost and accelerated the assembly. Similarly, BrIM can be applied to the planning stage of a project to help manage the consistent and intricate flow of various types of information as 4D CAD models have been developed to present optimized planning, scheduling, resource allocation and constructability. Alternatively, it can be applied during the construction phase to allow for real-time 4D space management of resources such as material, manpower, and machinery to avoid conflicts between the plans and current activities (Shah and Dawood, 2008; Zhou and Wan, 2010; Lee et al., 2012; Li et al., 2012).

2.3 The Bridge Conceptual Design Stage

Bridge projects are required to provide crossings over obstacles such as roads, facilities, and mass bodies of water. The bridge conceptual design stage starts by identifying the need for a bridge as it encompasses developing a number of alternative designs, comparing them and ultimately selecting the optimal design solution. The alternative design comparison process involves the consideration of a plethora of factors including, but not limited to, environmental impact assessments, feasibility studies, and life cycle cost analysis. These assessments are conducted in relation to the constraints the bridge project might face at the conceptual design stage. The constraints include constructability, aesthetics, sustainability, economics, structural safety, durability, and environmental compatibility (Nedev and Khan, 2011; BESAT, 2014). The process of the conceptual design stage follows four steps: 1) identifying the project needs, 2) identifying the applicable technology, 3) generation of alternative solutions and parameter analysis, and finally 4) alternative conceptual design selection. A designer will follow this process, as it helps simplify this role. During the project needs identification, the designer will explore and define the nature of the project needs so as to guide him to generate pertinent alternative designs. Identifying the available technology that is applicable to the nature of the project will help the designer to quickly and accurately produce alternative designs. The third step involves the production of alternative design solutions and each solution's feasibility with regards to a set of predetermined constraints. Finally, the designer will use all the information gathered and pick the optimum solution that satisfies the majority of the constraints and project needs (Kroll et al., 2011).

2.4 Sustainability Rating System

2.4.1 Sustainability and Infrastructure

Over the past 40 years, the United Nations Ecosystem Assessment has revealed that the current rate of natural resource consumption does not provide adequate resource renewal to meet the future demands of coming generations (CEM, 2008). Furthermore, in the U.S., the construction industry has been found to account for 30% of energy consumption as well as 6% of greenhouse gas emissions (Gambaste, 2005). Examples like these emphasize the need for the proliferation of sustainable development and practices in the construction industry.

In literature, the terms *sustainability* or *sustainable development* seem to have various definitions; however, a relatively agreed-upon definition is "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development (WCED), 1987; Jeon & Amekudzi, 2005; Oswald & McNeil, 2010). Similarly, the term *sustainable infrastructure* is defined as "allowing the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health and with equity within and between generations" while maintaining affordability, support for a vibrant economy, operational efficiency, provision of various transportation modes, emissions and waste limitation, reduction of non-renewable resource consumption, minimization of noise production and land use, and composition of recyclable components (Centre for Sustainable Transportation, 1998; Oswald & McNeil, 2010).

The life cycle of infrastructure must be considered to identify where sustainable practices and alternatives can be incorporated. According to the literature, the earlier in the project's life cycle sustainability is integrated as shown in Figure 2.1, the more efficient and sustainable the project will be. A useful tool is the life cycle assessment, which can assess the environmental impacts of a service, product, or system. This benefits the project for multiple applications in infrastructure including identifying sustainability indicators and evaluation (FHWA, 2011; Barrella, 2012).

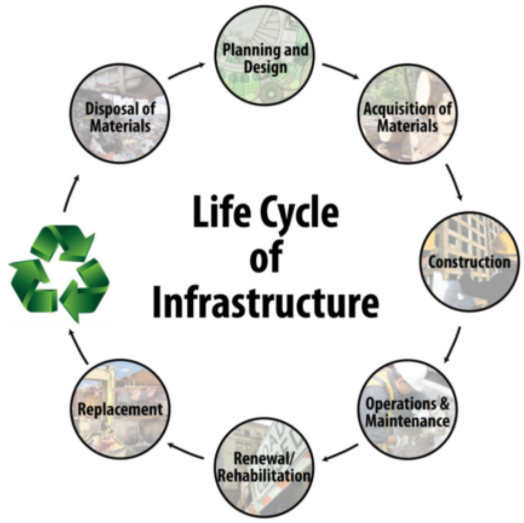


Figure 2.1. Infrastructure Life Cycle (FHWA, 2011)

2.4.2 Sustainability Indicators

Indicators are referred to as indices that are "devised to reduce a large quantity of data down to its simplest form, retaining essential meaning for the questions that are being asked of the data" (Ott, 1978; Oswald & McNeil, 2010). Thus, sustainability indicators aim at simplifying the process of measuring the reduction of human impact on the environment and promote sustainable practices. Since sustainability does not have one definition agreed upon unanimously, many institutes and governmental agencies have initiated the development of indicators that fall under a set of common sustainability factors. Such an entity is the Center for Sustainable Transportation in Canada, which conducted extensive literature review and programs involving stakeholders to identify a common set of sustainability indicators. Furthermore, Environment Canada stated that there seemed to be a consensus on three metrics: environmental preservation, social development, and economic development (Environment Canada, 1991; Environment Canada, 2003; Jeon & Amekudzi, 2005). In light of this conclusion, the sustainable development strategy of Ottawa, Canada (2001 - 2003) mentioned that Transportation Canada had adopted a set of sustainable development principles that are to be further developed into indicators. The principles are as follows:

1) Social principles, which are concerned with access, safety, health and quality of life,
2) Economic principles, which are concerned with affordability, cost internalization and efficiency,
3) Environmental principles, which are concerned with environmental stewardship, and pollution prevention, protection and conservation,
4) Management principles, which are concerned with public consultation and participation, leadership and integration (Jeon & Amekudzi, 2005).

2.4.3 Indicator Framework Categories

There are three main categories of indicator frameworks: linkage-based, impact-based, and influence-oriented frameworks.

2.4.3.1 Linkage-Based Frameworks

Linkages-based frameworks capture "the full range of indicators and metrics that cause particular conditions affecting sustainability, the impacts of these causes, and corrective actions that can be taken to address them" (Jeon & Amekudzi, 2005). One of the most widely used frameworks with commonly agreed upon indicators is the pressure-state-response (PSR) framework developed by Tony Friend and David Rapport in Canada as illustrated in Figure 2.2. The framework states that as certain human activities exert pressures on the environment a response is triggered as the state of the environment changes in term of quality and quantity. Society then responds to the changes in the state of the environment to take corrective and preventative actions (Gilbert and Tanguay 2000; Jeon & Amekudzi, 2005).

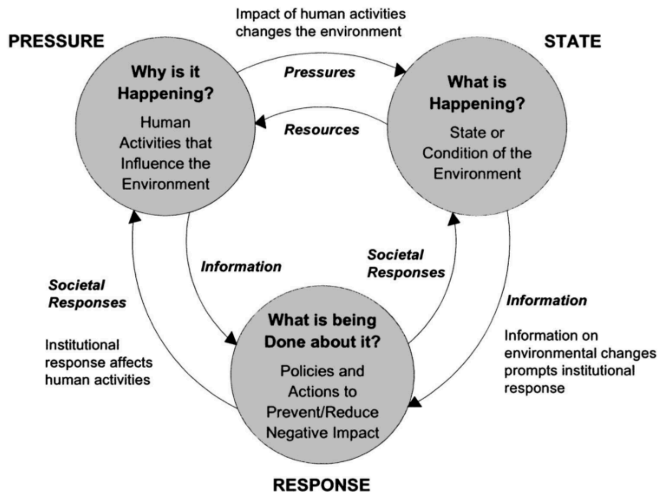


Figure 2.2. Pressure-State-Response Framework (Jeon & Amekudzi, 2005)

2.4.3.2 Impact-Based Frameworks

Impact-based frameworks capture the nature and extent of the impacts of various actions, whether social, environmental and/or economic, which collectively determine a system's sustainability. The three-dimensional framework is the most common impact-based framework. To exemplify, the Transportation Association of Canada (TAC) uses a three-dimensional appraisal framework focused on the economy, the natural environment, and society. In the economy dimension, the framework is expected to support a vibrant and diverse economy. In the natural environment dimension, the framework is expected to reduce emissions and waste production. As for the society dimension, the framework is expected to enhance quality of life, health and ultimately access equity (TAC, 1999; Jeon & Amekudzi, 2005).

2.4.3.3 Influence-Oriented Frameworks

Influence-oriented frameworks present categorized indicators based on the degree of influence that an agency has on the activities affecting the overall sustainability progress of an infrastructure system. A tiered framework developed by Transport Canada (TC) uses performance indicators to reflect the degree of influence that the organization has on their infrastructure in terms of sustainability progress. The framework's three levels of indicators are: 1) state level indicators, 2) behavioral indicators, and 3) operational indicators. State level indicators focus on describing the sustainable state of the infrastructure system. Behavioral indicators focus on the influence of the activities and behavior of stakeholders. Finally, operational indicators focus on describing the operations, actions, and mandate of the organization (TC), itself (Transport Canada (TC), 2001; Jeon & Amekudzi, 2005).

2.5 Infrastructure Sustainability Rating Systems

There exists a number of green rating systems for various types of projects; however, there has been an emphasis on the development of rating systems primarily for vertical projects. Examples of such rating systems include the popular Leadership in Energy and Environmental Design (LEED) and Green Globes. These systems focus on the sustainability aspects of building design and neighborhood development while conferring on some aspects of transportation. Recently, there has been an increased interest in and dedication to the development of a sustainability rating systems that solely focus on transportation planning, design, and construction. The infrastructure sustainability rating systems selected as benchmarks for this study due to their use and relevance are: 1) Greenroads™, 2) GreenLITES (Green Leadership in Transportation and Environmental Sustainability), 3) I-LAST (Illinois Livable and Sustainable Transportation) and, 4) Envision (Oswald & McNeil, 2010; Clevenger et al., 2013).

2.5.1 Greenroads™

Greenroads is a sustainability rating systems that was developed in 2009 by the collaboration of the University of Washington and CH2M HILL. The rating system facilitates tracking the level of sustainability in an infrastructure project by awarding credits for sustainable best practices. This is done using a holistic approach of evaluating infrastructure sustainability for construction and rehabilitation through a quantitative-based decision making methodology. Ultimately, it is a tool that focuses on assessing green highways, bridges, and tunnels throughout a project's life cycle. Greenroads is broken down into two categorized criteria: required and voluntary. For a project to seek Greenroads sustainability certification, it must fulfill all the project requirements and some of the voluntary criteria (depending on the level of certification the project seeks). There are 11 project requirements, namely: Environmental Review Process, Noise Mitigation Plan, Lifecycle Cost Analysis, Lifecycle Inventory, Educational Outreach, Waste Management Plan, Pollution Prevention Plan, Low Impact Development, Pavement Management System, Quality Control Plan, and Site Maintenance Plan. Similarly, there are six voluntary credits, namely: Environment and Water, Access and Equity, Construction Activities, Materials and Resources, Pavement Technologies, and Custom Credits. Figures 2.3 and 2.4 illustrate the credit breakdown and certification levels of the Greenroads rating system and Appendix A presents a Greenroads sample scorecard (Johnson, 2011; Anderson & Muench, 2013; Clevenger et al., 2013).

GREENROADS™ Rating Category	Points	Percent
Project Requirements	Required	--
Environment and Water	21	19
Access and Equity	30	28
Construction Activities	14	13
Materials and Resources	23	21
Pavement Technologies	20	19
Custom Credits	(10)	--
TOTAL	108	100

Figure 2.3. Greenroads Categories and Credits (Johnson, 2011)

Figure 2.4. Greenroads Certification Levels (Johnson, 2011)

2.5.2 GreenLITES (Green Leadership in Transportation and Environmental Sustainability)

GreenLITES was developed in 2008 by the New York State Department of Transportation (NYSDOT) to assess their projects' performances on sustainable best practices. The appraisal system aims to encourage sustainable development, appropriateness of design, and the construction of low- or no-cost maintenance infrastructure. It also seeks to identify areas that need improvement. The tool is applicable during the entire design stage of a project's life cycle and it is mandatory to be used for new infrastructure projects by the NYSDOT. GreenLITES focuses on the tri-axial factors of sustainability: economy, environment, and equity. Using these three factors as a premise, the system has a total of 175 credits that are spread across 5 categories: 1) Sustainable Sites, 2) Water Quality, 3) Material and Resources, 4) Energy and Atmosphere, and 5) Innovation. Similarly, there are four levels of GreenLITES certifications, namely: 1) GreenLITES Certified, 2) GreenLITES Silver, 3) GreenLITES Gold, and 4) GreenLITES Evergreen. Please refer to appendix B for a GreenLITES sample scorecard (Krekeler et al., 2010; Barrella, 2012; NYSDOT, 2012; Clevenger et al., 2013).

2.5.3 I-LAST (Illinois Livable and Sustainable Transportation)

The I-LAST sustainability rating system was developed by the collaboration of the Illinois Department of Transportation (IDOT), the Illinois Road and Transportation Builders Association (IRTBA), and the American Consulting Engineers Council (ACEC). The system is self-assessed, paper-based, and voluntary, with the purpose of evaluating highways depending on the applicable criteria selected by the project team. I-LAST is applicable during the design, and construction phases of a project. The rating system is broken down into eight categories, namely: 1) Planning, 2) Design, 3) Environmental, 4) Water Quality, 5) Transportation, 6) Lighting, 7) Materials and 8) Innovation. In total, the categories have 153 sustainable best practices criteria with a maximum of 233 credits to be earned. Since the system employs self-assessment, there are no calculations but rather yes/no answers assigned by the self-evaluator. Please refer to appendix C for the I-LAST sustainable rating system sample self-scoring scorecard (IDOT & IJSG, 2010; Clevenger et al., 2013).

2.5.4 Envision

Envision was developed by the collaboration of the Harvard Graduate School of Design and the Institute for Sustainable Infrastructure (ISI) under the Zofnass Program. The rating system is applicable for water storage and treatment, landscaping, energy generation, information systems, and transportation; additionally, it is versatile and can be employed during the majority of the phases in a project's life cycle (planning, design, construction, and operation). The core focus of the system is on the fundamental functions of a community, which include general life improvement and sustainable growth development. Envision has 60 credits distributed across five categories, namely: 1) Quality of Life, 2) Leadership, 3) Resource Allocation, 4) Natural World, and 5) Climate and Risk as shown in Figure 2.5. There are four certification levels in Envision:

Acknowledgement of Merit, Silver Award (a minimum of 8% in each category is required), Gold Award (a minimum of 15% in each category is required) and Platinum Award (a minimum of 20% in each category is required). The assessment process occurs over two stages, Stage 1 being a self-assessed checklist and Stage 2 involving a third-party audit to verify the work against the checklist and to conduct public recognition. Please refer to appendix D for the Envision scorecard (ISI, 2012; Clevenger et al., 2013; Georgoulias, 2015).

Figure 2.5. Envision Categories and Subcategories (Georgoulias, 2015)

2.6 Infrastructure Footprint Analysis

2.6.1 Footprint

The term "footprint" has been defined as the "quantitative measurement describing the appropriation of natural resources by humans," thus illustrating the imposition and impact of human activity on sustainability (Hoekstra, 2008; Cucek et al., 2012). In the context of sustainable development, the concept of footprints is present in sustainable development's three pillars: environmental protection (also known as ecology), economic prosperity and social dimension. Additionally, footprints ties in with the tool, Life Cycle Assessment (LCA), which is a tool that quantifies emissions, resource consumption, health, and environmental impacts that relate to a certain process, a product or an activity over their entire life cycle (cradle to grave). Footprints are considered in the second and third phases of the LCA, namely, Inventory Analysis and Impact Assessment. During the Inventory Analysis, the objective is to balance mass and energy to quantify the energy and material resources intake as well as to derive the emission and waste produced from the system under consideration. The quantities are then collected in the Impact Assessment and placed under a set of recognizable environmental impacts, such as climate change and acidification. The literature currently indicates that carbon, ecological, and water footprints are the major categories of footprints forming what is known as the "footprint family"; however, there is a number of various footprints that exist, for example, a nitrogen footprint, each with their own unique definition (De Benedetto & Klemes, 2009; Galli et al., 2011, 2012; Cucek et al., 2012).

2.6.2 Footprint Environmental Impacts

The emission of Green House Gases (GHG) into the atmosphere on a continuous basis has influenced and shaped the present climate change crisis. Altered meteorology, a rise in global temperatures, a change in ground water and sea levels, changes in soil conditions and precipitation are all being associated to the production of GHG. Furthermore, Figure 2.6 summarizes the findings from studies that indicate GHG production and climate change have had deteriorating effects on: 1) the ecosystems of water such as waterways and treatment plants; 2) power generation; 3) air quality; 4) frequency of rainfall; 5) transportation structures such as bridges, roads, airports and piers; and 6) many types of buildings such as commercial, industrial and public facilities (Brimblecombe and Grossi, 2007; IPCC, 2007; Isaksen et al., 2009; McIlgorm et al., 2010; Kumar and Imam, 2013). Infrastructure systems are essential for mobility needs; thus, it is important to study the effects of GHG and climate change on transportation structures. Roads, bridges, highways, airports and railway lines are designed to have long lifespans increasing their susceptibility to the effects of climate change. Moreover, transportation structures contribute to the production of GHG and an environmental footprint propelling the deteriorating effects of climate change on the environment and on themselves. For example, the durability of bridges is expected to be impacted by high temperatures with more thermal expansion, movement restrictions at bearings and expansion joints, increased corrosion of steel, increase of carbonization and corrosion of concrete, and an overall accelerated deterioration process. To address this issue, it is vital to be able to conduct reliable future estimates of footprints and climate conditions. Quantifying these factors will help manage the effects on existing structures to ensure continuous functionality as well as influence designs of future projects towards sustainable options (DoT, 2005; Holper et al., 2007; Kumar and Imam, 2013).

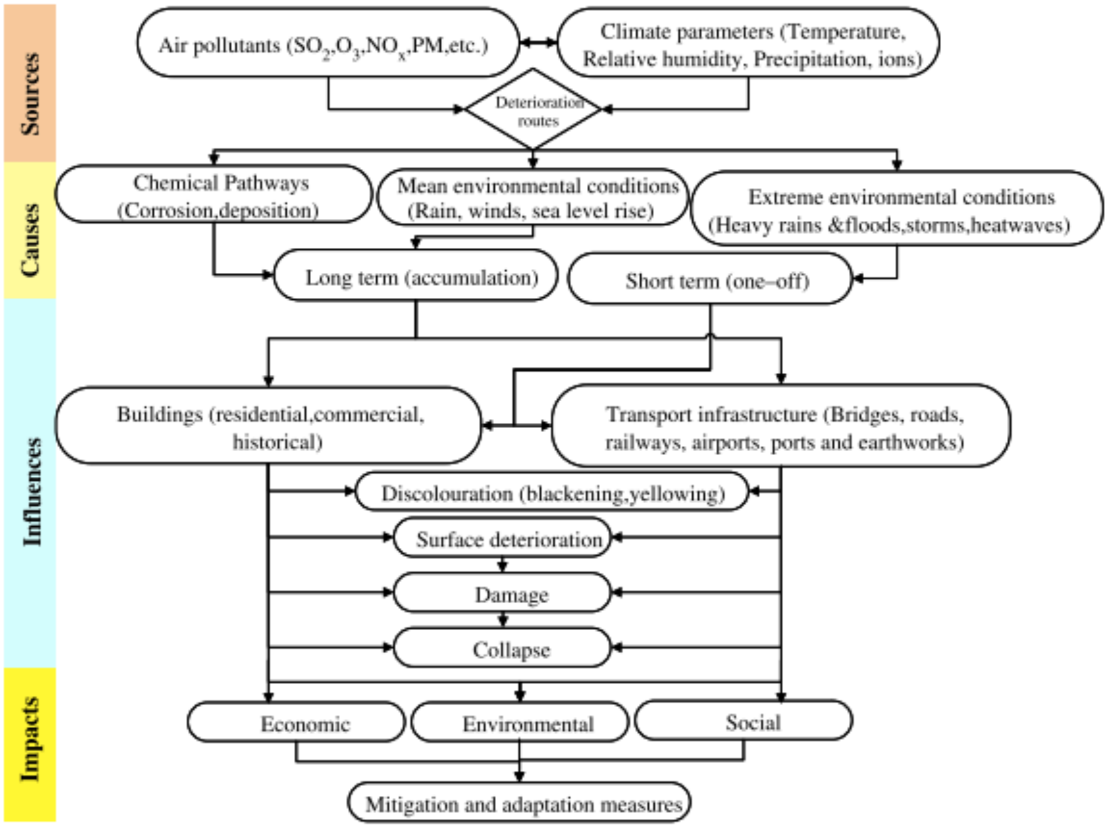


Figure 2.6. Environmental Pollutants' Impacts on Infrastructure (Kumar and Imam, 2013)

The identification of point-source production locations of GHG is imperative to be able to establish mitigation and remedial action plans. Carbon Dioxide (CO_2) is one of the main contributors of GHG to the atmosphere, which is why it is considered to be a major footprint category. CO_2 has the highest growth rate, longest atmospheric lifetime and largest atmospheric concentration out of all the GHGs. It is mainly produced from the consumption of fossil fuels and energy by the transportation and industrial sectors. According to studies, the annual emission of CO_2 has increased from 21 to 38 Gt between 1970 and 2004, estimating an 80% growth rate. The transportation sector alone is accountable for approximately 20 to 25% of the world's CO_2 emission and this could potentially rapidly increase to about 35 to 50% by the year 2050 (Nakicenovic et al., 2000; Climate change, 2007; Fuglestvedt et al., 2008; Kumar and Imam, 2013).

Figure 2.7 depicts the CO_2–equivalent emissions contribution to GHG in terms of composition and sector production:

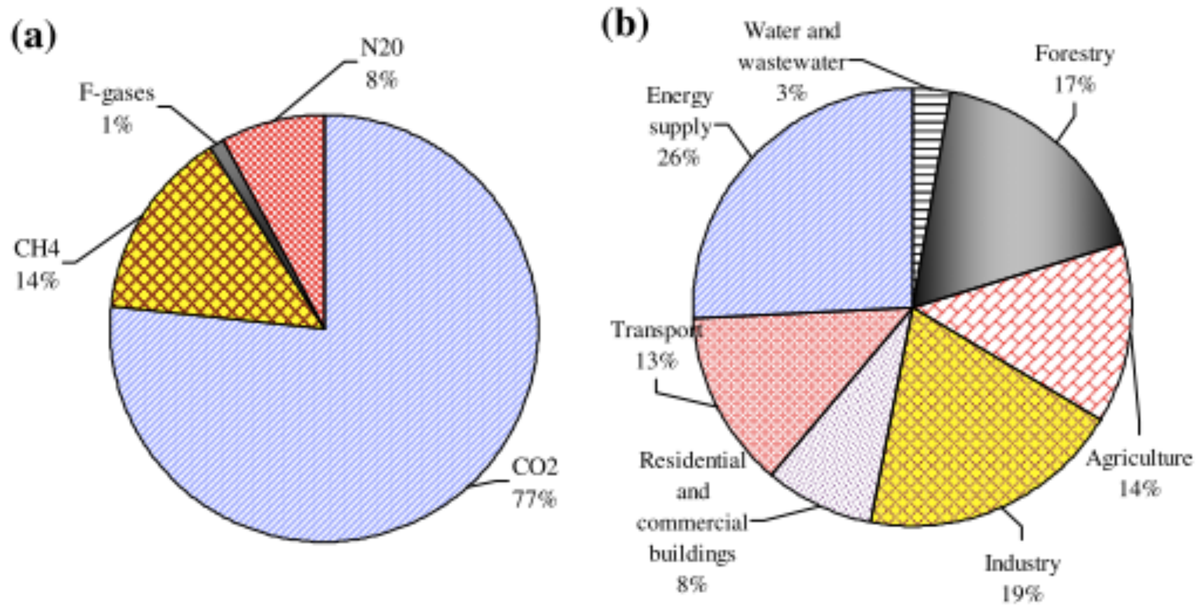


Figure 2.7. (a) CO2–equivalent emissions of GHG Composition and (b) CO2-Equivalent Emissions of GHG Production per Sector (IPCC, 2007; Kumar and Imam, 2013)

2.6.3 Footprint Indicators

As a part of measuring sustainable development, footprint indicators were identified and defined to provide a basis for sustainable decision-making. Sustainability indicators are classified under four groups: 1) indicators of energy and material flow, 2) indicators with territorial dimensions, 3) indicators of LCA, and 4) indicators of environmental risk assessment. Footprint indicators belong to the first and third groups as they relate to the consumption of energy and resources and the procedures of LCA (Herva et al., 2011; Cucek et al., 2012). Based on the major footprint categories the suggested indicators are: “Carbon footprint; Water footprint; Energy footprint (land, renewables, non-renewables); Emission footprint (emissions to air, water and soil, waste materials); Work environment footprint (work environment and toxicological impacts)” (Schmidt et al., 2004, Cucek et al., 2012).

2.7 Measuring Infrastructure Footprint

2.7.1 Environmental Performance Strategy Map (EPSM)

EPSM was developed to compensate for the applicability limitations of an LCA due to the partial inclusion of cost factors. Or rather, it was developed to strengthen the analysis of ecological footprint and the LCA tools. An EPSM is the integration of environmental, toxicological, resource, and financial considerations into a single analysis. This analysis illustrates environmental and social footprints and regards cost as an additional category, making it a good source of input for strategic decision-making. The objective of an EPSM is to provide a single indicator for each option being analyzed by utilizing a deviation-from-target methodology, where a maximum target is set for each footprint and the normalized percentages are expressed as the distance to the target. The five quantifiable footprints (carbon, water, energy, emission and work environment) are used as indicators and combined to form a single Sustainable Environmental Performance Indicator (SEPI). The advantage of the EPSM is the single SEPI as it simplifies and eases the decision-making process of a given option from environmental and sustainability perspectives. The footprint estimation is variable depending on each footprint's definition; thus, each indicator has an exclusive quantifiable calculation (De Benedetto and Kleme, 2009; IPPC, 2009; Cucek et al., 2012).

2.7.2 Carbon Footprint (CF)

CF is the total emitted CO_2 and other GHG over the life cycle of a product, service and/or activity. It was derived as a Global Warming Potential indicator and is calculated tantamount to the area of the land/project under consideration. The typical time horizon considered is 100 years. The chemistry based equation for calculating the carbon footprint is (De Benedetto and Kleme, 2009):

$$CF = M_{CO_2} * \frac{1 - F_{CO_2}}{S_{CO_2}} * EF \qquad \textbf{Eq. 1}$$

Where, CF is the footprint of indirect land occupation by fossil fuel and cement related CO_2 emissions (m^2 y), M_{CO2} is the product specific emission of CO_2 (kg CO_2), F_{CO2} is the fraction of CO_2 absorbed by the oceans, S_{CO2} is the sequestration rate of CO_2 by biomass (kg CO_2 m^{-2} y^{-1}) and EF is the equivalence factor for forests. This equation is used only when $M_{CO2,}$ F_{CO2} and S_{CO2} can be quantified. The footprint's unit of measure is expressed in m^2 (De Benedetto and Kleme, 2009; IPPC, 2009; Cucek et al., 2012).

2.7.3 Water Footprint (WF)

WF is measured by two components: the direct volume of fresh water consumed and/or polluted by the production/manufacturing/activity and the indirect volume of fresh water consumed and/or polluted that transmits throughout the process. The footprint encompasses blue, green and grey water footprints, which are sub-category footprints that represent, respectively, the consumption of ground and surface water, consumption of rainwater, and the volume of water required for the dilution of pollutants to achieve water quality standards. This footprint is measured in L/m^2 (De Benedetto and Kleme, 2009; Mekonnen and Hoekstra, 2010; Cucek et al., 2012).

2.7.4 Energy Footprint (ENF)

ENF can be defined as "the sum of all those areas used to provide non-food and non-feed energy" or as the representation of "the area required to sustain energy consumption, and is measured as the area of forest that would be required to absorb the resulting CO_2 emissions" (WWF, 2002; GFN, 2009). It is measured by multiplying the final energy consumed with the land need indices and then adding the result to the footprint of the whole energy supply. The footprint unit is m^2 (Cucek et al., 2012).

2.7.5 Emission Footprint (EMF)

EMF is the representation of the quantity of emissions into "the air (e.g., SO_2, particles, CO, CO_2), water (e.g., chemical oxygen demand (COD), nitrogen and phosphorus), and soil (through spillage in the soil)" (Cucek et al., 2012). It is measured by the comparison of emission rates to soil, ground water and air versus the replenishment rate per unit area of the natural resources. Soil's replenishment rate is derived by the decomposition of biomass to produce compost. Ground water's replenishment rate is taken from the seepage rate given by local precipitation. Air's replenishment rate is assumed to be the natural exchange rate between forests and air per unit area, which is known for the majority of airborne substances. This assumption is made because there is no defined natural replenishment rate for air. The footprint is measured in m^2 (De Benedetto and Kleme, 2009).

2.7.6 Work Environment Footprint (WEF)

Finally, WEF is an included footprint by the LCA method. The main reason for its inclusion is that it is an indicator that can be used to examine the implementation effects of environmental product improvement on deteriorating working environment. Therefore, the method assesses the changes in work environmental impacts and the overall worker safety when alternative work materials and processes are considered and chosen. The WEF is measured by the collection of statistics to calculate the number of reported lost days of work per weight unit of product. The categories regarded for assessment include fatal accidents, hearing damages, cancer, airway diseases and psychosocial diseases. This footprint is measured in number of lost days of work per person (Schmidt et al., 2004; De Benedetto and Kleme, 2009).

2.8 Summary

This chapter described the extensive literature review that was conducted to identify the current literature on the research topic. The concept was to integrate a new module that introduces the notions of bridge sustainability to the pre-existing model. Initially, a recap of the definitions of BIM, BrIM and the conceptual design stage were covered to define the model. This was followed by a review of the literature on the proposed sustainability module. After that, sustainability as a concept was defined and its applicability in relation to infrastructure was explained. Sustainability measurement methods were explored and indicator frameworks were listed and outlined. Similarly, existing infrastructure sustainability rating systems were identified and their mechanics briefly summarized. This part of the literature review was the key component that lead to the establishment of the methodology and ultimately the synthesis of the Bridge Sustainability Rating System (BrSRS). The third part of the literature review covered the definition of footprints, their relation to infrastructure and sustainability, a list of footprint indicators and their respective measurement methods. This will help the development of the sustainability module further by establishing the methodology to create an EPSM for bridge projects.

Chapter Three

Methodology

3.1 Introduction

This chapter will explain in depth the methodology established from the literature review stage. The methodology will cover the three modules that will be developed and added to the pre-existing model, namely, 1) a BrSRS, 2) the BrEPSM, and 3) 3D CAD modeling. Each module will be developed following a series of steps identified from the literature and the methodology will be laid out to fit the research objectives. The first two modules will be synthesized separately and then developed into the model while the 3D CAD module will be directly integrated into the existing knowledge-based system.

3.2 Model Components

The model was initially developed with two modules: 1) a knowledge-based module and 2) a cost estimating module. The knowledge-based module is a system developed by the incorporation of two knowledge-bases, the first being a heuristic knowledge-base containing rules of thumb gathered from interviews conducted with bridge design experts and the second being algorithmic, containing the Ministry of Transportation of Ontario's (MTO) highway geometric design guidelines, bridge structural codes, and the navigational waterway guidelines. Two practicing bridge design experts in Toronto were interviewed to gather bridge design rules of thumb. "One of the selected experts is currently working in the public sector, Head of structural department of Ministry of Transportation of Canada, and the other expert is currently working in the private sector, Senior structural engineer in an international consultancy engineering company" (Al-

Dosary, 2014). The conceptual cost estimating module prepares the cost estimate of the bridge based on the dimensions and bridge type, which are output from the knowledge-based module. The module utilizes cost data collected from various bridge projects constructed in North America and applies the necessary time and location adjustment factors. To provide the model with BrIM capabilities and incorporate sustainable design features, the following modules will be developed and integrated with the previous two modules: 1) BrSRS module, 2) BrEPSM module, and 3) a 3D CAD module. The BrSRS and BrEPSM modules enhance the conceptual design of bridge projects by allowing users to consider sustainable options early on in the projects' life; however, the modules design and evaluate projects regarding their entire life cycle. The BrSRS will permit the user to customize a sustainable bridge in accordance with a developed rating system while the BrEPSM will provide the user with a preliminary EPA, which is relevant to the project's forecasted footprint. The 3D CAD module will be integrated with the knowledge-based system as it will rely on the system's output to model the conceptual bridge. A link will be established between the modules while the model will allow for rapid exchange of information by developing the BrIM capability of the model. Figure 3.1 illustrates the components of the model.

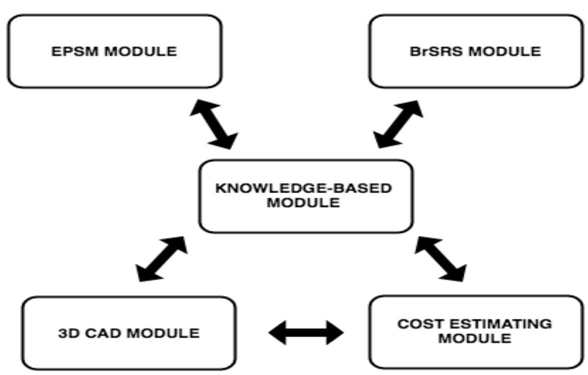


Figure 3.1 - Model's Component Modules

The design process of a bridge requires a structured procedure that follows logical strategies of information management. This is due to the need of avoiding errors as bridge projects are complex

(Lansdown, 1989). Thus, the development of the modules will follow a logical flowchart reflecting the various phases of the conceptual design stage. Figure 3.2 depicts the model's flowchart.

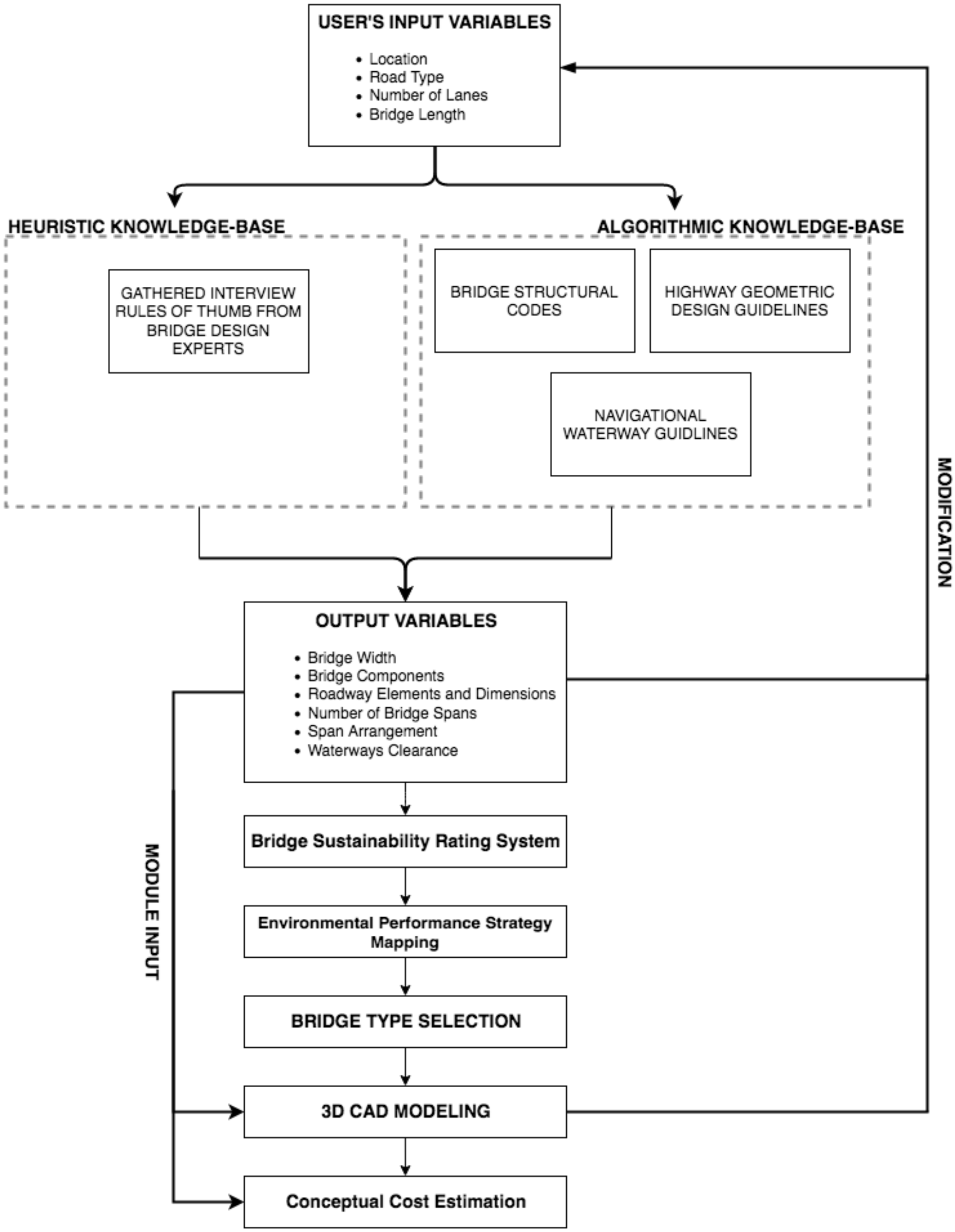


Figure 3.2 - Model's Flowchart

3.3 Bridge Sustainability Rating System Synthesis

Oswald and McNeil (2010) conducted an extensive literature review and identified a gap in the documentation of the methodology of sustainability rating systems such as LEED. However, there exists a universal methodology for synthesizing sustainability rating systems using sustainable indicators as the premise. The methodology comprises a seven-step procedure to develop sustainability indicators and a sustainability rating system within a decision-making model. The seven steps are as follows (Bossel, 1999; Oswald & McNeil, 2010):

1. Define criteria for selecting the infrastructure under evaluation;
2. Develop sustainability indicator categories;
3. Develop sustainability indicators for each category;
4. Transform indicators into credits by identifying measurements associated to each;
5. Prioritize credits by assigning weights;
6. Allocate points; and
7. Develop rating scale.

This methodology was found to be common in the creation of the various infrastructure sustainability rating systems covered in the literature review. Thus, it will be adopted as the methodology to develop the BrSRS.

3.3.1 Bridge Criteria Definition

The research focuses on bridges as infrastructure projects as they vary in scale and are quite complex projects to design and execute. Bridges are comprised of two components: 1) a structural component and 2) a road or highway component. Is it important to identify the criteria that define infrastructure sustainability, as they are necessary to ensure the synthesized rating system is applicable to both bridge projects and road and highway projects since a bridge's composition differs from that of roads and highways. Thus, the components and stages of a bridge project were classified and included as part of the criteria set. The criteria were classified as follows:

- Construction material
  - The superstructure of a bridge can be made by combining various materials including steel, concrete and steel.
  - The deck portion of the bridge constitutes the roadway, which will be made of asphalt and concrete.
- Classification
  - The classification of the bridge's intended use depends on the need for the bridge project as bridges can be classified as highway, railway, pipeline, and airport runway. This classification will determine the site location and surrounding environmental factors.
- Roadway characteristics
  - Roads have various characteristics that determine their alignment, level of service, accessibility, and mobility.
- Environmental impact
  - The construction phase of a bridge project will undoubtedly have adverse effects on the environment. Factors affected include, but are not limited to air, soil, vegetation, water, natural habitats, and biodiversity.

3.3.2 Bridge Sustainability Indicator Categories

Indicators are used to simplify the process of measuring the impacts that human activities have on the environment. Simultaneously, they offer an approach to promoting sustainable practices within policy and public domains (Mitchell, 1996). Therefore, indicators are utilized in the definition of the credits that will make up the rating system. First off, the factors that are used to evaluate the sustainability of bridges are narrowed down in order to develop the indicators. This is done by a thorough review of the existing infrastructure rating systems and a determination of the vital factors that will influence the development of the indicator categories. The final factors chosen for indicator category development are:

- Governmental policies and regulations,
- Construction methodology,
- Land use and site selection/location,
- Physical characteristics of infrastructures, and
- Usage of and need for the project.

After the consideration of the factors, the indicator categories were developed by identifying the existing credits in various rating systems that are pertinent to bridge projects and their objectives were defined. Credits that were not completely aligned with the characteristics of bridge projects were adjusted or refined to evaluate their suitability to the chosen type of infrastructure. For example, the materials and resources category was refined to incorporate the super-structural elements of bridges. The following are the indicator categories that were developed, their respective definitions and their objectives:

- Project Requirements
    - This category is established to provide a characteristics baseline, drawing upon commonality among the various bridge project types. All credits in this category are mandatory, so as to define the minimum sustainable practices/features of a "green bridge" and emphasize their importance. The category aims to ensure that every project performs an environmental impact assessment, a life cycle cost

analysis and life cycle inventory; moreover, it targets lowering infrastructure development impact.

- Environment and Water
  - This category focusses on the physical aspects of the surroundings of the bridge project that might be adversely affected by it, either directly or indirectly. The category aims to reduce a bridge project's impacts on its surrounding environment and water sources.
- Access and Equity
  - This category focusses on the demands on the road by motor vehicles, bicycles and pedestrians. The category aims to emphasize the importance of safety, accessibility, and road efficiency in terms of design.
- Construction Activities
  - This category focusses on the impacts of the project's execution phase. The category aims to minimize emissions, reduce construction materials waste, and improve the overall construction quality.
- Materials and Resources
  - This category focusses on the allocation of construction materials and the project's demands for resources and energy. The category aims to minimize the consumption of raw materials and reduce energy consumption.
- Potential for Innovations
  - This category is referred to as a "catch all" type and aims at promoting sustainability innovation and influencing projects to go above and beyond

standards. This is common among most of the existing rating systems and is referencing the LEED's rating system structure.

3.3.3 Bridge Sustainability Indicators Development

Once the categories were set, the next step is developing the list of indicators that will essentially become credits. As previously mentioned, the credits in existing infrastructure sustainability rating systems are used to develop the indicators and are adjusted to relate to bridge projects. A cross-reference analysis is carried out among the four rating systems considered in the literature review to determine the commonalities and draft a list of applicable potential credits. Each credit that is chosen is then adjusted and reworded to reflect the development of bridge projects. This method of indicator development is reliable as existing credits already incorporate sustainable implementation frameworks, such as LCA, planning for community energy, material intensity per service unit and material flow analysis, as fundamental inputs (Oswald & McNeil, 2010). This means that each credit will contain at least one aspect of sustainable practice implementation and promotion. Any missing components of a bridge that are not encompassed by the indicators are either included individually under one of the categories or simply may not be included due to the difficulty in developing a measureable indicator for them, for example, the reuse and recycling of major structural components of bridges.

In the development of the indicators, the system is broken down further into sub-categories and activities/work-items. For the sake of organization and programming, an ID system is concurrently developed for the sub-categories. The IDs are developed by combining the initials of every category with a numbering system. The following is an example of the ID codes:

- Project Requirements
    - PR-1 Lifecycle Cost Analysis

- PR-1.1 Perform a Lifecycle Cost Analysis
- PR-1.2 Lifecycle Inventory

– PR-2 Noise Mitigation Plan

- PR-2.1 Use of Noise Barriers
- PR-2.2 Provision of a Buffer Zone

3.3.4 Indicator Measurements

Measurements provide project stakeholders the ability to determine if their projects fulfil each individual credit's objectives/requirements; therefore, each indicator must be measurable in the field. Since the indicators stem from existing rating systems, the methods of some indicators' measurement are adjusted to reflect bridge project development. Many of the indicators' measurements are based on engineering judgment and thus imitate the formats of the existing rating systems' requirements. For example, to acquire the recycled Hot Mix Asphalt credit, one of two conditions must be fulfilled. Either 30% of the amount of Hot Mix Asphalt should be of a recycled source or 50% of the total material structure should be of a recycled source and must be used for the shoulder, subgrade, sub-base and/or the base layers of the road. After the indicators' measurements are developed, the indicators are aggregated and condensed into a total number of 58 sustainable indicators. For further details, the full BrSRS breakdown with the developed sub-categories and indicators list can be found in Appendix E.

3.3.5 Credit Weight Assignment and Point Allocations

Credit weight assignment is performed to establish a priority gauge, which depends on how important the activity/work-item is in contributing to sustainability. This is done by allocating points according to the importance of the credit's objectives; thus, establishing a prioritized weight assignment process. The existing rating systems conducted rigorous studies to develop the priority hierarchy for the credits with respect to sustainability. The results of the research and development process provided empirical data representing each activity's/work-item's overall long-term social, economical, and most importantly, ecological impacts. These results are the premise that influenced the weight assignment of credits in existing rating systems (Soderlun et al., 2008; Anderson & Muench, 2013). For example, one of the studies involved administering a survey distributed to prominent transportation engineers and practitioners in various agencies. Then the Analytic Hierarchy Process (AHP) decision-making model is implemented to determine survey answer consistencies and assign weights based on results. AHP is a model that simplifies complex, unstructured decision-making processes by assigning quantitative variables to subjective and/or qualitative judgments based on their relative importance (Saaty, 1982; Oswald & Mcneil, 2010). Therefore, the existing rating systems' weights assignment are validated and reliable for the use in the synthesis of the BrSRS. Subsequently, because each existing rating system included different, but essentially compatible empirical data and evidence, it is decided that the synthesis of the BrSRS is performed by combining four existing infrastructure sustainability rating systems to strengthem the system's substantiality.

Since the BrSRS credits are essentially an amalgamation of existing rating systems' credits, the same credit weight assignment structure is used with one minimal omission. Each existing system includes a "custom credits" category that acts like bonus achievable points and provide project team members the flexibility of customizing credits to suit their projects (Muench et al., 2012; Anderson & Muench, 2013). Since the model targets bridge projects at their conceptual design stage, the "custom credits" category is viewed as an unnecessary complication as detailed designs and specifications are not required for such a category. The BrSRS point allocation breakdown that is developed for each credit can be found in Appendix E.

3.3.6 Rating Scale Creation

The development of a rating scale is imperative as it is the tool that will classify the different levels of certification and the associated domain of cumulative points that establish the minimum and maximum thresholds for each level. Project team members will refer to this scale to determine which certification they desire to seek for their project and they will aim to design their project with sustainability features that will accumulate enough points within the specified range of the chosen target certification level. Existing rating systems referenced the structure of the rating scale developed by LEED and each mimicked the scale with minor adjustments to fit their own systems' point allocations. LEED has four levels of certification defined, namely, certified, silver, gold, and platinum. The minimum and maximum point thresholds are set based on pre-determined percentages of the total possible cumulative points (Oswald & McNeil, 2010). Taking the Greenroads infrastructure rating system, as an example for comparison, it is found that the system applied the LEED structure and has four levels of certification: bronze, silver, gold, and evergreen. Each level's thresholds are set as follows:

- Bronze: 30% to 40% of the total possible credit points
- Silver: 40% to 50% of the total possible credit points
- Gold: 50 to 60% of the total possible credit points
- Evergreen: 60+% of the total possible credit points (Anderson & Muench, 2013)

To keep the methodology consistent, the same structure is implemented and the BrSRS scale is developed with four levels of certification. Because the established total of possible cumulative points for the system is 100, the minimum and maximum thresholds are left essentially as they are in the existing systems; however, a minor change is implemented. Rather than having the minimum threshold of a certification level the same as the maximum threshold of a previous certification level, the minimum threshold of each certification level after the first is set as follows:

$$\boldsymbol{Minimum\ threshold\ of\ next\ level = Maximum\ threshold\ of\ previous\ level + 1} \quad \textbf{Eq. 2}$$

This is done to remove any ambiguity associated with determining the level of certification a project falls under and to have clearly defined thresholds. Table 3.1 lists the developed BrSRS scale with the four levels of certification and their associated minimum and maximum thresholds domain:

Table 3.1 - BrSRS Levels of Certification and Domains

Certification Level	Points Domain
Certified	30≤ x ≤40
Silver	41≤ x ≤50
Gold	51≤ x ≤60
Evergreen	61≤ x ≤100

3.4 Environmental Performance Strategy Mapping

BrEPSM is an analysis technique that provides visual representation of the ecological footprint of a project or process. The technique is derived from LCA tools and thus follows a similar procedural framework. The steps for performing BrEPSM are as follows:

1. Data collection,
2. Footprint calculations, and
3. Map building.

3.4.1 Data Collection

The first step in building the BrEPSM is gathering the required data for each variable involved in the calculation of the list of footprints regarded by the techniques for environmental impact analysis. The footprints under consideration by the technique are: 1) carbon, 2) water, 3) energy, 4) emissions, and 5) work environment. According to each footprint's definition and method of measurement established by the literature review, the following variables are identified as the required data:

1. Carbon emission rates,
2. Water consumption rates,
3. Water resource availability,
4. Electricity consumption rates,
5. Effluent/emission rates into water, air, and soil,
6. Average worker absence from work due to illness or death, and
7. Average number of workers (per project).

As most of these variables are, in essence, measured and their data is collected over a period of time, it is best to search for such data from a reliable and public source such as Statistics Canada. Data for most of the variables are found on Statistics Canada website (http://www.statcan.gc.ca) where they are available for public download. The cited link is the generic Statistics Canada governmental website, all raw data tables from Statistics Canada is presented in Appendix F. Data for the remaining variables that are not available on Statistics Canada webpage are found on other reliable websites operated by governments or organizations, or in journal papers. Table 3.2 outlines the sources of the acquired data and the data's time period range per variable along with any comments noted regarding the quality of the data.

Table 3.2 – Collected Data Sources and Time Periods Summary

Variable	Source	Years	Comments
Carbon Emission	Statistics Canada (http://www.statcan.gc.ca)	1990-2014	
Water Consumption	Statistics Canada (http://www.statcan.gc.ca)	2005, 2007, 2009, 2011	Measured every 2 years
Water Resource Availability	United Nations (UN) Statistics Division (http://unstats.un.org/UNSD/environment/waterresources.htm)	1997, 2002, 2007, 2012, 2014	Measured every 5 years
Electricity Consumption	Statistics Canada (http://www.statcan.gc.ca)	2010-2014	
Effluent/emission into water, air and soil	Statistics Canada (http://www.statcan.gc.ca) (De Benedetto & Kleme, 2009; Cucek, Klemes & Kravanja, 2012)	2004-2008	
Average Worker Absence from Work Due to Illness or Death	Statistics Canada (http://www.statcan.gc.ca)	2011-2015	
Average Number of Workers	Statistics Canada (http://www.statcan.gc.ca)	2011-2015	

As Table 3.2 illustrates, all variables' data are obtained from reliable sources and the shortest time period of the data was 4 years. Therefore, the overall quality of the data is acceptable for the BrEPSM technique. Because the time periods are extremely dispersed, the data is compiled and inputted in a forecasting model to identify patterns in the data and provide values for future years. However, the lack of time period alignment between the variables is noted as a weakness for the forecasting model. For the purpose of the conceptual design stage, this estimation is acceptable as it will be regarded as a conceptual environmental performance assessment project. Furthermore, the majority of the data is chosen to be presented per province so as to correspond with the structure of the model itself. Data collection is limited to Canada only for the purpose of this module's development and does not include the United States as the model does. This is a decision based on the researcher's main focus and interest in Canada as a target location. All summary tables of the collected data that are utilized for the following step are found in Appendix F.

3.4.2 Footprint Calculation

The BrEPSM technique makes use of footprints as indicators for the analysis of a project's impact on the environment. This is done by integrating the five calculated footprints of the project under analysis into a single indicator and this will allow project team members to compare and analyze multiple project designs concurrently (De Benedetto & Kleme, 2009). The Sustainable Process Index (SPI) is the indicator measurement method that the literature has cited myriad times as the most effective way to compute footprints with relation to a project. The method relates footprint estimation to the required total area in order to provide renewable and non-renewable raw materials, produce energy, installation process needs and products and by-products storage. Therefore, the computed footprint estimations are associated with the area of the proposed project under analysis, so as to establish pertinence to the project's environmental impact and present the value of the indicator as a normalized percentage for ease of comprehension, comparison, and representation (Krotscheck & Narodoslawsky, 1996; Eder & Narodoslawsky, 1999; Ferng, 2005).

3.4.2.1 Footprint Equations

Using the SPI method, the following equations are derived from each footprint's definition and are used by the BrEPSM technique to estimate a project's normalized footprints. The carbon footprint equation estimates the CO_2 emission relative to a project's land area. The estimated footprint is then normalized to as a percentage for comparison and representation in the BrEPSM. The equations are as follows:

$$\mathbf{Carbon\ Footprint} = \mathbf{Project's\ Estimated\ CO_2\ (t) \times CO_2\ Replenishment\ Rate\ (^{m^2}/_{t})} \qquad \textbf{Eq. 3}$$

$$\boldsymbol{Normalized\ Carbon\ footprint} = \left[\frac{\boldsymbol{Carbon\ Footprint\ (m^2)}}{\boldsymbol{Total\ Project\ Area\ (m^2)}}\right] \times \mathbf{100} \qquad \textbf{Eq. 4}$$

The water footprint is essentially the total consumption rate of direct and indirect water used in project activities. The footprint is normalized as a percentage for comparison and representation in the BrEPSM. The equations are as follows:

$$\boldsymbol{Water\ Footprint} = \boldsymbol{Project's\ Water\ Consumption\ Rate\ (t)} \qquad \textbf{Eq. 5}$$

$$\boldsymbol{Normalized\ Water\ Footprint} = \left[\frac{\boldsymbol{Project's\ Water\ Consumption\ Rate\ (t)}}{\boldsymbol{Total\ Water\ Resource\ Available\ (t)}}\right] \times \mathbf{100} \qquad \textbf{Eq. 6}$$

The energy footprint is an estimation of the total electricity consumption rate for various project demand categories relative to the generation of energy rate. Then the footprint is normalized as a percentage for comparison and representation in the BrEPSM. The equations are as follows:

$$\boldsymbol{Energy\ Footprint} = \boldsymbol{Project's\ Electricity\ Consumption\ Rate\ (MJ)} \times \boldsymbol{Electricity\ Replenishment\ Rate\ (^{m^2}/_{MJ})} \qquad \textbf{Eq. 7}$$

$$\boldsymbol{Normalized\ Energy\ Footprint} = \left[\frac{\boldsymbol{Energy\ Footprint\ (m^2)}}{\boldsymbol{Total\ Project\ Area\ (m^2)}}\right] \times \mathbf{100} \qquad \textbf{Eq. 8}$$

The emissions footprint equation consists of the calculation of effluents from the project into the water, soil and air. The water emission calculates the seepage rate of waste into the ground water relative to the replenishment rate of ground water. The air emission calculates the release of air pollution relative to the natural exchange rate of substances between forests and air. The soil emission calculates the contamination of the soil relative to the replenishment rate dictated by the decomposition of biomass. All three emission types are added and related to the total area of the project. Then the total emissions footprint is normalized as a percentage for comparison and representation in the BrEPSM. The equations are as follows:

$$\boldsymbol{Water\ Emission = Project's\ \ Water\ Emission\ (t) \times Water\ Replenishment\ Rate\ ({}^{m^2}/_{t})} \qquad \textbf{Eq. 9}$$

$$\boldsymbol{Air\ Emissions = Project's\ \ Air\ Emissions\ (t) \times Air\ Replenishment\ Rate\ ({}^{m^2}/_{t})} \qquad \textbf{Eq. 10}$$

$$\boldsymbol{Soil\ Emissions = Project's\ \ Soil\ Emissions\ (t) \times Soil\ Replenishment\ Rate\ ({}^{m^2}/_{t})} \qquad \textbf{Eq. 11}$$

$$\boldsymbol{Normalized\ Emissions\ Footprint = \left[\frac{(Water+Air+Soil\ Emissions)\ (m^2)}{Total\ Project\ Area\ (m^2)}\right] \times 100} \qquad \textbf{Eq. 12}$$

The work environment footprint is estimated as a factor of worker absences due to impact categories such as fatal accidents, skin diseases, psycho-social diseases, hearing damage, cancer and musculo-skeletal disorders/injuries. Absences are related to the average number of workers employed for a project and then the footprint is normalized as a percentage for comparison and representation in the BrEPSM.

$$\boldsymbol{Work\ Environment\ Footprint = \frac{Average\ Worker\ Absence\ from\ Work\ (days)}{Average\ Number\ of\ Workers}} \qquad \textbf{Eq. 13}$$

$$\boldsymbol{Normalized\ Work\ Environment\ Footprint = \left[\frac{Work\ Envrionment\ Footprint\ (days\ per\ person)}{National\ Average\ of\ Absence\ Days\ per\ Worker}\right] x\ 100} \qquad \textbf{Eq. 14}$$

3.4.2.2 Equation Constants and Assumptions

Following the case-study example published by De Benedetto and Kleme (2009), there are some variables in the calculation of the footprints that had to be taken as constants or assumed due to the difficulty associated with measuring them. The components of the emissions footprint, the replenishment rates of water, air and soil, and the carbon footprint replenishment rate are computed as per their definitions, but are hard to quantify due to the non-existence of any historical data. However, a detailed literature review reveals that there are pre-calculated constants for the replenishment rates that can be generally assumed rather than having to be calculated individually based on the local setting of the project under analysis (Sandholzer and Narodoslawsky, 2007; De Benedetto & Kleme, 2009). Similarly, the average number of workers for a project can't be determined without collecting years' worth of historical data of the total number of workers ("workers" does not only reflect labor, but includes all individuals that are involved in the project from its conception to its realization) on various bridge projects in Canada. No such database exists and to set up such a database for the conceptual design stage would be an extensive undertaking. It is decided to consult practitioners in order to obtain a number they think may reflected the average from their years of experience on the construction and/or renovation of bridge projects. The following constants and assumed values are used for the calculation of the footprints for building the BrEPSM based on the literature and the experience of engineering practitioners (De Benedetto & Kleme, 2009):

- Water replenishment rate= 1 m^2/t,
- Air replenishment rate= 7634 m^2/t,
- Soil replenishment rate= 2.38 m^2/t,
- Carbon replenishment rate= 2.7 m^2/t, and
- Average number of workers per project= 4000.

3.4.2.3 Forecasting Model

The model is required to have the capabilities to provide the conceptual design of future bridge projects. Thus, it is imperative to run the collected data in a forecasting model to be able to predict future values of the variables involved in the footprint calculations and eventually plot a proposed project's BrEPSM. The linear regression method is chosen because the compiled data is limited, is not too wide spread out and the model is predicting at the conceptual stage; thus, a more complex method, such as polynomial regression, is not required for the purpose of this module. Microsoft Excel has a built-in forecasting capability that implements a linear regression model on a string of known x and y values and predicts a future point on a linear fitted trend line. The model's syntax and equations are shown as equations 15, 16, 17 and 18. The Excel syntax function is depicted by equation 15, where x is the forecasting target year and the known y's and x's are the variables of the collected historical data. The linear regression model Excel implements uses equation 16 to determine the future value of y. Equation 16 represents the linear line trend and requires the values of a y intercept and slope, which are calculated using equations 17 and 18, respectively. Where, x is the known number of years, $\bar{x}$ is the average of the years, y is the recorded data value and $\bar{y}$ is the average of the data points.

$$\boldsymbol{FORECAST(x, known\_y's, known\_x's)} \quad \textbf{Eq. 15}$$

$$\boldsymbol{y = a + bx} \quad \textbf{Eq. 16}$$

$$a = \bar{y} - b\bar{x} \quad \textbf{Eq. 17}$$

$$b = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2} \quad \textbf{Eq. 18}$$

The known x values represent the list of years' data that are recorded in and are the independent array of data points, while the y values represent the actual measurement of the variable being forecasted and are the dependent array of data points. If the variance of the independent array is equal to zero, the model would not be able to compute a value. Fortunately, this problem is never encountered and all predicted values are computed. For the purpose of this research, the prediction length is set to three years into the future, as some of the historical data is not enough to predict any more points beyond that. Thus, the predicted years are 2016, 2017 and 2018 as the latest data is 2015.

3.4.3 Map Building

Once the impact of each footprint is calculated, the BrEPSM can be built. The map consists of graphing the calculated normalized footprints' percentages on a radar graph, also known as a spider-web graph. Plotting the five percentages identifies a meaningful combination as measurements can be compared easily. This facilitates the comparison of different project designs with the graphical representation and can be used as an input to select the optimal design choice. The graph is based on the "deviation-from-target" methodology, which involves setting a maximum percentage limit and expresses the values as the distance between the normalized percentages and the set target. Ultimately, the objective of the plot is to lower the impact of a project's footprints on the environment expressed as the overall indicator's percentages (across all five factors). The maximum target is set to be 50% and is based on scientific consensus and regulatory requirements stated in the literature (De Benedetto & Kleme, 2009).

3.4.4 Sustainable Footprints Reduction

In order to tie-in the BrEPSM module with the BrSRS module, the BrEPSM plot is to include a sustainable bridge plot concurrently with a conventional bridge plot. The initial computed footprints and the BrEPSM that is built depicts the indicators for a conventional bridge as no project sustainable features have been taken into account. To account for the footprint reduction of a sustainable project design, the results of a case study are referenced. The study involved implementing a sustainability rating system on the construction phase of a new project and measured the changes in environmental impact. According to Zou and Moon (2014), implementing the sustainability rating system on the project resulted in the improvement of the overall site's air quality, water consumption, emissions and waste management, energy efficiency, and worker's health and safety, based on the measurement of a set of Key Performance Indicators (KPI). The percentage reductions of the environmental impacts are quite significant and substantial and the case study's results are used for the BrEPSM module to demonstrate the implications of utilizing a BrSRS and designing a sustainable bridge project. Table 3 lists the percentage reductions documented by Zou and Moon's case study and the ones used for plotting the sustainable bridge alternative's BrEPSM (2014):

Table 3.3 - KPI Improved and Footprints Reduction Percentages

KPI	Footprint	Percentage (%)
Air quality	Carbon	52.29
Water consumption	Water	17.56
Emissions and waste management	Emissions	51.74
Energy efficiency	Energy	33.33
Worker's health and safety	Work Environment	33.02

3.5 3D CAD Modeling

To provide the model with BrIM capabilities, it is decided to integrate 3D modeling of the conceptual bridge design with the existing modules. The entire model is coded in Visual Basic and thus it is best to choose a modeling software that is compatible with the coding. After considering multiple options, AutoCAD is the chosen software due to its flexibility, ease of manipulation and quick response to Visual Basic commands due to its open architecture. Furthermore, Autodesk products are currently the predominantly used software by design engineers in the industry. The integration process is established in two steps: 1) creation of bridge type templates and 2) Visual Basic coding to redraw each template with the output of the knowledge-based system.

3.5.1 Bridge Templates

The knowledge-based system has six embedded bridge types integrated via the highway geometric design guidelines and structural codes that the model can recommend, depending on the data input by the user. This is done by the model as it specifies certain restrictions and conditions of each bridge type that must be satisfied, such as the length or width coefficients and then determines which bridge type is applicable for the user's input. The six bridge types users have the option of selecting from are as follows:

1. Arch
2. Beam/Girder
3. Frame
4. Slab
5. Temporary Modular
6. Truss

In order for AutoCAD to model each of these bridges, six template files are created that render each bridge type in 3D. The templates modeled each bridge with their basic features to facilitate easy integration into the model and to coordinate with the limited data output from the knowledge-based system, given that the output and model will reflect the conceptual design of these bridges. Bridges are initially drawn in 2D wire framing from a profile vantage point so as to utilize AutoCAD's solid extrusion and surface creation capabilities. AutoCAD's "PRESSPULL" command can extrude 3D objects from bounded areas and create surfaces from open objects, which allows for the rendering of complex shapes in 3-dimensional visualization. Figures 3.3 and 3.4 exemplify a 2D wireframe profile of a beam/girder initially drawn and then extruded into a solid object with a surface using the "PRESSPULL" command on AutoCAD.

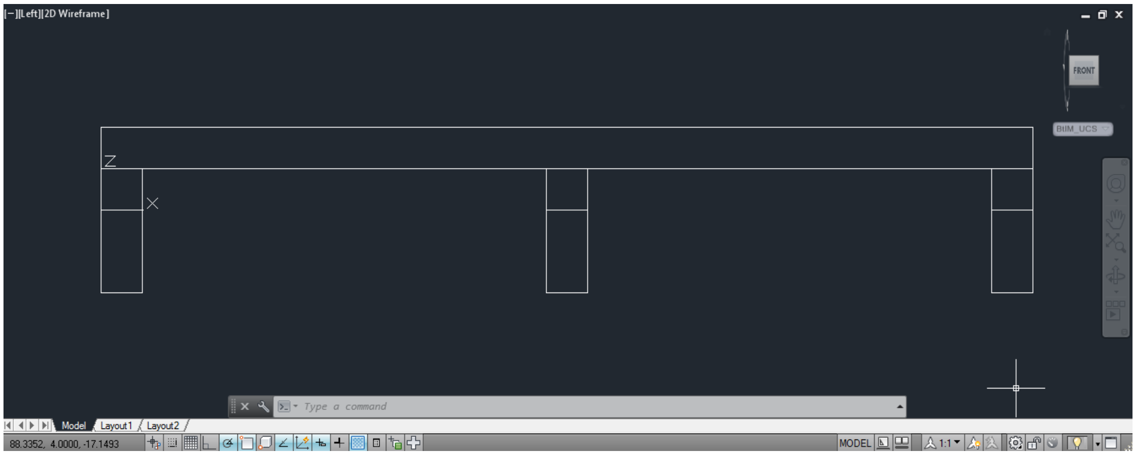


Figure 3.3 - 2D Wireframe Profile of a Beam/Girder Bridge

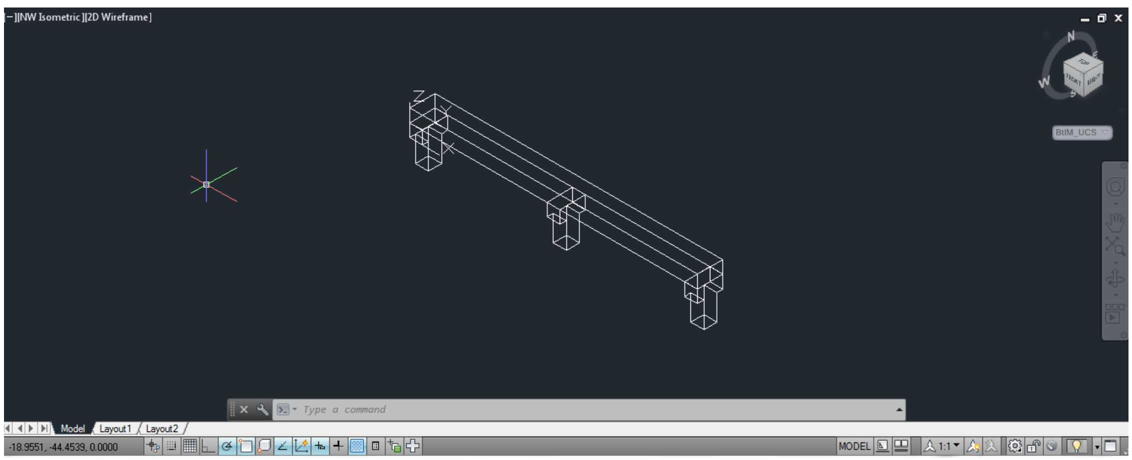


Figure 3.4 - 3D Extruded Wireframe of a Beam/Girder Bridge

3.5.2 AutoCAD Integration

The knowledge-based system processes the input given by the user and outputs rudimental dimensions of the conceptual bridge. These dimensions will be the input for AutoCAD to render the bridge in 3D. The knowledge-based system's bridge dimension output is as follows:

1. Bridge width,
2. Bridge length,
3. Longest span,
4. Bridge's total area, and

5. Parapet width.

The integration process is based on the “Graphics.DrawLine” (GDL) methodology outlined by Microsoft for .NET Framework and Visual Studio. The method uses Visual Basic coding to draw a line between two pointF structures with pre-determined pen-style settings. PointF structures are a pair of floating (x-, y-) coordinates that define points in a 2D plane ("Graphics.DrawLine Method", 2016). Since the six bridge types are already modeled in template AutoCAD files, the method is applied by identifying the pointF structures of each line in the template files and placing them in the Visual Basic script and virtually redrawing the bridge as per the output parameters of the KBS. Figure 3.5 exhibits the exemplary GDL method code snippet:

```
Overloads Public Sub DrawLine( _
   ByVal pen As Pen, _
   ByVal pt1 As Point, _
   ByVal pt2 As Point _
```

Figure 3.5 - Graphic.DrawLine Method Code Snippet

Where, ‘Pen’ determines the color, width and line-type, ‘pt1’ is the first point structure to connect and ‘pt2’ is the second point structure to connect. To adjust the dimension of the line between the two points, a modification is added to the code to obtain the dimension from a specified text box of the knowledge-based system’s output and to use it as the distance between the two points and this specifies the length parameter of each line object part of the overall bridge 3D rendering. Figure 3.6 is an exemplary Visual Basic code snippet that establishes a connection for communication between Visual Studio (the model) and AutoCAD drawings:

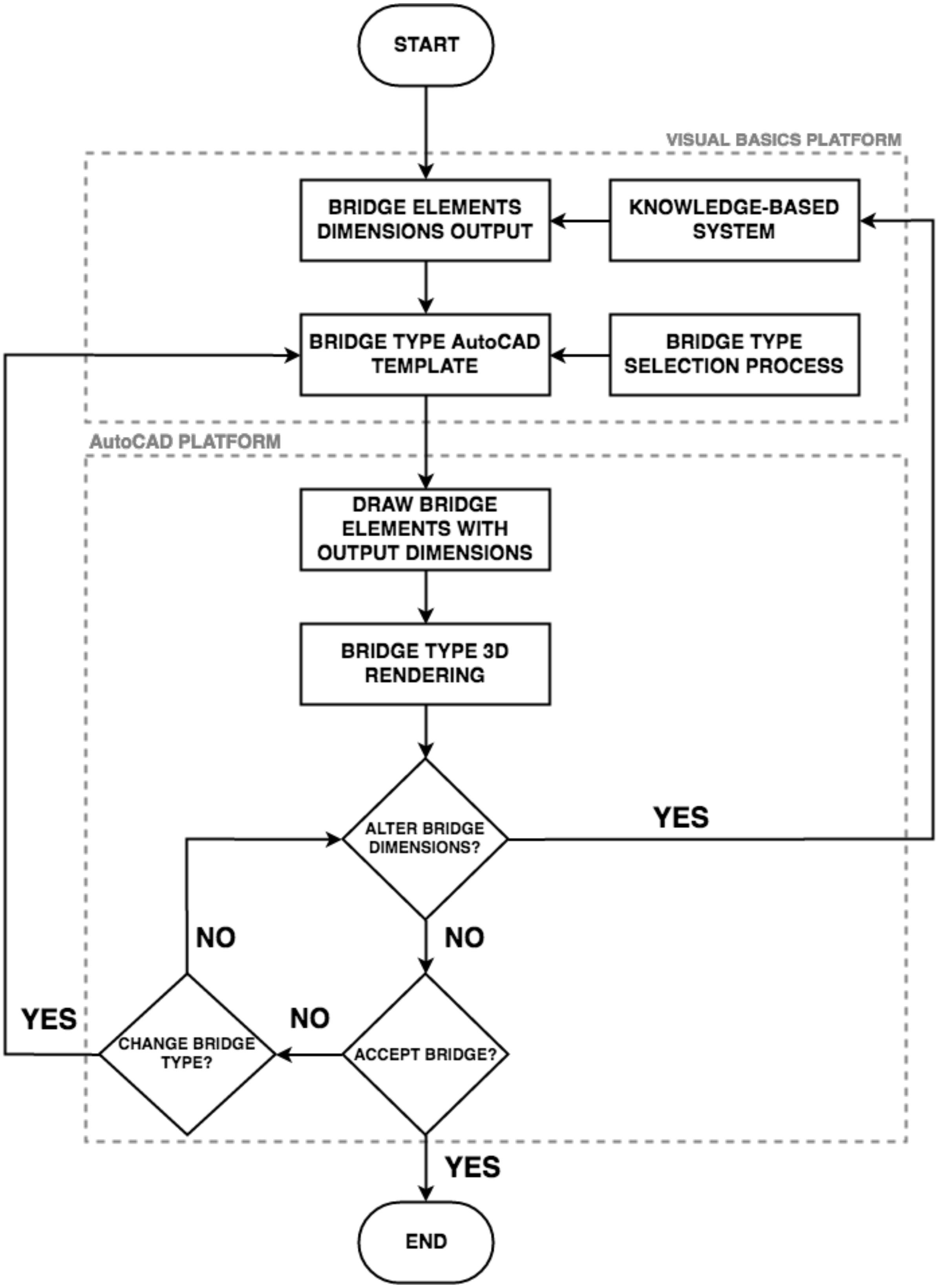
```
Imports Autodesk.AutoCAD.Interop.AcadDocumentClass
Imports Autodesk.AutoCAD.Interop.Common

Public Class Form1
    Public vAcadApp As Autodesk.AutoCAD.Interop.AcadApplication
    Public vAcadDoc As Autodesk.AutoCAD.Interop.AcadDocuments


    Private Sub Form1_Load(sender As System.Object, e As System.EventArgs) Handles MyBase.Load
        vAcadApp = New Autodesk.AutoCAD.Interop.AcadApplication
        vAcadApp.Visible = True
    End Sub
End Class
```

Figure 3.6 - Communication Connection between Visual Studio and AutoCAD Code Snippet

This code is modified to allow Visual Studio to receive as well as send information from and to AutoCAD. Essentially, this is to create a two-way communication channel between the model and AutoCAD for rapid information exchange so that the model is able to receive any values from modifications users implement on the 3D model of the conceptual bridge in AutoCAD and reiterate the design based on the visual modifications. This process of information retrieval from AutoCAD is complex; thus, only the bridge length is the only parameter that is retrieved. This simplifies the process and is additionally due to the bridge length being the primary parameter for the reiteration calculation process by the model. Therefore, the data flow between the model's knowledge-based system and AutoCAD is developed following an easy, straightforward sequence to establish a user-friendly platform. Figure 3.7 illustrates the 3D modeling data flow logic.



igure 3.7 - Data Flow between the Model and AutoCAD

3.6 Summary

This chapter covered the methodology that will be followed in the creation and integration of 3 modules that are added to the pre-existing model, namely, 1) a BrSRS, 2) an BrEPSM, and 3) 3D CAD modeling. The BrSRS followed a seven-step process to create sustainable rating system, as outlined by Bossel (1999) and Oswald and McNeil (2010). Creating a sustainability rating system dedicated to bridge projects involved the consideration of the various components that comprise a bridge as these types of projects are part structural part infrastructure. Various existing infrastructure sustainability rating systems were studied and used in the synthesis of the BrSRS. Credits were adjusted to align with the elements and needs of bridge projects. Similarly, the BrEPSM is a technique that can be used to evaluate the environmental impact of an engineering design by utilizing footprints as indicators. Data was gathered from credible sources, such as Statistics Canada, to establish a historical database that can be used to forecast footprints of construction projects. The BrEPSM ultimately presents the users with the environmental impacts of both a conventional and sustainable bridge project in the visual form of a radar graph for comparison.

The 3D modeling module followed the GDL methodology that uses Visual Basic coding to command AutoCAD to draw objects and ultimately redraw the 3D rendering of each bridge type. To expedite the exchange of information between the model and AutoCAD, the six bridge types in the knowledge-based system were drawn in AutoCAD as template files to identify the coordinates and length parameter of each line object for the GDL method. The dimensions output by the knowledge-based system are used as the input for AutoCAD to draw the bridges from the templates to scale.

Chapter Four

Model Development

4.1 Introduction

The proposed modules are researched in depth to further enhance the model's capabilities and the methodology of implementation is outlined. Improving the model consisted of the additional integration of the BrSRS, the BrEPSM and AutoCAD modules, which is conducted in three main phases of development. The modules are each developed and integrated separately due to their differing purposes. Moreover, the outlined logical sequence of the model's flowchart in the methodology section dictated the developmental steps and integration location within the model. The synthesis of the BrSRS was presented in the methodology chapter and its development covers its presentation and the parameters of how users can use the module. The BrEPSM compiled database and formulas are developed in the model to carry out the calculation process autonomously. The 3D CAD bridge type's templates are integrated to communicate with the knowledge-based system. All modules integration is accomplished using VB.NET coding on the Visual Studios interface.

4.2 BrSRS Module Integration

As outlined in the methodology section, the BrSRS was produced by synthesizing a new system from existing systems and redefining credits to suit bridge projects. The finalized BrSRS contains 6 indicator categories, 22 indicator sub-categories and a total of 58 activities/work-items that represent the actual credits. Therefore, the rating system has a hierarchy consisting of three tiers. The module's representation is required to display the following information for users: 1) the hierarchy, 2) the description of each credit, 3) the conditions/restrictions of each credit, and 4) the allocated points of each credit. Moreover, the module has to give users the ability to select the credits they wish to incorporate in their bridge's design as well as a tally that accumulates the points of the selected credits and indicates the certification level. Figures 4.1, 4.2 and 4.3 illustrates the chosen representation of the BrSRS module in the model's interface.

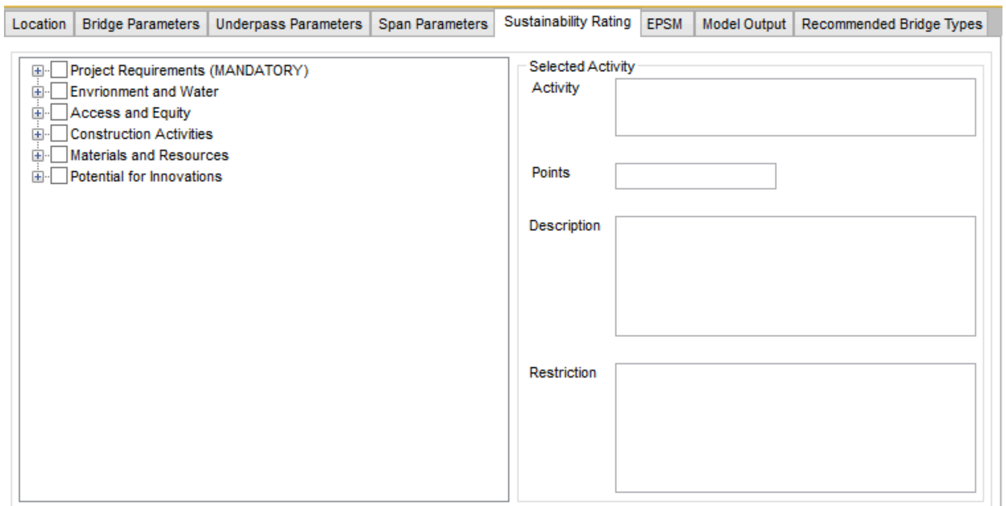


Figure 4.1 - BrSRS Module Information Representation

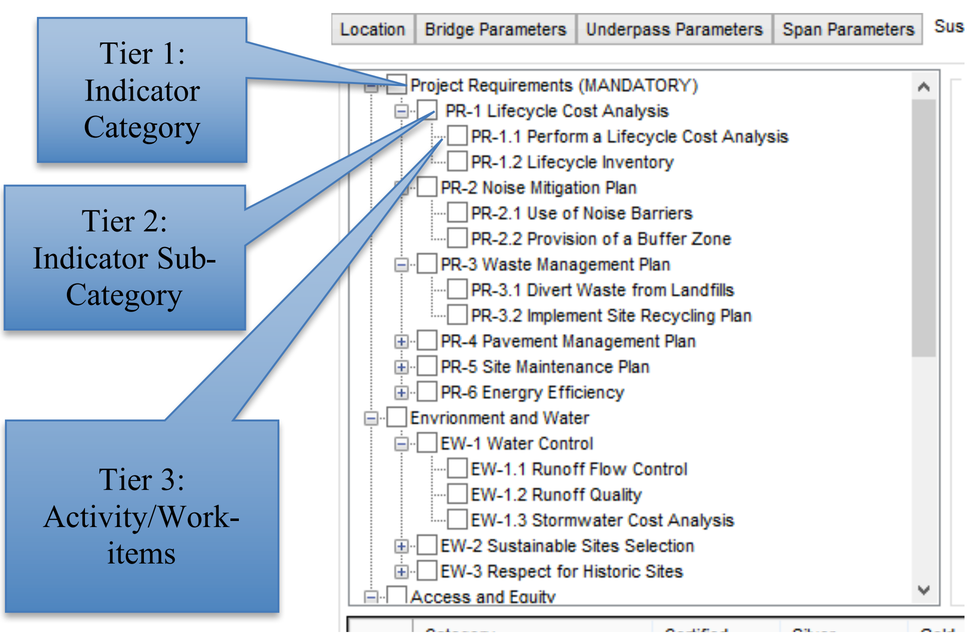


Figure 4.2 - Expanded Hierarchy Tiers

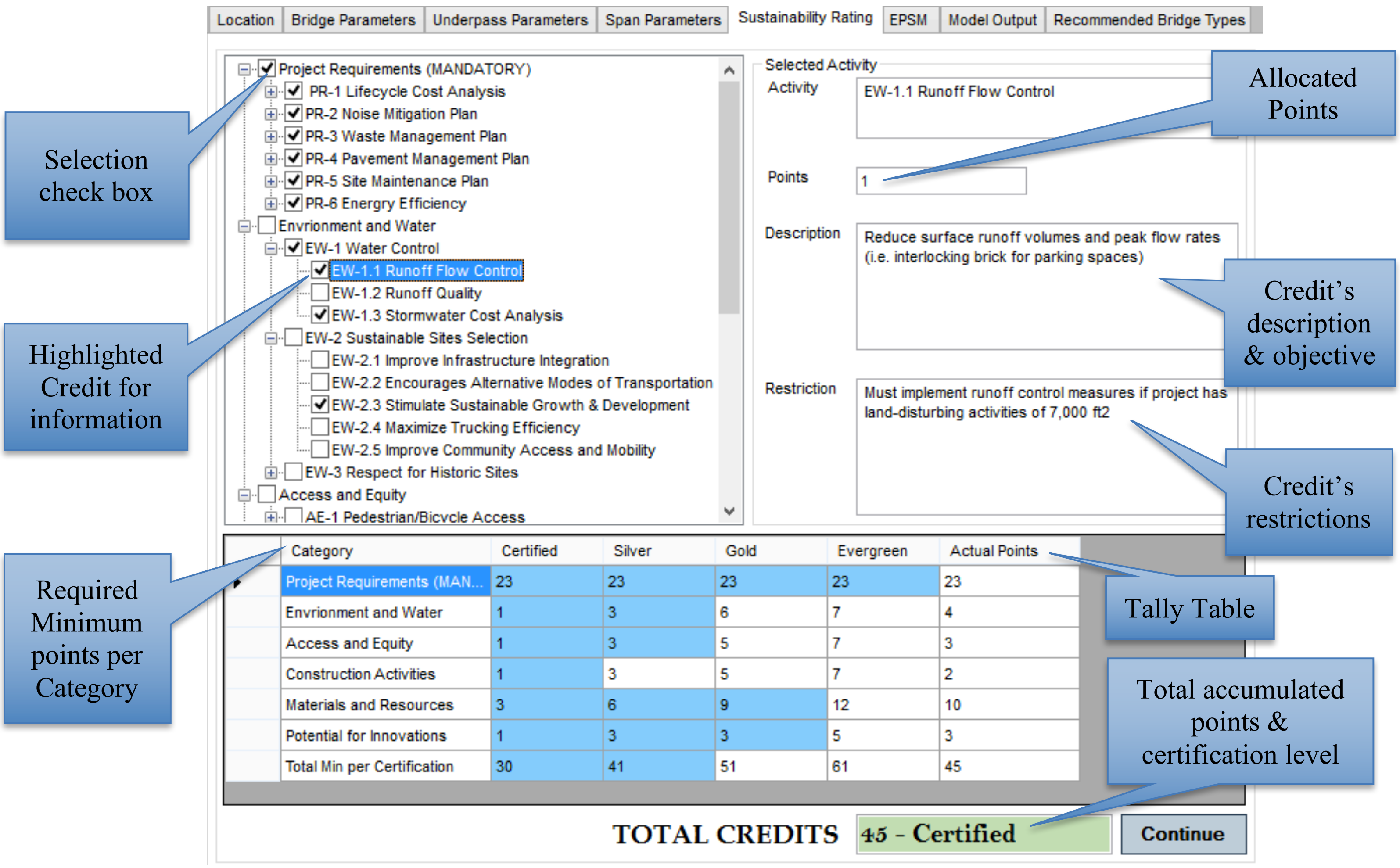


Figure 4.3 - BrSRS Information Display, Tally Table, and Certification Level

The BrSRS is the fifth step in the model's process after the user has finished entering the input data required by the knowledge-based system, but before the system displays its output and recommends bridge types. This is to motivate users to consider looking at sustainable bridge design options. A tree diagram is chosen to represent the three tiers of the BrSRS as it gives users the ability to expand and collapse the different levels freely. To select and accumulate points, simple check boxes are placed next to every single indicator category, sub-category and activity/work-item. By clicking on the higher level, all options contained within that main branch are automatically selected. Similarly, users can select credits individually by clicking the check boxes directly associated with the desired credit (as illustrated in Figure 4.3). Each credit aims to achieve an objective and has conditions that must be fulfilled. This information is vital so that users can fully understand each credit's requirements and how each one aims to contribute towards the overall sustainability of the bridge project. Credits can be highlighted, and text boxes designated to the right of the BrSRS's tree diagram display the allocated points for the highlighted credit, its objective and restrictions (as illustrated in Figure 4.3). Figure 4.4 displays the sample code establishing the tree diagram and associating each credit's description and restrictions.

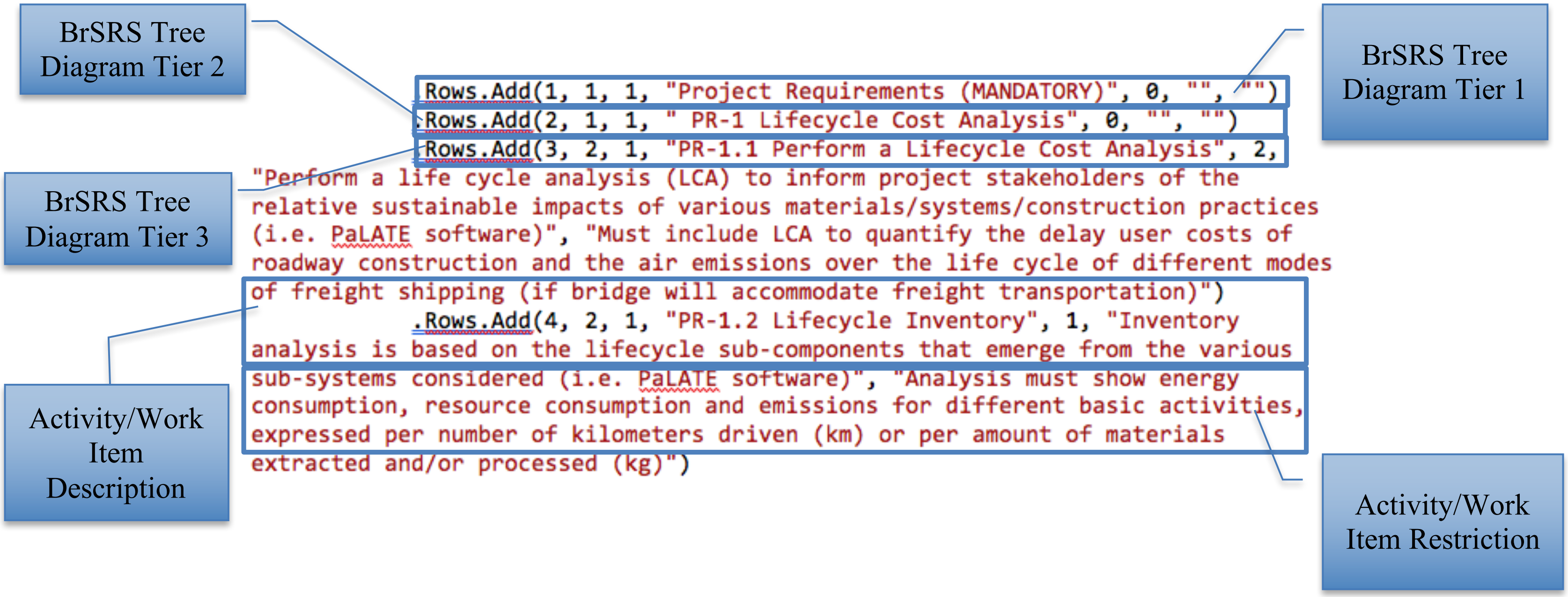


Figure 4.4 - BrSRS Tree Diagram Sample Code

The established certification levels have established a minimum threshold of points that need to be accumulated in order to be achieved. However, there are minimum thresholds set for every indicator category per certification level. Anticipating that users will not be aware of the minimum thresholds, a tally table is included to display the minimum threshold for each indicator category per certification level. As users select the sustainability credit they wish to include in their bridge's design, the table will highlight the thresholds they have surpassed in blue indicating the certification level they have achieved or how many points remain per category in order to achieve the level they desire. As illustrated in Figure 4.3, the selected options amount to a total of 45 points but have only achieved the certified level, even though the minimum point threshold for the certified level is 31 points. This is because the minimum credit threshold of the Construction Activities category required one more point to be satisfied. Thus, users can use the tally table to their advantage by optimally choosing credits that award them enough points to achieve their desired certification level.

4.3 BrEPSM Module Integration

The development of the BrEPSM model encompassed three steps: 1) compiling a database, 2) forecasting future values using a linear regression model, and 3) listing the equations required to calculate the normalized footprints' percentages. To integrate the module with the rest of the model, the implementation process includes integrating the database, embedding the footprint equations into the module and instructing the module to plot the results on a radar graph. The equations of the footprints are straightforward and not complex; thus, they are embedded directly in the VB.NET code, rather than setting up an Excel spreadsheet, to enable the module to produce results quickly. Figures 4.5, 4.6 and 4.7 illustrate samples of the code embedding the database and equations in the model.

Column definition

```
'.Columns.Add("Prov", GetType(String))
'.Columns.Add("Year", GetType(Integer))
'.Columns.Add("F1", GetType(Double))
'.Columns.Add("F2", GetType(Double))
'.Columns.Add("F3", GetType(Double))
'.Columns.Add("F4", GetType(Double))
'.Columns.Add("F5", GetType(Double))
'.Columns.Add("F6", GetType(Double))
'.Columns.Add("F7", GetType(Double))
```

Row definition

Figure 4.5 - BrEPSM Database Column Definition Sample Code

```
'.Rows.Add("AB", 2016, 337800, 16131, 61860, 74500, 20440, 8.52)
'.Rows.Add("AB", 2017, 344500, 16131, 62070, 73500, 21020, 8.44)
'.Rows.Add("AB", 2018, 351200, 16131, 62280, 72600, 21400, 8.36)
'.Rows.Add("BC", 2016, 225300, 8619, 56600, 74500, 41040, 8.52)
'.Rows.Add("BC", 2017, 227300, 8619, 56890, 73500, 42560, 8.44)
'.Rows.Add("BC", 2018, 229300, 8619, 57180, 72600, 41210, 8.36)
'.Rows.Add("MB", 2016, 74200, 7206, 36680, 74500, 18900, 8.52)
'.Rows.Add("MB", 2017, 7500, 7206, 37160, 73500, 18900, 8.44)
'.Rows.Add("MB", 2018, 75900, 7206, 37640, 72600, 18900, 8.36)
```

Figure 4.6 - BREPSM Database Row Definition and Data Points Sample Code

```
'Carbon Footprint
'(((F1*2.7)/Area)*100
'F6 -(F6 * 0.5229)

'Energy Footprint
'((F2*F3)/Area)*100
'F7 -(F7 * 0.3333)
```

Figure 4.7 - BrEPSM Normalized Footprint Equations Sample Code

A spreadsheet is defined within the model that includes the forecasted values produced from the linear regression model. The columns are first defined with short references for the variables in the equations. The references are as follows:

- F1 = Carbon emission rates,
- F2 = Water consumption rates,
- F3 = Water resource availability,
- F4 = Electricity consumption rates,
- F5 = Effluent/emission rates into water, air and soil, and
- F6 = Average worker absence from work due to illness or death.

Defining the rows included listing the forecasted data points for each variable per province per future year (as illustrated in Figure 4.6). Once the database was properly defined, the code listed the equations and the instructions of how to carry out the normalized calculations for each footprint (as illustrated in Figure 4.7). The model performs all the calculations in the background and presents the normalized percentage results in the form of a summary table as well as the plotted radar graph. In order for the module to initiate the calculation process, users must select the province and year in which they plan on constructing their bridge project. The province is automatically entered from the knowledge-based location input, so the redundancy of users inputting the location is eliminated. The years are listed in a dropdown menu and once users select the year the model computes the percentages and generates the results and graph. Results for both a conventional and sustainable bridge are displayed simultaneously for comparison. Figures 4.8 and 4.9 illustrate the BrEPSM module implementation.

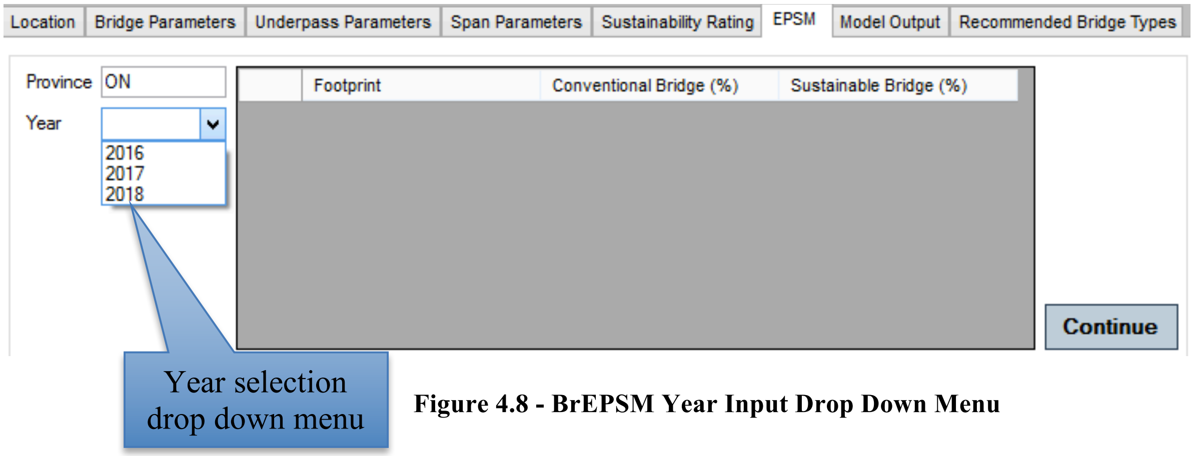
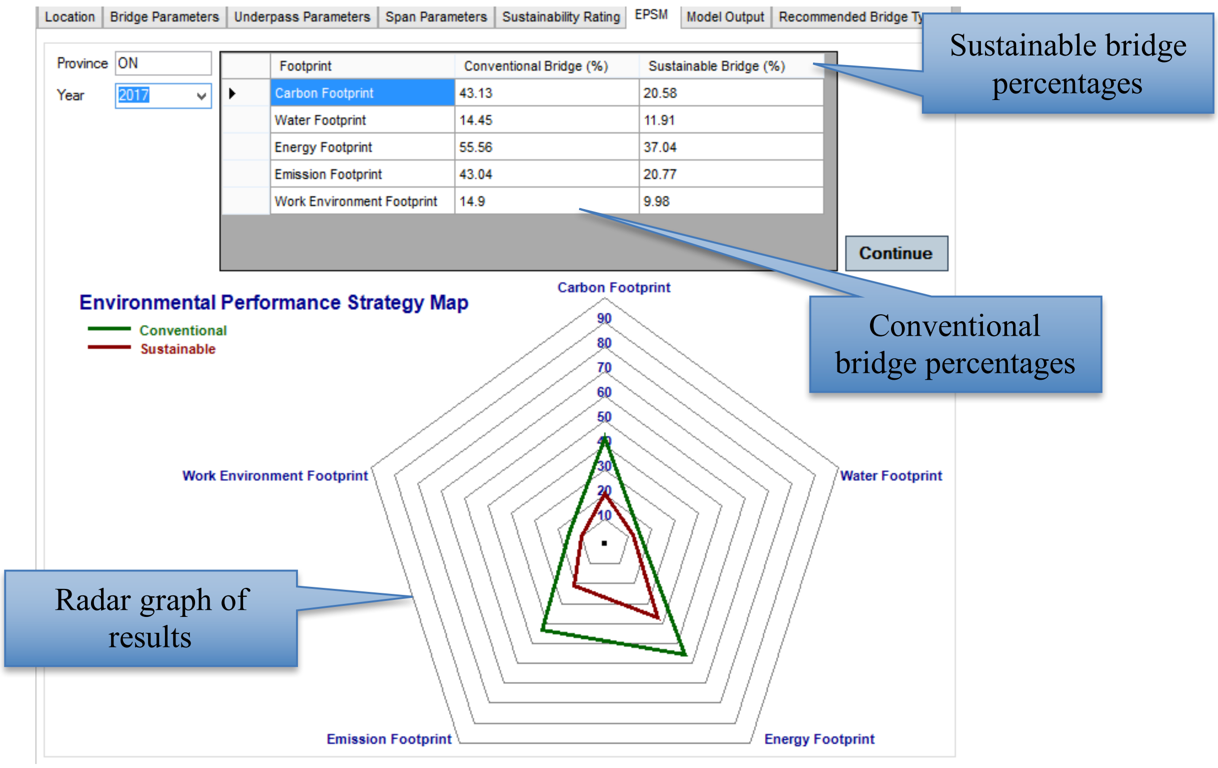


Figure 4.8 - BrEPSM Year Input Drop Down Menu



	Footprint	Conventional Bridge (%)	Sustainable Bridge (%)
	Carbon Footprint	43.13	20.58
	Water Footprint	14.45	11.91
	Energy Footprint	55.56	37.04
	Emission Footprint	43.04	20.77
	Work Environment Footprint	14.9	9.98

Figure 4.9 - BrEPSM Generated Results

4.4 3D CAD Module Integration

The 3D CAD module requires two inputs: 1) the output from the knowledge-based system to draw the conceptual bridge to scale and 2) the selected bridge type to open the corresponding AutoCAD template file. The module is placed as the penultimate step of the model's process in order for users to visualize their conceptual design bridge before generating the conceptual cost estimates. Dimensions are displayed in the model's output step as users get to review the results before continuing to the bridge selection step. Figure 4.10 exhibits the dimension results of the knowledge-based system that AutoCAD utilizes to draw the bridge to scale.

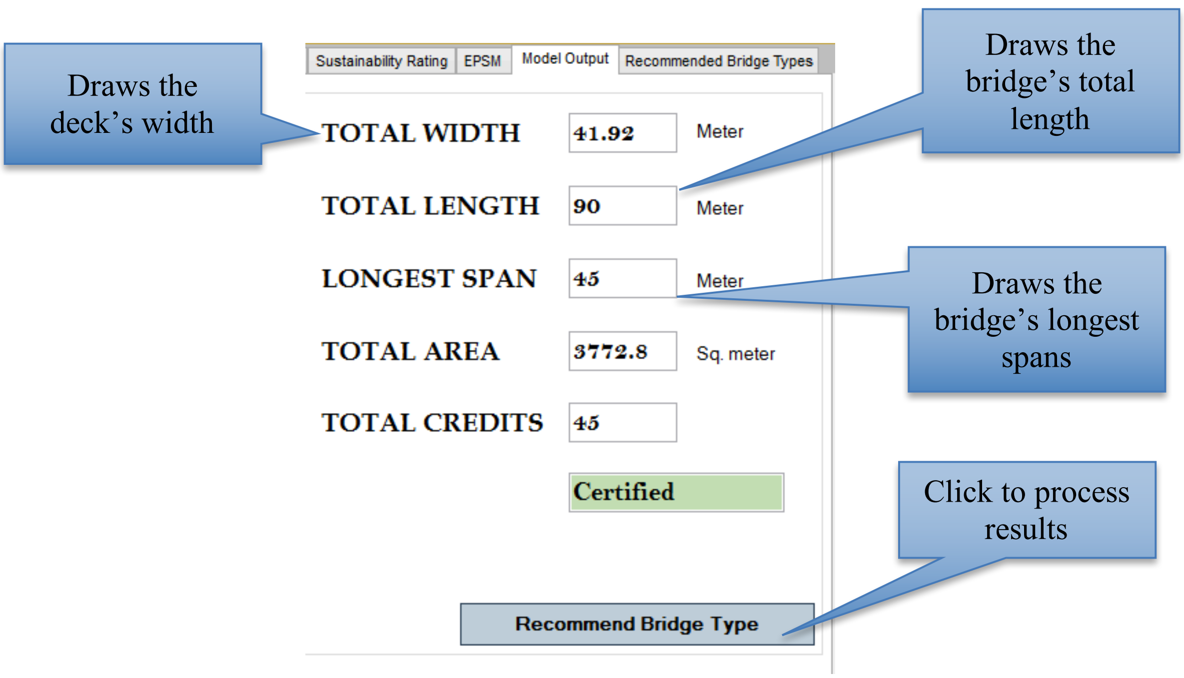


Figure 4.10 - AutoCAD Dimensions Input from the Knowledge-Based System's Output

When users confirm the results, they can click on the recommend bridge type button for the model to process the results through the algorithmic knowledge-base and determine which bridge types fit the input data and criteria. A list of recommended bridge types is generated and users have the options of selecting the recommended bridge type, sub-category, material type, and span type before launching AutoCAD to model the conceptual bridge in 3D. AutoCAD opens the template file associated with the selected bridge type and draws it to scale. Users can alter the dimensions of the bridge freely and then go back to the model to select the "Length Take-Off" options, which allows the model to retrieve the changed dimensions from AutoCAD and place it as the new input for the knowledge-based system in the second step of the model's process. This triggers the calculation reiteration for a new bridge design. Figures 4.11, 4.12, and 4.13 illustrate the 3D CAD module implementation.

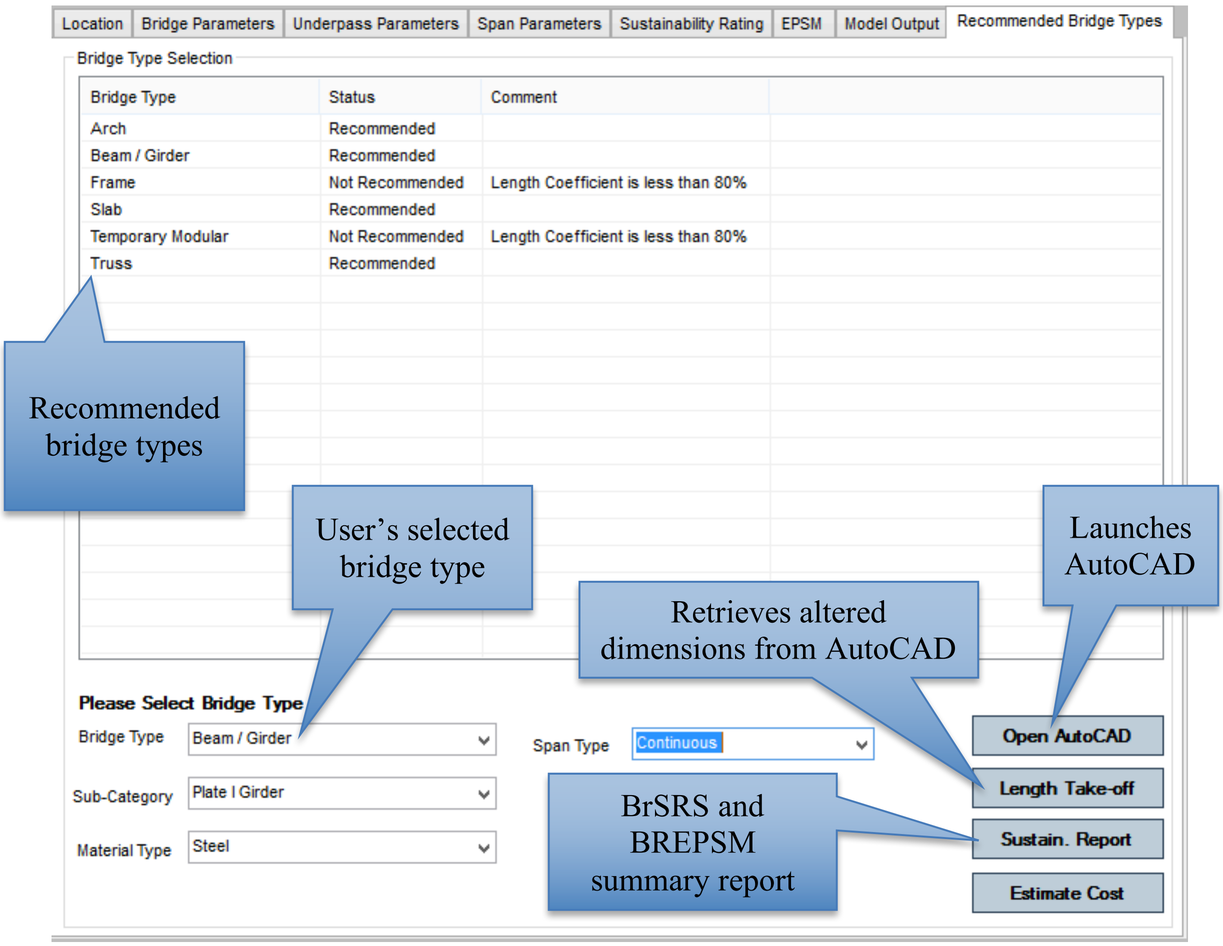


Figure 4.11 - Bridge Type Selection, AutoCAD Launch and Length Take-Off Options

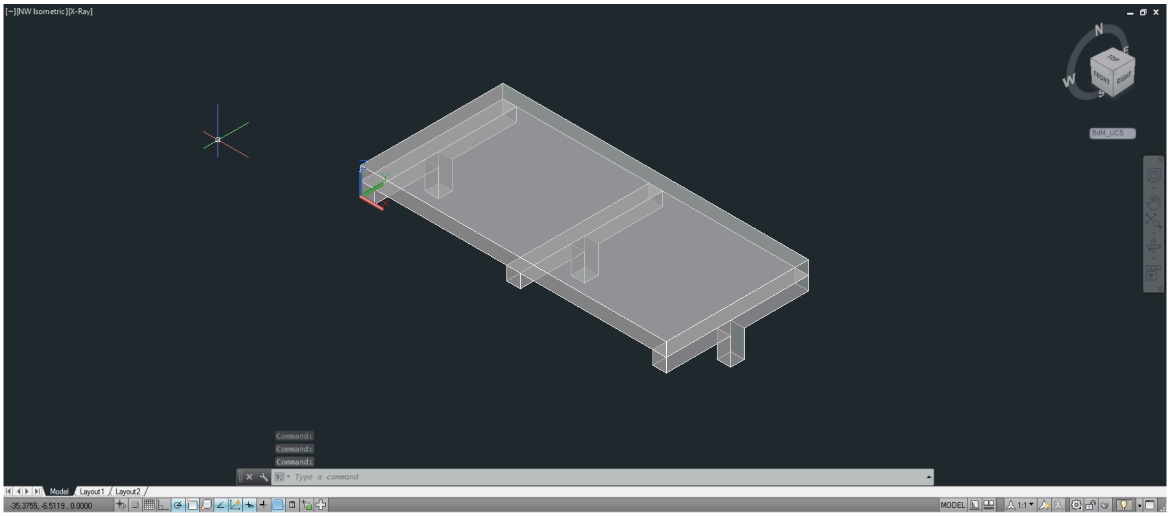


Figure 4.12 - 3D Model of Selected Bridge Type (Beam/Girder)

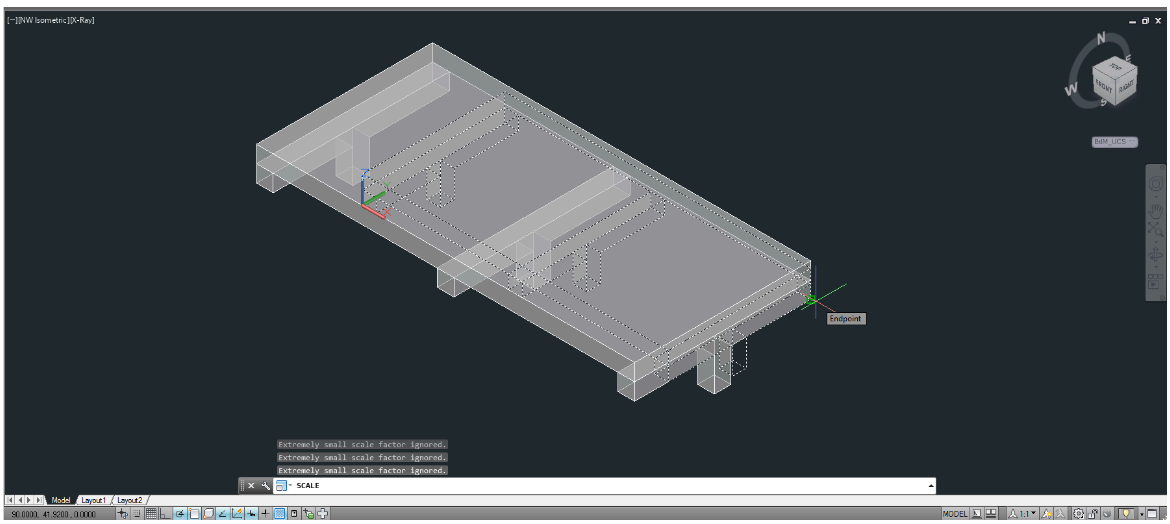


Figure 4.13 - Bridge Dimension Alteration

Before users can go through the final step of the model, which is the conceptual cost estimation module, they can select to see a sustainability report. The report lists all the sustainable features they selected in the BrSRS and the results of the BrEPSM for a final review. Figure 4.14 illustrates the sustainability report implementation.

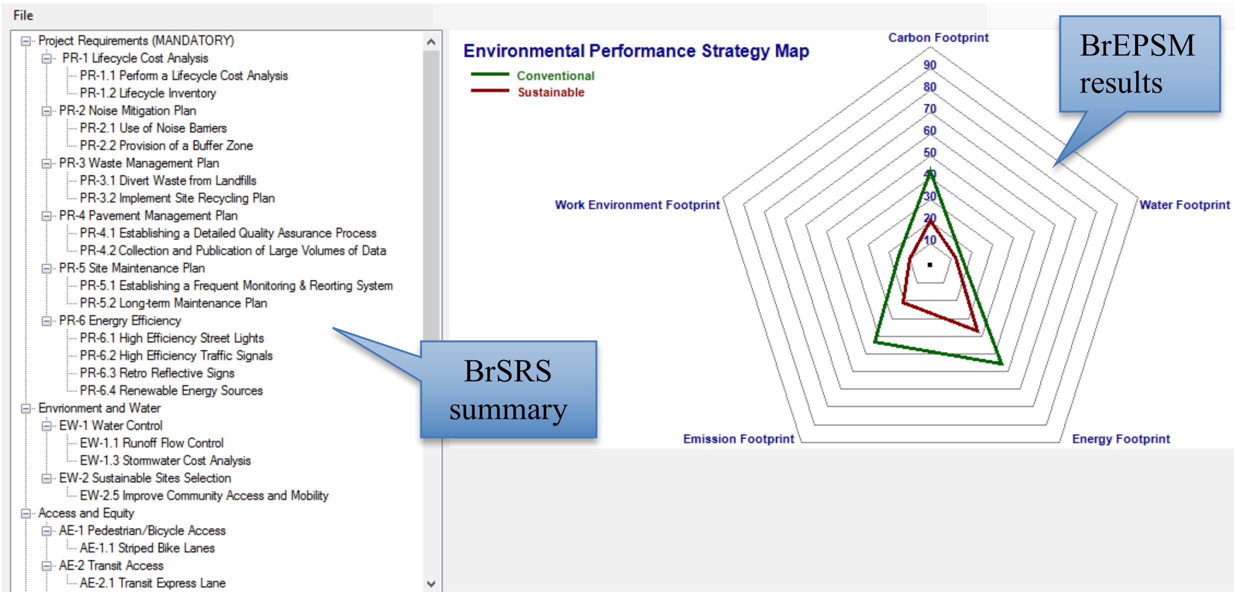
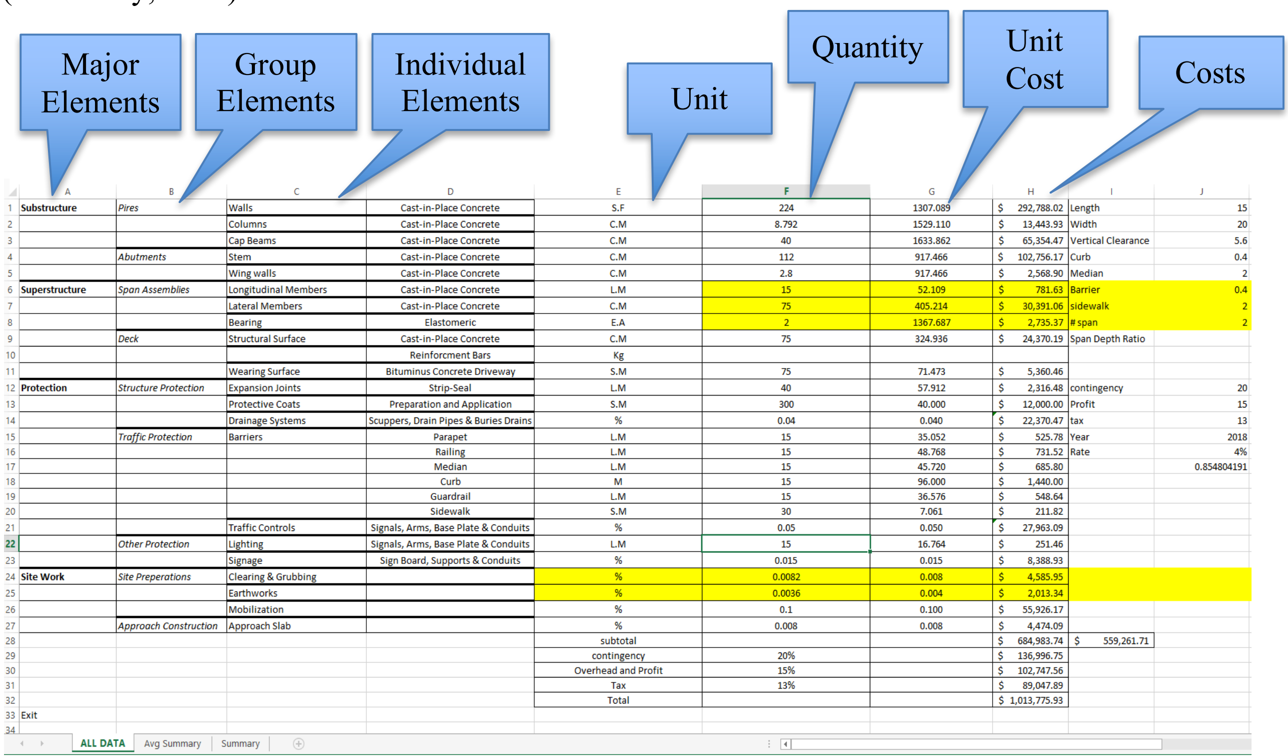


Figure 4.14 - Sustainability Report

4.5 Conceptual Cost Estimate Module Integration

The initial development of the model encompassed the knowledge-based system and a conceptual cost estimating module. The cost estimating module uses the output values of the knowledge-based system as input to generate the costs of the bridge project. This is accomplished by a developed Excel spreadsheet for each bridge type that imports the knowledge-based output for the cost calculation. The Excel spreadsheet is based on collected cost data of previously constructed bridge projects since no published cost data is available and is created in accordance with ASTM UNIFORMAT II standards. The resources of the collected cost data are from various constructed bridges across North America. Figures 4.15 exhibits the formatted cost estimating Excel spreadsheets (Al-Dosary, 2014). The module is integrated in the model's VB.NET interface and presents users a form to input required data for the Excel spreadsheet to compute the conceptual cost estimation. The required data inputs are the bridge's column system type, the abutment type, the tax percentage of the province, the year the project's construction is to commence and the estimations of the contractor's contingency, profit and overhead percentages as shown in Figure

4.16. Once the required data is input, the data is transferred to the Excel spreadsheet and cost adjustments for location and inflation are applied. Then the results are sent back to the module and displayed in three cost estimation report forms: a detailed conceptual cost estimation report, a conceptual cost estimate by project elements report, and a summary conceptual cost estimate report (Al-Dosary, 2014).



	A	B	C	D	E	F	G	H	I	J
1	**Substructure**	*Pires*	Walls	Cast-in-Place Concrete	S.F	224	1307.089	$ 292,788.02	Length	15
2			Columns	Cast-in-Place Concrete	C.M	8.792	1529.110	$ 13,443.93	Width	20
3			Cap Beams	Cast-in-Place Concrete	C.M	40	1633.862	$ 65,354.47	Vertical Clearance	5.6
4		*Abutments*	Stem	Cast-in-Place Concrete	C.M	112	917.466	$ 102,756.17	Curb	0.4
5			Wing walls	Cast-in-Place Concrete	C.M	2.8	917.466	$ 2,568.90	Median	2
6	**Superstructure**	*Span Assemblies*	Longitudinal Members	Cast-in-Place Concrete	L.M	15	52.109	$ 781.63	Barrier	0.4
7			Lateral Members	Cast-in-Place Concrete	C.M	75	405.214	$ 30,391.06	sidewalk	2
8			Bearing	Elastomeric	E.A	2	1367.687	$ 2,735.37	# span	2
9		*Deck*	Structural Surface	Cast-in-Place Concrete	C.M	75	324.936	$ 24,370.19	Span Depth Ratio	
10				Reinforcment Bars	Kg					
11			Wearing Surface	Bituminus Concrete Driveway	S.M	75	71.473	$ 5,360.46		
12	**Protection**	*Structure Protection*	Expansion Joints	Strip-Seal	L.M	40	57.912	$ 2,316.48	contingency	20
13			Protective Coats	Preparation and Application	S.M	300	40.000	$ 12,000.00	Profit	15
14			Drainage Systems	Scuppers, Drain Pipes & Buries Drains	%	0.04	0.040	$ 22,370.47	tax	13
15		*Traffic Protection*	Barriers	Parapet	L.M	15	35.052	$ 525.78	Year	2018
16				Railing	L.M	15	48.768	$ 731.52	Rate	4%
17				Median	L.M	15	45.720	$ 685.80		0.854804191
18				Curb	M	15	96.000	$ 1,440.00		
19				Guardrail	L.M	15	36.576	$ 548.64		
20				Sidewalk	S.M	30	7.061	$ 211.82		
21			Traffic Controls	Signals, Arms, Base Plate & Conduits	%	0.05	0.050	$ 27,963.09		
22		*Other Protection*	Lighting	Signals, Arms, Base Plate & Conduits	L.M	15	16.764	$ 251.46		
23			Signage	Sign Board, Supports & Conduits	%	0.015	0.015	$ 8,388.93		
24	**Site Work**	*Site Preperations*	Clearing & Grubbing		%	0.0082	0.008	$ 4,585.95		
25			Earthworks		%	0.0036	0.004	$ 2,013.34		
26			Mobilization		%	0.1	0.100	$ 55,926.17		
27		*Approach Construction*	Approach Slab		%	0.008	0.008	$ 4,474.09		
28					subtotal			$ 684,983.74	$ 559,261.71	
29					contingency	20%		$ 136,996.75		
30					Overhead and Profit	15%		$ 102,747.56		
31					Tax	13%		$ 89,047.89		
32					Total			$ 1,013,775.93		
33	Exit									
34										

ALL DATA | Avg Summary | Summary

Figure 4.15 - Conceptual Cost Estimating Module Excel Spreadsheet

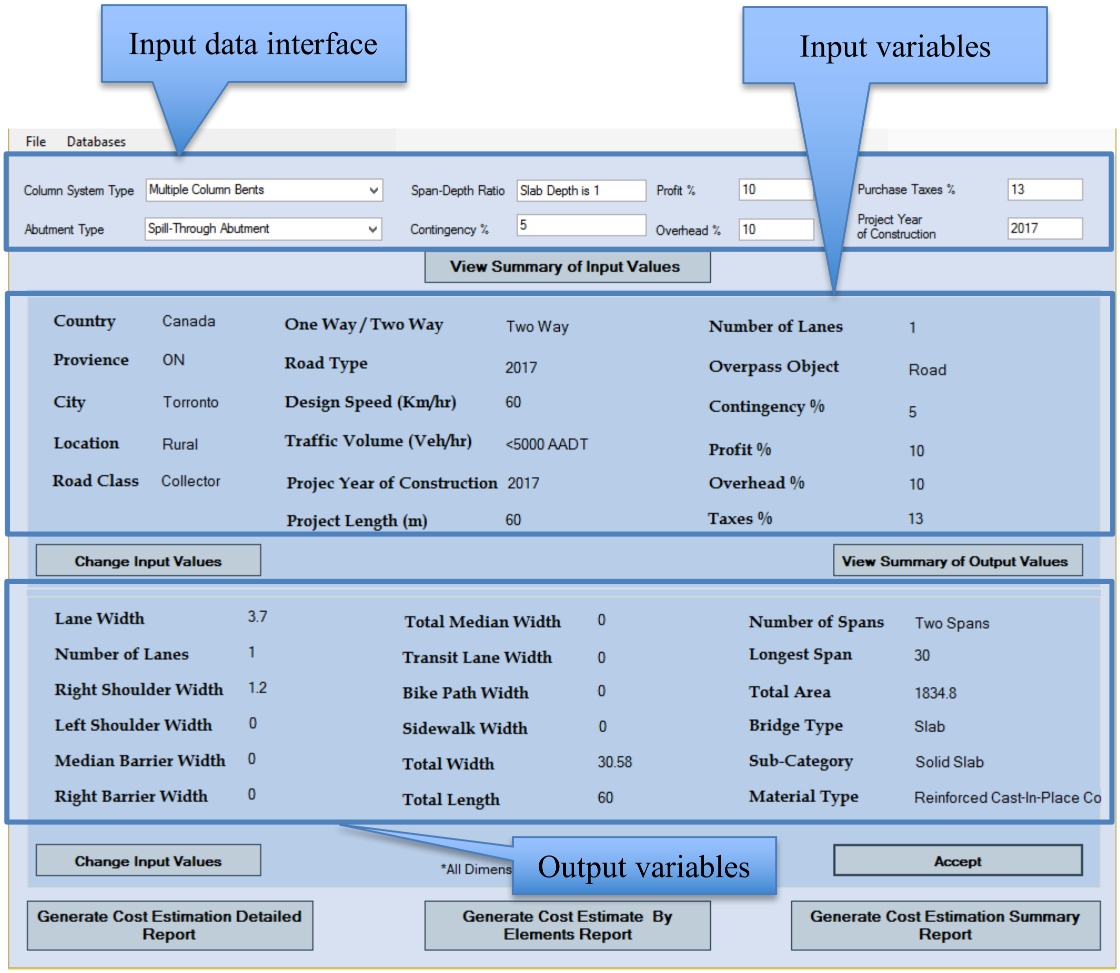


Figure 4.16 - Conceptual Cost Estimating Module Interface

4.6 Summary

This chapter covered the model's development and how the three new modules (BrSRS, BrEPSM, and 3D CAD) were coded via VB.NET and integrated with the previously developed Conceptual Cost Estimating module in the model. The BrSRS is presented as a tree diagram to display the different tiers of the system and to allow the user to have complete control, expanding and collapsing the levels as they desire. A tally table was included to identify the minimum point thresholds per certification level so that users can keep track of their accumulated points. The BrEPSM module has its forecasted data embedded along with the normalized footprint equations. Calculations are run in the background once users select the year and the results are tabulated and plotted on the radar graph. The 3D CAD module is accessible once a bridge type is selected and the dimensions are drawn from the knowledge-based system's output. Users can alter the 3D bridge in AutoCAD and have the model retrieve the length change to trigger a design recalculation. Before obtaining the conceptual cost estimates, users can review the sustainability options selected from the BrSRS and the BrEPSM results in the optional sustainability report summary.

Chapter Five

Model Validation

5.1 Introduction

This chapter aims to test the developed model's overall capabilities with an emphasis on the three new modules. Two of the modules propose sustainable bridge project designs; however, there is a lack of documentation for any existent sustainable bridge project that was designed and rated by an infrastructure rating sustainability system. Consequently, it is difficult to validate the model's results since there is no data to compare the results to it. In light of this fact, the purpose of the validation in this thesis is to test the workability of the model in terms of the input, the generated output, and the resultant analysis. An existing conventional bridge project is selected and simulated through the model to provide an alternate design where the bridge is sustainable. The selected bridge is the Lakeshore Drive Bridge located in Ontario. Bridge projects are governmental projects and thus their information is confidential and difficult to acquire; thus, this bridge was selected because conceptual data was available. The bridge information that is entered into the model is presented in Table 5.1 and pictures of the bridge are shown in Figures 5.1, 5.2, and 5.3.

Table 5.1 - Lakeshore Drive Bridge Project Information

Project Parameters	Model Input Data
Country	Canada
Province	Ontario
City	Toronto
Location	Rural
Road Class	Undivided
Design Speed	60 Km/h
Length	60 meters
Number of Spans	2
Number of Lanes Per Direction	1
Direction	Two way
Underpass Object	Roadway
Underpass Road Class	Highway
Underpass Number of Lane/Direction	2
Underpass Direction	Two Way
Underpass Median Width	8 meters
Underpass Road Barrier Type	No Barrier
Column System Type	Multiple Braced Pier Column
Abutment Type	Spill-through Abutment
Special Lanes	None

Figure 5.1 - Lakeshore Drive Bridge Arial View (Google Earth™)

Figure 5.2 - Lakeshore Drive Bridge Deck View (Google Earth™)

Figure 5.3 - Lakeshore Drive Bridge Side View with Highway ON-11 Underpass (Google Earth™)

The validation process followed the model's steps sequence, which is as follows:

1. Location: project's location data input,
2. Bridge parameters: project's characteristics input,
3. Underpass parameters: underpass type selection and characteristics input,
4. Span parameters: bridge span selection,
5. Sustainability Rating (BrSRS): selecting sustainable bridge design features,

6. BrEPSM: project's environmental impact assessment,
7. Model output: dimensions generated by the knowledge-based system,
8. Recommended bridge types: bridge type selection,
9. 3D CAD modeling: rendering the selected bridge type as a conceptual model, and
10. Conceptual cost estimation: generating the bridge project's conceptual cost estimate.

5.2 Location

The first step is to enter the location information of the project into the knowledge-based system. This involves selecting the country, province, city, location, road class, road direction, road type, design speed and traffic volume from the drop-down menus. Each menu's options will be customized automatically depending on the selected options in the fields before it. Figure 5.4 illustrates the data entry for the first step.

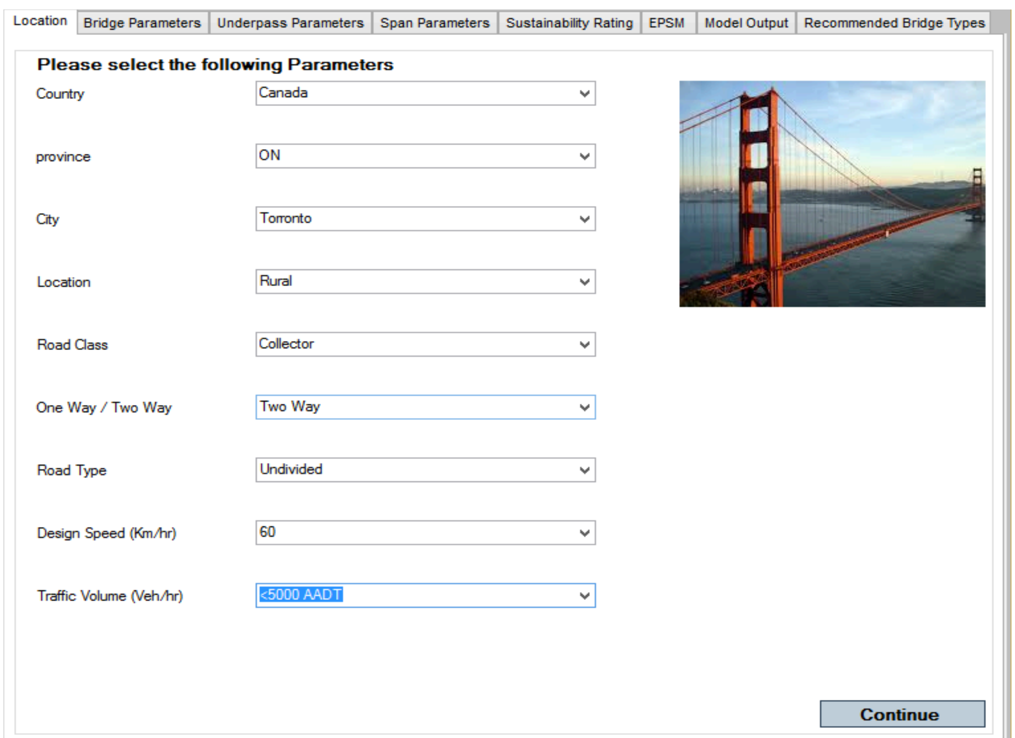


Figure 5.4 – Entry of Location Variables

5.3 Bridge Parameters

The second step is to enter the bridge parameters required by the knowledge-based system to define their traits, which will be used to determine which guidelines and code criteria are satisfied. This includes entering the project's length, the number of lanes per direction, and specifying if the bridge has special lanes (bike, pedestrian or transit). Corresponding to the information for the Lakeshore Bridge, the project length is set to 60 meters, the number of lanes per direction is one and there are no special lanes. Figure 5.5 illustrates the data input for this step.

Figure 5.5 - Bridge Parameters Data Entry

5.4 Underpass Parameters

The third step is to identify if the underpass is a road or waterway and then input the parameters concerned with the underpass type. Following the selected project's information, the underpass is set as a road and the entered data includes the underpass' road class, direction, road type, number of lanes per direction, median width and barrier type. Figure 5.6 illustrates the information that was input for the underpass.

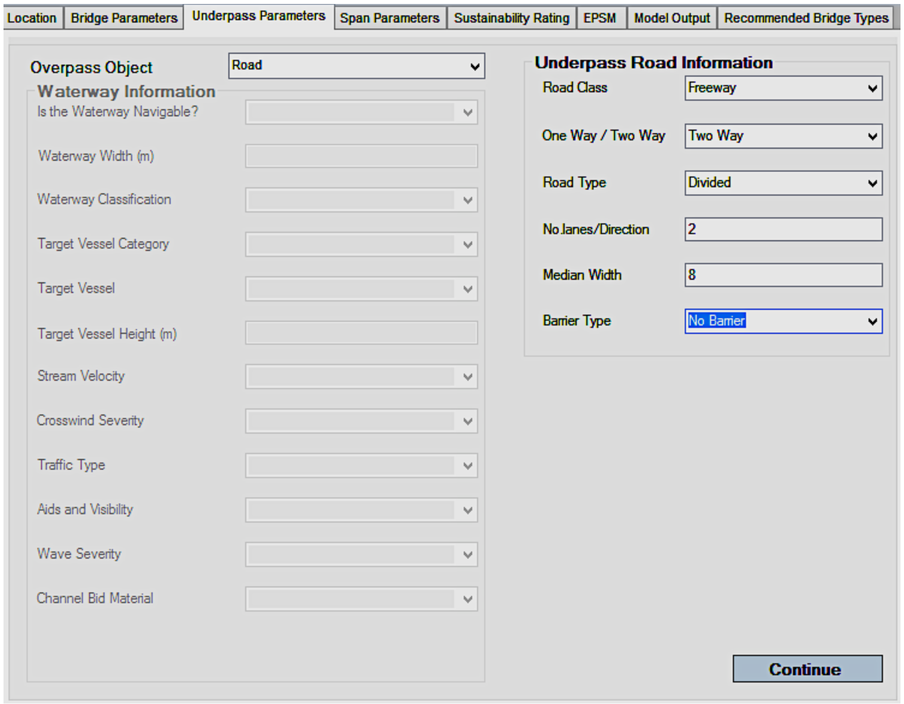


Figure 5.6 - Underpass Information Entry

5.5 Span Parameters

The fourth step is to select the number of spans and the model will suggest the span arrangement that the project should have. In this instance, the selected number of spans is two, corresponding to the actual project's information. The model proposes to make each of the two spans an equal length of 30 meters. The model then inquires if the user wants to design a sustainable bridge or a conventional bridge. Figure 5.7 illustrates the span parameter selection, suggested span arrangement and the sustainability modules trigger question.

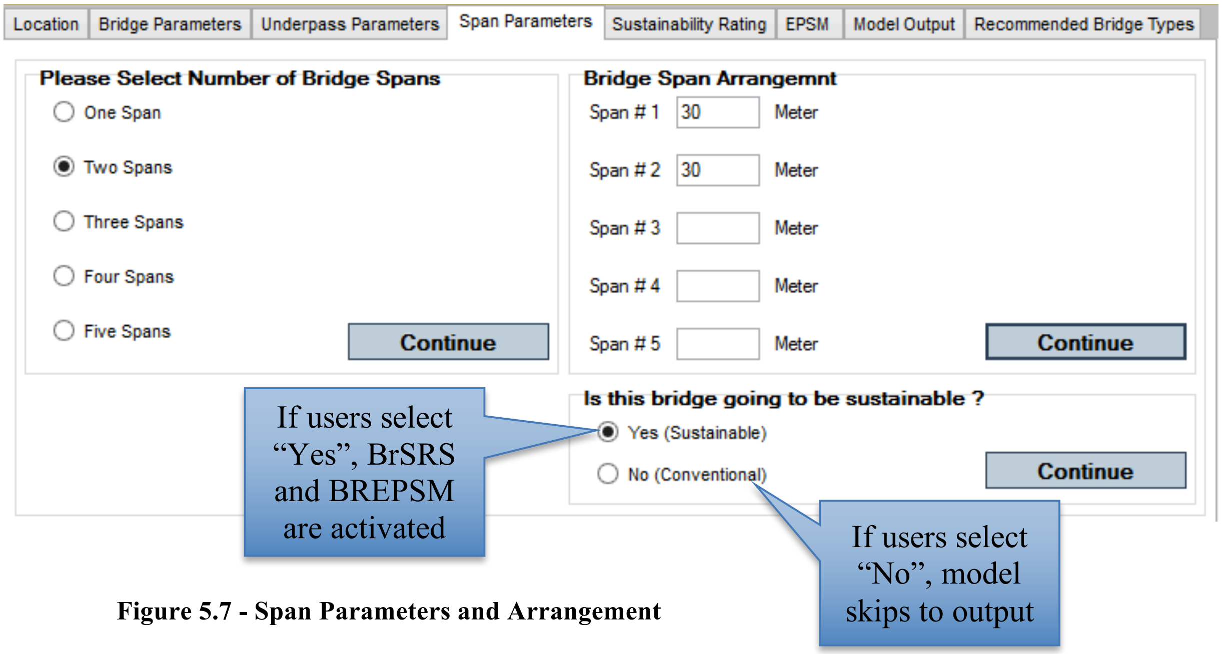


Figure 5.7 - Span Parameters and Arrangement

5.6 Sustainability Rating (BrSRS)

The fifth step is the BrSRS module, which is only activated if users indicate in the previous question that they want to design a sustainable bridge. This step is to provide insight on an alternative sustainable bridge design for the Lakeshore Drive Bridge. The sustainable activities/work-items selected from the list in the BrSRS were selected on the basis that the desired certification level is the first one. The accumulated points satisfied the minimum threshold indicating that a bridge project with the selected sustainable features is considered to be certified as a green bridge. Figure 5.8 illustrates the selected sustainable design options and the BrSRS certification level.

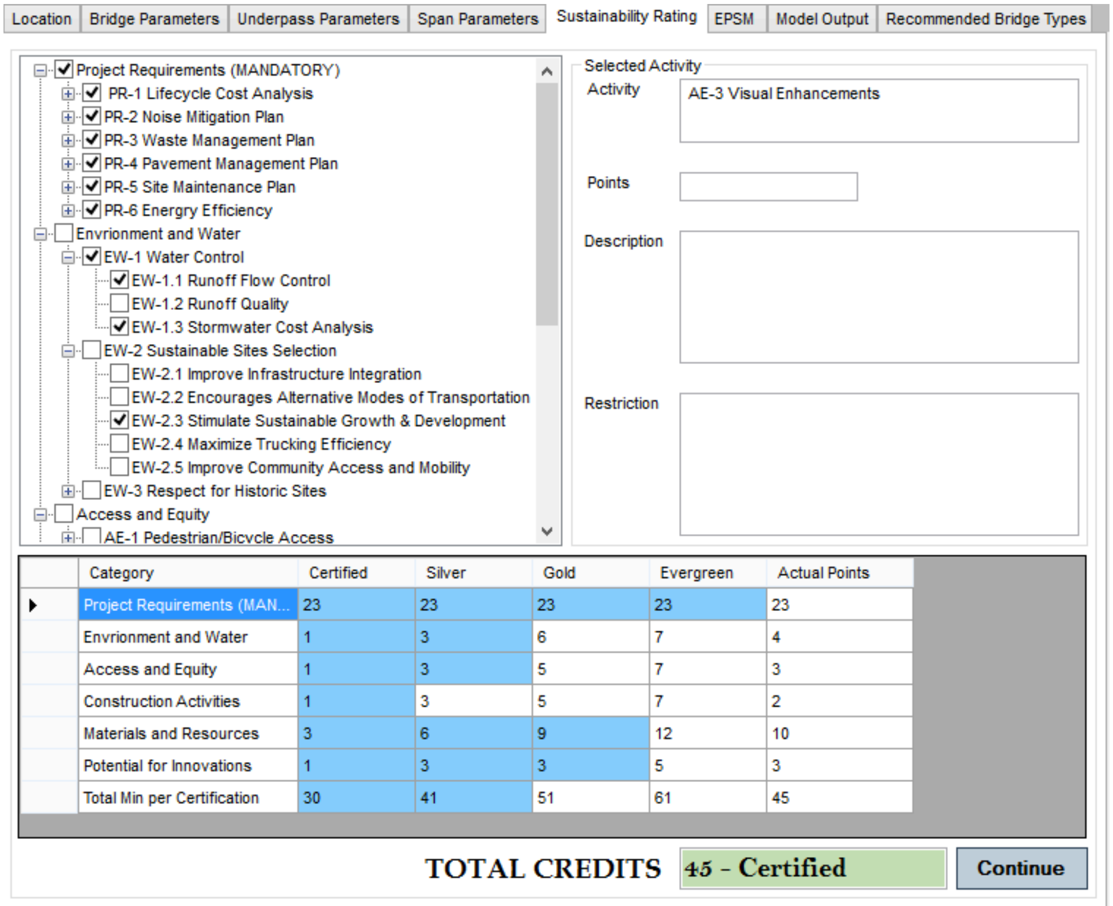


Figure 5.8 - Sustainable Bridge Design Using the BrSRS Module

5.7 BrEPSM

The sixth step is the environmental impact assessment that is carried out by the BrEPSM technique. The province selection is automatically set from the location step and for the sake of the validation, the project was assumed to be constructed in the year 2017. The module displays the results summary table for both scenarios if the bridge were conventional or sustainable for comparison. Significant reductions are noted in terms of the carbon, energy, and emission footprints. Figure 5.9 illustrates the BrEPSM module results.

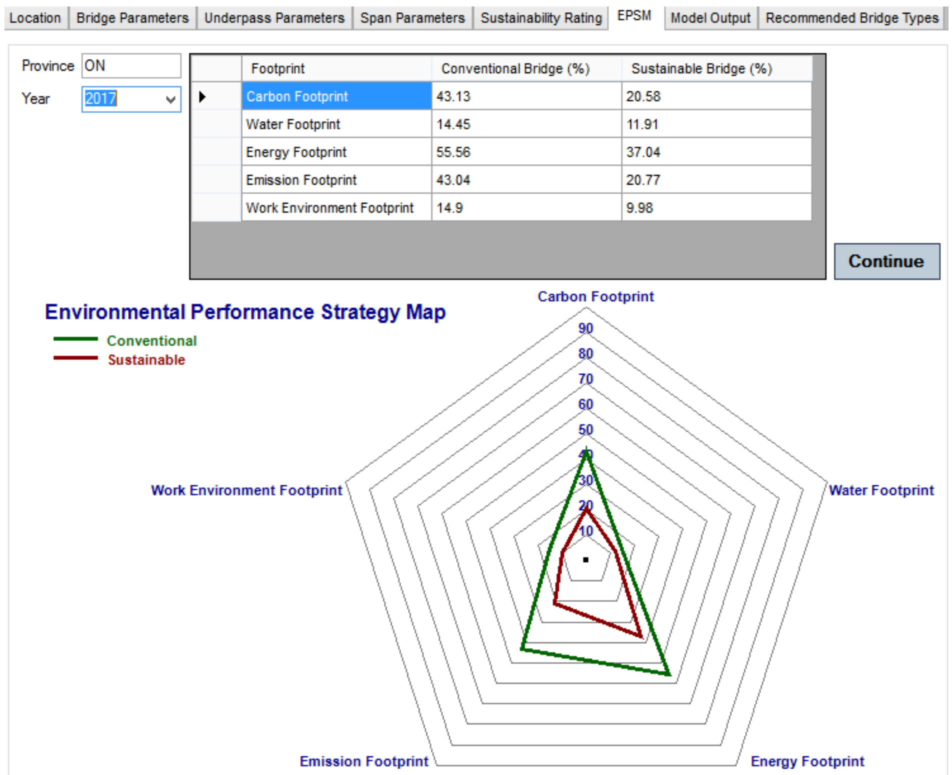


Figure 5.9 - BrEPSM Results for the Conceptual Sustainable Lakeshore Drive Bridge

The BrEPSM results table in Figure 5.9 illustrates the environmental impact across the 5 indicator footprints between a conventional and sustainable bridge. A conventional bridge is constructed using traditional construction methods and materials; however, a sustainable bridge is constructed using environmental impact reducing construction methods and materials. It is salient that the sustainable bridge has significant reductions as the CF is reduced by 22.55%, the WF is reduced by 2.54%, the ENF is reduced by 18.52%, the EMF is reduced by 22.27% and the WEF is reduced by 4.92%.

5.8 Model Output

The seventh step is to obtain and review the output of the knowledge-based system. The model's detailed output includes the lane width, right and shoulder width, the special lane width, and parapet width; however, this bridge did not have any special lane and thus the model output would display zero for that parameter. Similarly, the model's output summary includes the bridge's total width, total length, longest span, total area and the total BrSRS credits and certification level. Figure 5.10 illustrates the knowledge-based system's output based on the input information that corresponds to the Lakeshore Drive Bridge.

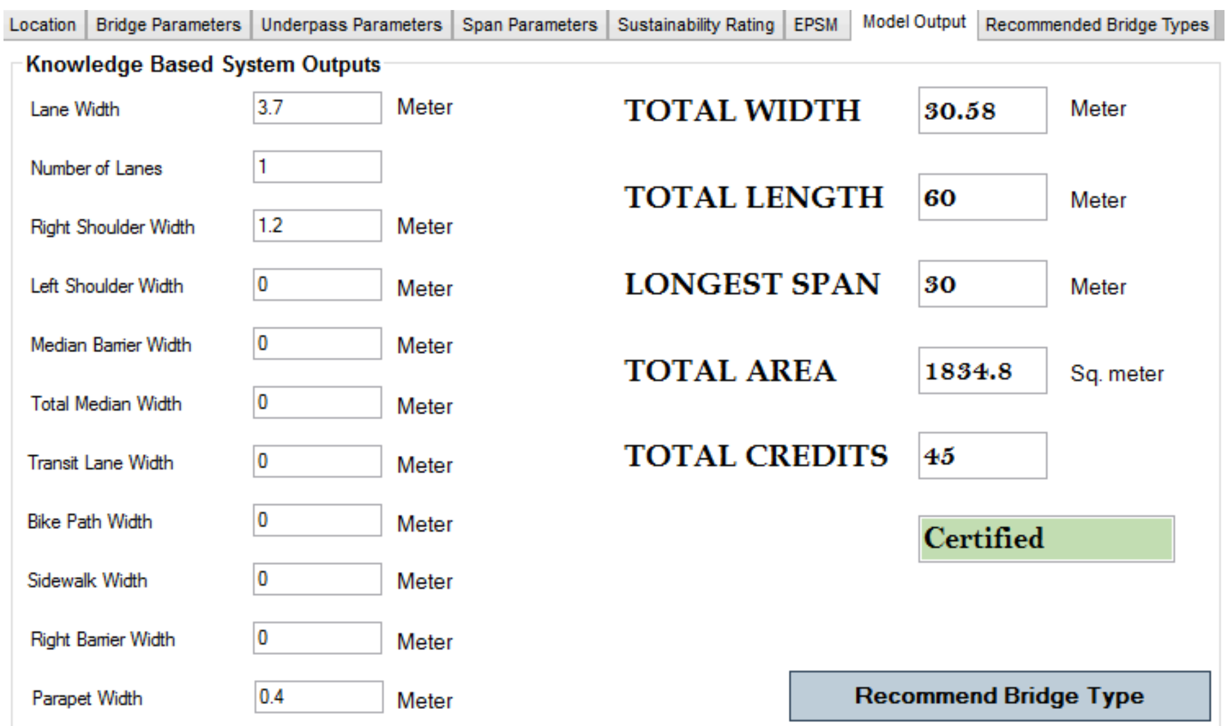


Figure 5.10 - Knowledge-Based System's Detailed and Summary Output

5.9 Recommended Bridge Types

The eighth step is the recommended bridge type selection. Using the model's output, the knowledge-based system recommends from a list of bridges which types are both applicable to the project's constraints and simultaneously satisfy the design guidelines and codes. The model suggested three types of bridges, namely, beam/girder, frame, and slab, along with the reasons why other types were not recommended. The desired bridge type is selected, in this case the slab, and more specific information is entered relating to the bridge's sub-category, material type and span type. From this panel, users have the options to launch AutoCAD and view the conceptual bridge in 3D, click the "Length Take-Off" button and retrieve the changed dimensions, view the sustainability modules' summary report and launch the conceptual cost estimating module. Figure 5.11 illustrates the bridge type selection process, specific information input and options available to users.

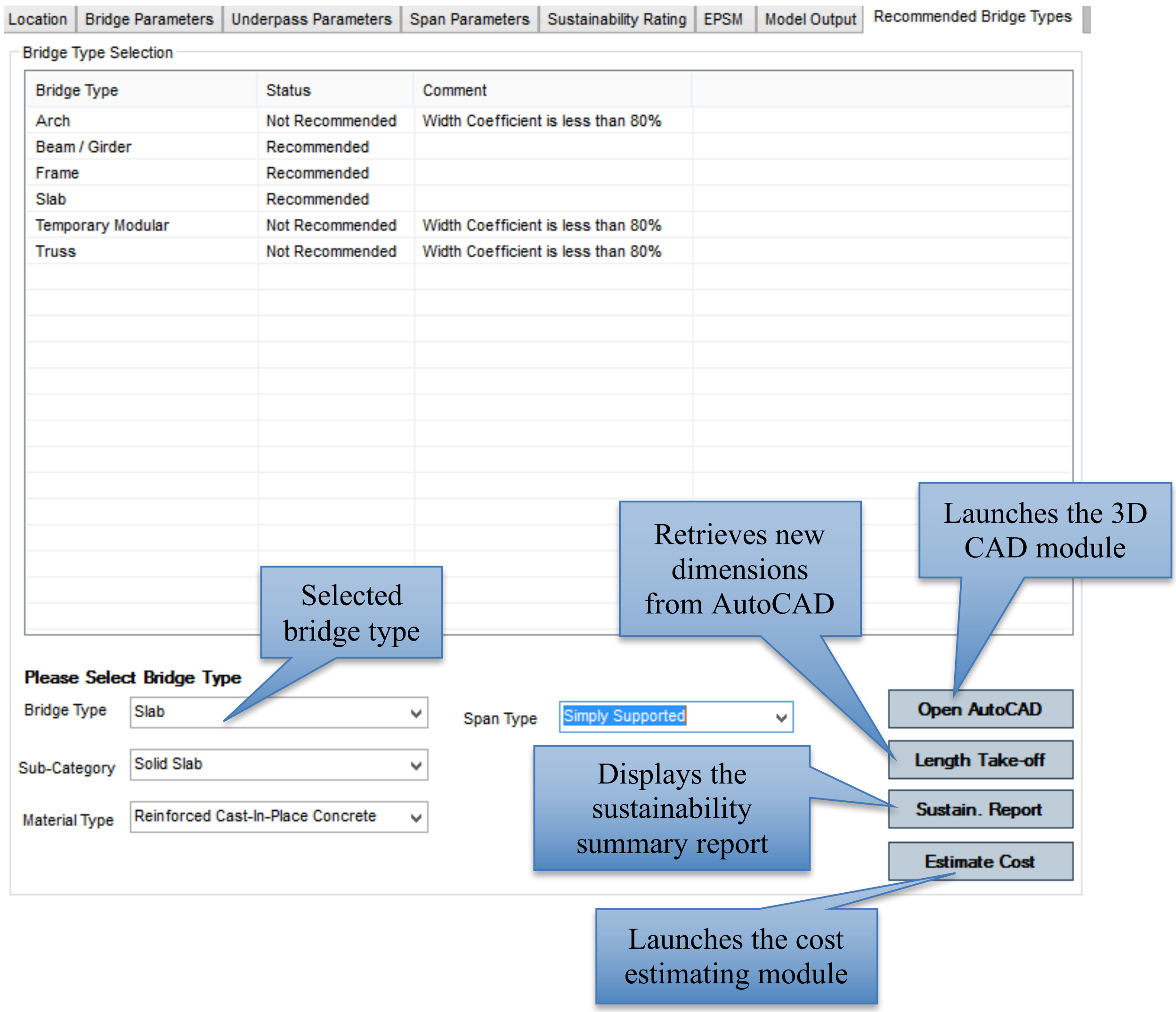


Figure 5.11 - Bridge Type Selection Process

5.10 3D CAD Modeling

The ninth step is viewing the conceptual bridge in a 3D rendering and making changes to its dimensions (if needed). AutoCAD opens the template file for the slab bridge type and uses the summary output dimensions listed in the model output step (Figure 5.10) to draw the bridge to scale. For simplicity, the bridge is scaled via the AutoCAD command "SCALE" to alter the dimensions then the "Length Take-Off" button is clicked so that the model retrieves the new bridge length and places it in the knowledge-based system (bridge parameter step) to trigger the recalculation of the bridge design. Figures 5.12 illustrates the sequence of the 3D CAD model and length take-off.

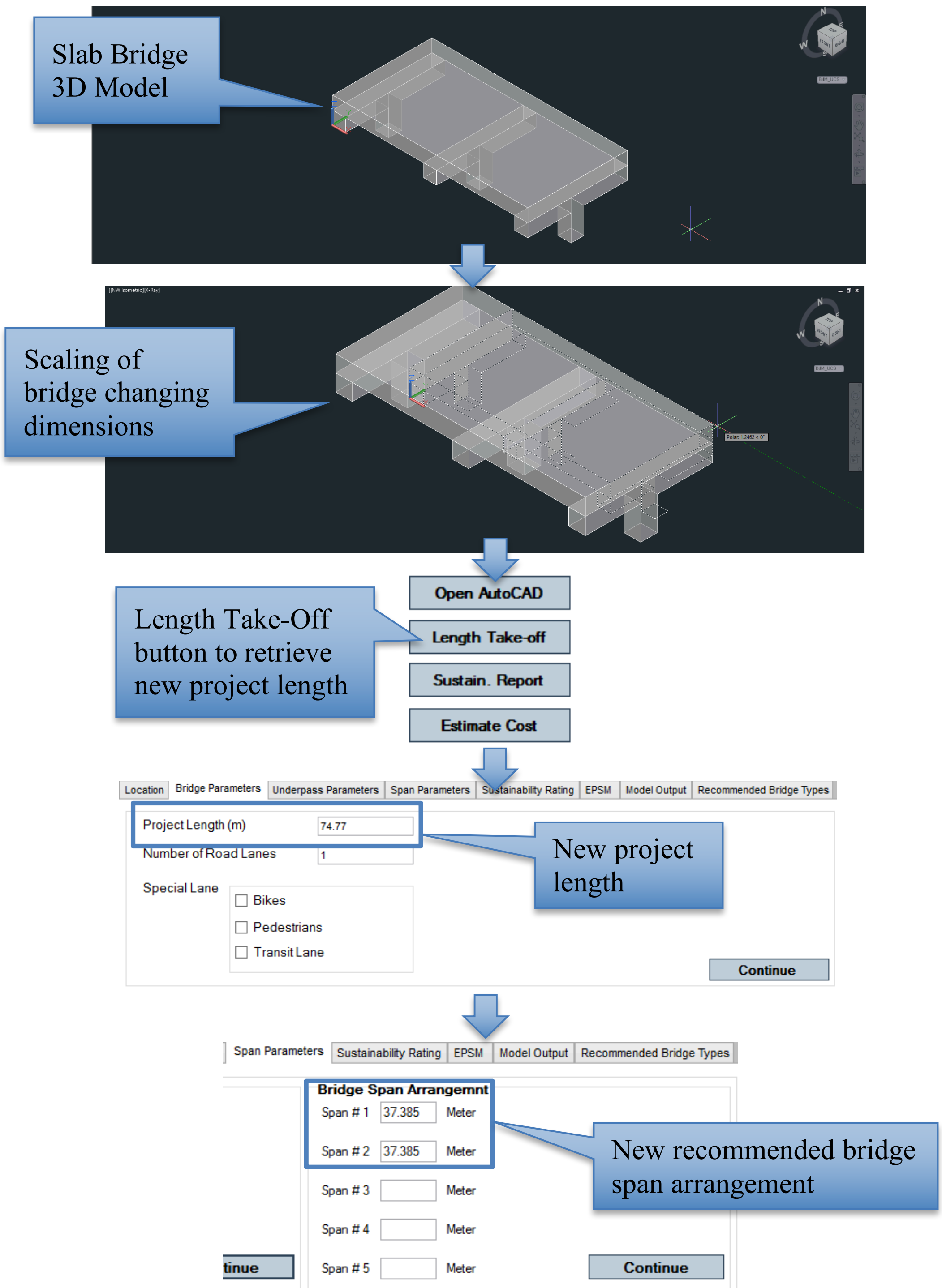


Figure 5.12 - 3D CAD Modeling Sequence

5.11 Sustainability Summary Report

The tenth step is to review and document all the results of the sustainability module. This is done through the generated sustainability summary report that lists all the sustainable activities/work-items selected in the BrSRS module and displays the footprint comparison radar graph generated by the BrEPSM module. Figure 5.13 illustrates the generated sustainability results summary report. Since this bridge was constructed as a conventional bridge, it is not possible to compare the data and the sustainability report results.

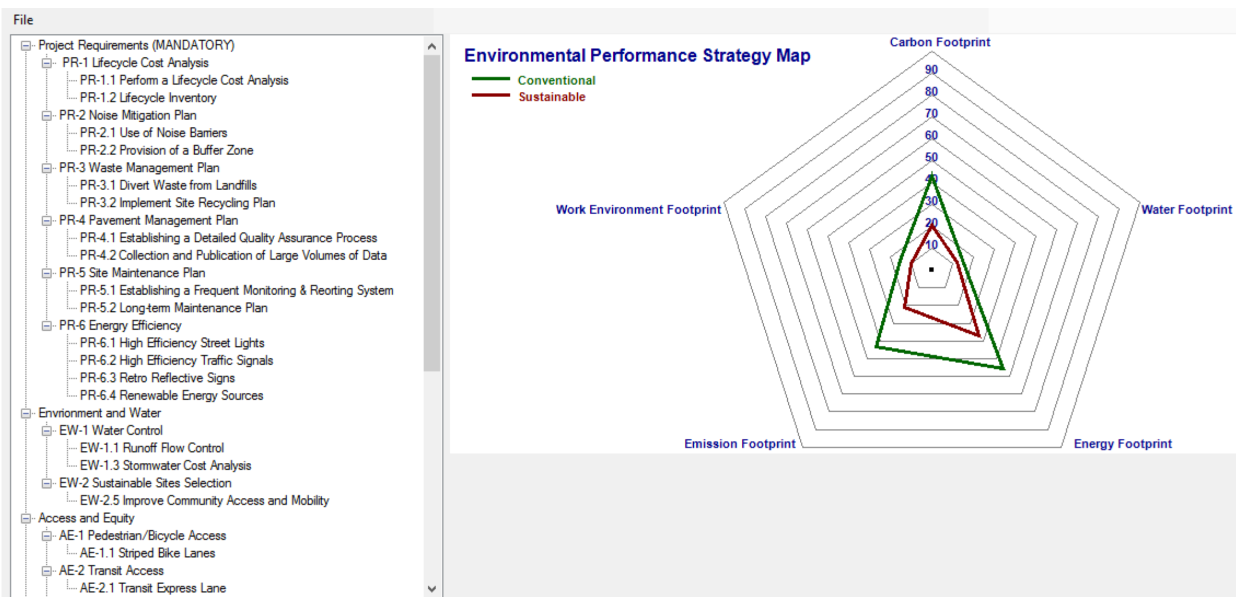


Figure 5.13 - Generated Sustainability Summary Report

5.12 Conceptual Cost Estimation

The final step is to use the conceptual cost estimation module to generate the conceptual cost estimates of the bridge project. Certain input data is required by the module in conjunction with the knowledge-based output to estimate the costs. The required data is as follows: 1) the bridge's column system type, 2) the abutment type, 3) the tax percentage of the province, 4) the year the project's construction is to commence and 5) the estimations of the contractor's contingency, profit and overhead percentages. The selected column system type is multiple column bents, the selected abutment type is spill-through abutment, the tax percentage is set to 13% as per the current percentage of the province of Ontario; the project year of construction is set to 2017 as pre-selected in the BrEPSM module and the contractor's percentages are assumed to be 5% contingency; 10% profit; and 10% overhead as shown in Figure 5.14. The input values are accepted and no modifications are desired; therefore, the next step is to view the conceptual cost estimates reports.

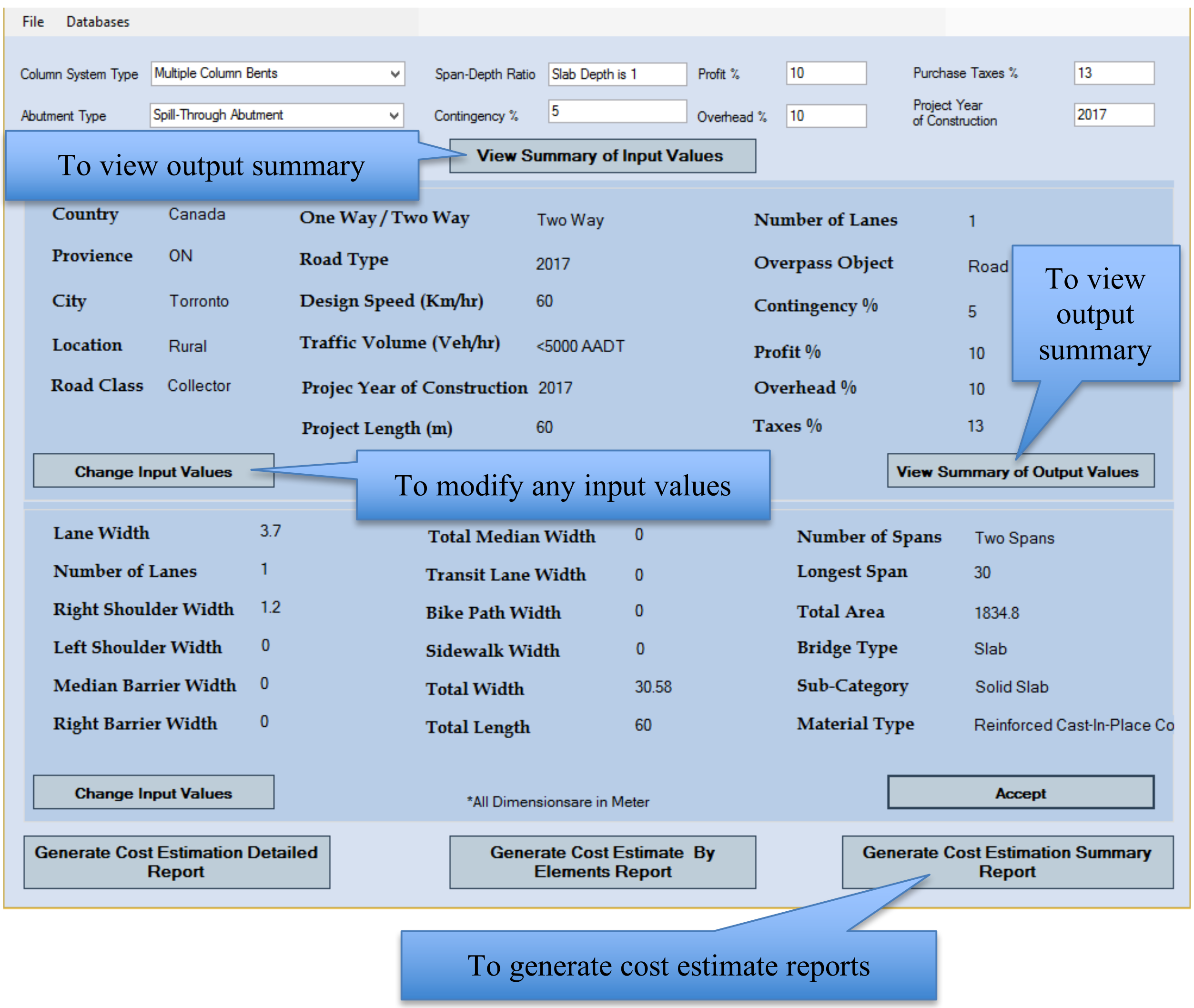
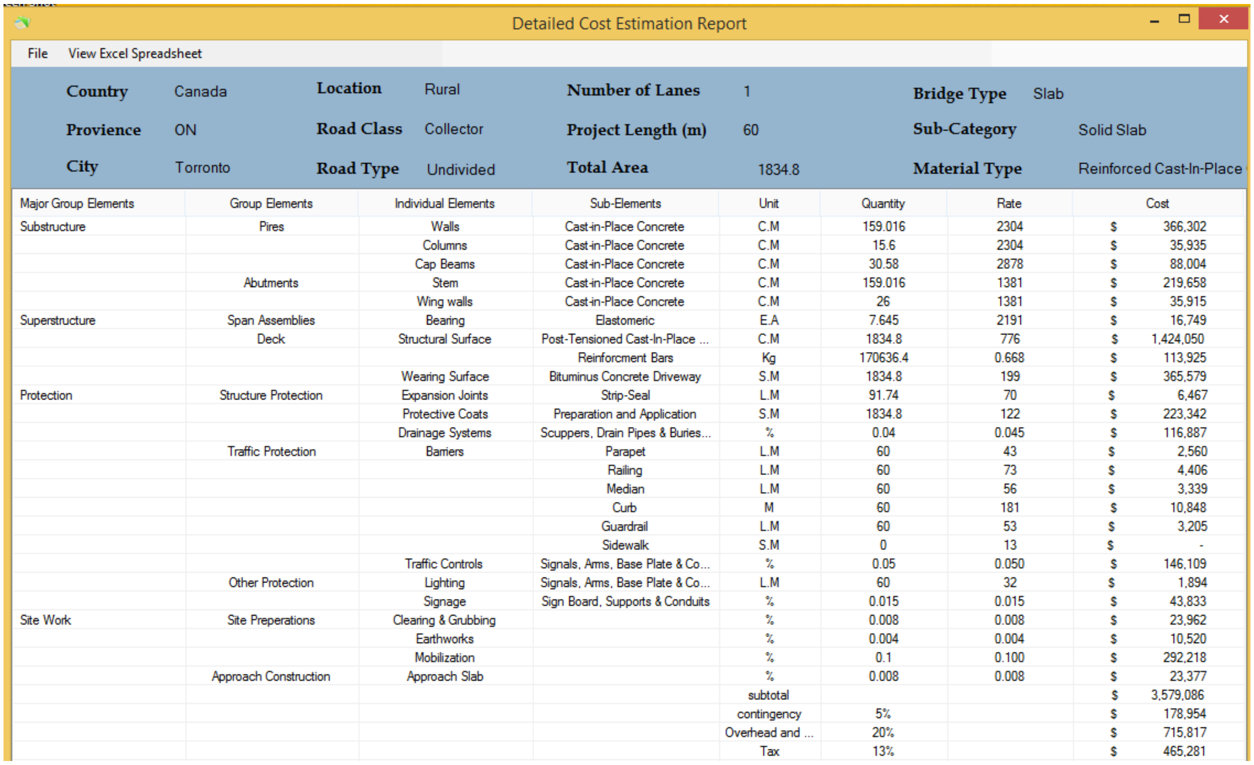


Figure 5.14 - Conceptual Cost Estimating Module Data Input

There are three breakdown forms of the cost estimate report generated by the module. The first form is a detailed conceptual cost estimation report as shown in Figure 5.15, the second form is a conceptual cost estimate by project elements report as shown in Figure 5.16, and the third form is a summary conceptual cost estimate report as shown in Figure 5.17.



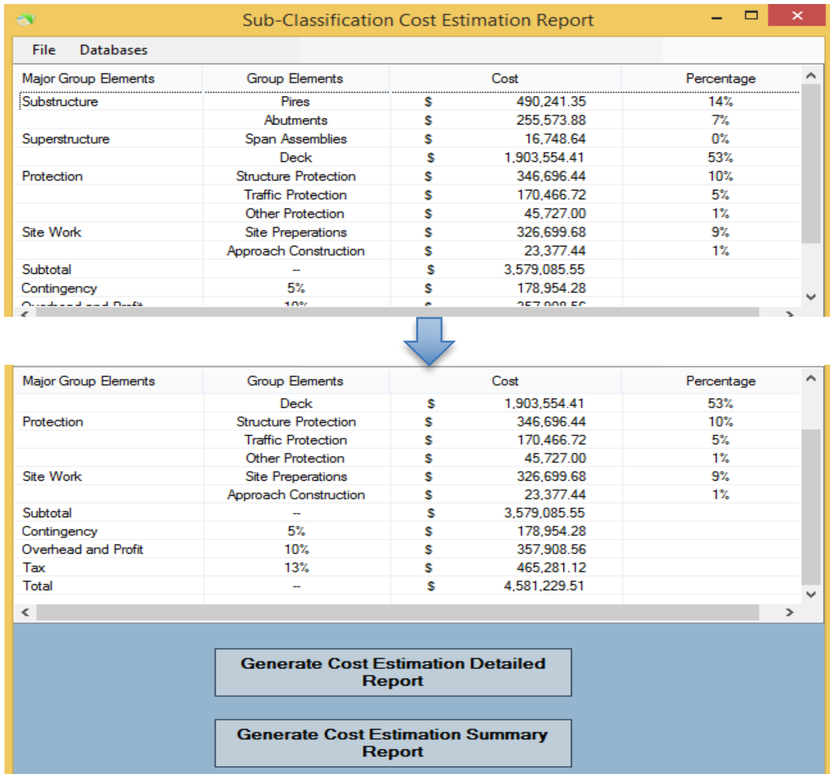
Detailed Cost Estimation Report

File | View Excel Spreadsheet

Country	Canada	**Location**	Rural	**Number of Lanes**	1	**Bridge Type**	Slab
Provience	ON	**Road Class**	Collector	**Project Length (m)**	60	**Sub-Category**	Solid Slab
City	Torronto	**Road Type**	Undivided	**Total Area**	1834.8	**Material Type**	Reinforced Cast-In-Place

Major Group Elements	Group Elements	Individual Elements	Sub-Elements	Unit	Quantity	Rate	Cost
Substructure	Pires	Walls	Cast-in-Place Concrete	C.M	159.016	2304	$ 366,302
		Columns	Cast-in-Place Concrete	C.M	15.6	2304	$ 35,935
		Cap Beams	Cast-in-Place Concrete	C.M	30.58	2878	$ 88,004
	Abutments	Stem	Cast-in-Place Concrete	C.M	159.016	1381	$ 219,658
		Wing walls	Cast-in-Place Concrete	C.M	26	1381	$ 35,915
Superstructure	Span Assemblies	Bearing	Elastomeric	E.A	7.645	2191	$ 16,749
	Deck	Structural Surface	Post-Tensioned Cast-In-Place ...	C.M	1834.8	776	$ 1,424,050
			Reinforcment Bars	Kg	170636.4	0.668	$ 113,925
		Wearing Surface	Bituminus Concrete Driveway	S.M	1834.8	199	$ 365,579
Protection	Structure Protection	Expansion Joints	Strip-Seal	L.M	91.74	70	$ 6,467
		Protective Coats	Preparation and Application	S.M	1834.8	122	$ 223,342
		Drainage Systems	Scuppers, Drain Pipes & Buries...	%	0.04	0.045	$ 116,887
	Traffic Protection	Barriers	Parapet	L.M	60	43	$ 2,560
			Railing	L.M	60	73	$ 4,406
			Median	L.M	60	56	$ 3,339
			Curb	M	60	181	$ 10,848
			Guardrail	L.M	60	53	$ 3,205
			Sidewalk	S.M	0	13	$ -
		Traffic Controls	Signals, Arms, Base Plate & Co...	%	0.05	0.050	$ 146,109
	Other Protection	Lighting	Signals, Arms, Base Plate & Co...	L.M	60	32	$ 1,894
		Signage	Sign Board, Supports & Conduits	%	0.015	0.015	$ 43,833
Site Work	Site Preperations	Clearing & Grubbing		%	0.008	0.008	$ 23,962
		Earthworks		%	0.004	0.004	$ 10,520
		Mobilization		%	0.1	0.100	$ 292,218
	Approach Construction	Approach Slab		%	0.008	0.008	$ 23,377
				subtotal			$ 3,579,086
				contingency	5%		$ 178,954
				Overhead and ...	20%		$ 715,817
				Tax	13%		$ 465,281

Figure 5.15 - Detailed Cost Estimate Report



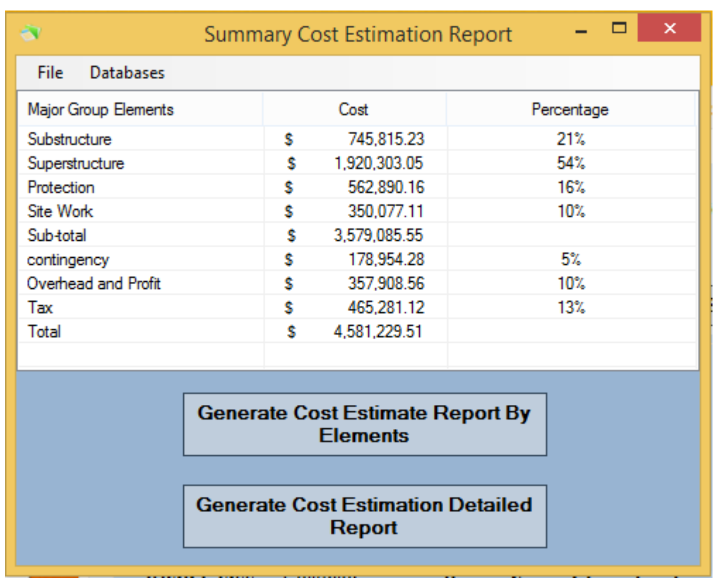
Sub-Classification Cost Estimation Report

File Databases

Major Group Elements	Group Elements		Cost	Percentage
Substructure	Pires	$	490,241.35	14%
	Abutments	$	255,573.88	7%
Superstructure	Span Assemblies	$	16,748.64	0%
	Deck	$	1,903,554.41	53%
Protection	Structure Protection	$	346,696.44	10%
	Traffic Protection	$	170,466.72	5%
	Other Protection	$	45,727.00	1%
Site Work	Site Preperations	$	326,699.68	9%
	Approach Construction	$	23,377.44	1%
Subtotal	--	$	3,579,085.55	
Contingency	5%	$	178,954.28	

Major Group Elements	Group Elements		Cost	Percentage
	Deck	$	1,903,554.41	53%
Protection	Structure Protection	$	346,696.44	10%
	Traffic Protection	$	170,466.72	5%
	Other Protection	$	45,727.00	1%
Site Work	Site Preperations	$	326,699.68	9%
	Approach Construction	$	23,377.44	1%
Subtotal	--	$	3,579,085.55	
Contingency	5%	$	178,954.28	
Overhead and Profit	10%	$	357,908.56	
Tax	13%	$	465,281.12	
Total	--	$	4,581,229.51	

Figure 5.16 - By Project Element Cost Estimate Report



Summary Cost Estimation Report

File Databases

Major Group Elements		Cost	Percentage
Substructure	$	745,815.23	21%
Superstructure	$	1,920,303.05	54%
Protection	$	562,890.16	16%
Site Work	$	350,077.11	10%
Sub-total	$	3,579,085.55	
contingency	$	178,954.28	5%
Overhead and Profit	$	357,908.56	10%
Tax	$	465,281.12	13%
Total	$	4,581,229.51	

Figure 5.17 - Summarized Cost Estimate Report

As the cost estimate reports exhibit, the conceptual cost estimate of constructing this concrete slab bridge project in the year 2017 is \$4,581,229.51. The actual cost of the project is unavailable as it is private and confidential information. However, an alternative means to estimate the actual cost for comparison is using the MTO Parametric Estimating Guide (2011). The guide states that the cost to construct a deck between the area of 750 m^2 to 2999m^2 is approximately \$2,420. The actual area of the Lakeshore Drive Bridge as obtained from the output in Figure 5.10 is 1,834.8 m^2. Thus, the estimated cost of the bridge for the year of 2011 is \$4,438,280. A time adjustment is required to obtain the estimated cost in the year 2017. The time adjustment equation is as follows:

$$F = P\,(1+i)^n \qquad \textbf{Eq. 19}$$

Where,

P = past cost of the completed project in the year 2011

i = inflation rate (Commonly assumed to be 3% as a practical value in the Canadian industry based on the MTO Parametric Cost Estimating guide)

n = number of time periods (years)

Hence, the estimated cost of the Lakeshore Drive bridge in the year 2017 is $\$4{,}438{,}280\,(1+0.03)^6 = \$5{,}299{,}538$.

The project's conceptual cost in the year 2017 was estimated by the model as \$4,581,299.51. Thus, a comparison of both values indicates that there is a percentage error of 13.5%, which is acceptable for conceptual estimation. The difference in the cost can be reflective of various factors; however, the prominent factor being that the model is based on a compilation of published cost value, while the actual cost using the parametric cost estimate has a higher accuracy level.

5.13 Summary

This chapter covered the steps taken to validate the model. An existing project was selected and its input information was processed through the series of modules the model is made up of. The workability of each module and of the model as a whole was tested in terms of obtaining the desired output, the logical sequence of the dataflow, and the analysis of the results. Lakeshore Drive Bridge was selected as the existing bridge project and its information was used to redesign the bridge from a conventional to a sustainable one. The model provided a summary report with the sustainable design options for the redesigned bridge that highlighted the required activities/work-items to have a Certified sustainable bridge project. Moreover, the report estimated the environmental impact of the new redesigned bridge if it were to be constructed in the year 2017. Significant reductions in impact are noted with the sustainable redesign versus a conventional design. The visualization of the conceptual bridge redesign was carried out by the 3D CAD module and rendered as a slab bridge type. A change of dimensions in the 3D model activated the knowledge-based system calculation reiteration process suggesting new span arrangements and dimensions. Furthermore, the conceptual cost estimation module estimated the cost of the bridge project in the forms of three cost estimated reports namely being, a detailed cost estimate report, a by project element cost estimate report and a summary cost estimate report.

Chapter Six

Conclusion and Future Recommendations

6.1 Conclusion

The notion of Bridge Information Modeling (BrIM) was created to use technological advancements to enhance the procedures involved in all the life cycle stages (cradle to grave) of a bridge project. Furthermore, BrIM can manage all the information related to a bridge project in an efficient and organized manner strengthening communication between all stakeholders. This capability can be quite useful, especially with an increased flow of information when introducing new considerations to a project's design, such as sustainability. There is a gap in literature regarding sustainability when it comes to bridge projects. Combining sustainability concepts with BrIM concepts at the conceptual design stage enriches the method in which a project is designed, visualized, and ultimately managed. The methodology presented in this thesis described the development and integration of three new modules with a pre-existing model. The modules are interrelated and work together to introduce a sustainable bridge project design approach and implement the concept of BrIM. The five modules the BrIM model is comprised of are: 1) a knowledge-based system module, 2) a conceptual cost estimating module, 3) a bridge sustainability rating system (BrSRS) module, 4) an environmental performance strategy mapping module, and 5) a 3D CAD modeling module. Using conceptual data input, the knowledge-based system generates preliminary bridge parameters and dimensions, based on codes, guidelines, and design experts' knowledge and experience. The conceptual cost estimating module calculates the conceptual costs of the bridge project based on the output of the knowledge-based module. The BrSRS is an approach to introducing sustainable features into conceptual bridge design. The

BrEPSM is a module that is paired with the BrSRS module as it assesses the environmental impact of a conventional bridge design versus a sustainable one using footprint indicators. The 3D CAD module is a prominent aspect of BrIM as it renders the conceptual bridge in 3D and enhances the project's visualization and design.

The model's advantages are as follows:

1. Generates a conceptual bridge design with parameters based on rudimentary input.
2. Integrates a sustainable bridge design approach and gives users the option to design either a conventional or a sustainable bridge.
3. Conducts a forecasted environmental impact assessment of the conceptual bridge project comparing the impacts between a conventional and a sustainable design.
4. Models the conceptual bridge in 3D for enhanced project design visualization and modification.
5. Generates the conceptual cost estimates for feasibility studies of various design options.
6. Provides professional summary reports for documentation.

6.2 Research Contribution

The purpose of the model is to facilitate an easy and smooth method of conceptually designing bridge projects. Stakeholders can be assisted by the model to quickly prepare conceptual designs and cost estimates for feasibility studies and to provide reliable output for decision making. Therefore, the research contributions are as follows:

1. A pre-existing model that generated conceptual bridge parameters was enhanced by integrating a 3D CAD module with a two-way channel of communication for rapid dataflow, establishing a BrIM tool. The module can import the output information from the model to render the conceptual bridge design in 3D and to scale as well as send any

changes done in the model space back to the model to recalculate the appropriate parameters corresponding to the changes.

2. A sustainability design approach was developed and integrated into the model to provide users the option to conceptually design either a conventional or sustainable bridge project. Additionally, a forecasting environmental impact assessment tool was developed and integrated to emphasize the benefits of the sustainable design options.

6.3 Research Limitations

The developed model has the following limitations:

- The algorithmic knowledge-base is limited to codes and guidelines that do not include criteria beyond a certain project length, which is 100 meters, and it is limited to six bridge types only.
- The BrSRS considers limited aspects of bridge superstructure components.
- The BrEPSM database can only forecast data points up to the year 2018; thus, the model can only estimate the environmental impacts of projects for the years 2017 and 2018.
- The 3D CAD module renders the bridges in simple wireframe design.
- The cost estimation module is based on compiled cost data of previous projects and is not updated.

6.4 Future Expansions

The developed model has enhanced capabilities; however, the model is not perfect and there is always room for improvement. The following is a list of recommendations for improving the model:

1. Improve the AutoCAD templates to display a greater level of detail for superior visualization capabilities.
2. Expand the algorithmic knowledge-base to include more codes and guidelines that cover longer bridge spans and more bridge types to provide additional design options.
3. Integrate a scheduling module that can propose a timeline and work breakdown structure (WBS) for the conceptually proposed bridge, while incorporating the sustainability activities/work-items selected in the BrSRS.
4. Update the databases of the cost estimation and BrEPSM model to improve the reliability of their output.
5. Change the 3D CAD module software integration from AutoCAD to Civil 3D as Civil 3D contains all the capabilities of AutoCAD with the added benefit of being able to create surfaces and alignments and to generate profiles for infrastructure projects.

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Appendix A: Greenroads™ Scorecard

Greenroads™

Project Name	
Location (City, State)	
Project Manager	
Project Budget	million (USD)
Current Status (Circle)	Planning Design Construction Complete

Project Requirements (PR)		PR Max: 11			
No.	Title		Y	?	N
PR-1	Environmental Review Process	Req			
PR-2	Lifecycle Cost Analysis	Req			
PR-3	Lifecycle Inventory	Req			
PR-4	Quality Control Plan	Req			
PR-5	Noise Mitigation Plan	Req			
PR-6	Waste Management Plan	Req			
PR-7	Pollution Prevention Plan	Req			
PR-8	Low-Impact Development	Req			
PR-9	Pavement Management System	Req			
PR-1	Site Maintenance Plan	Req			
PR-11	Educational Outreach	Req			

Environment & Water (EW)		EW Max: 21	Y	?	N
EW-1	Environmental Management System	2			
EW-2	Runoff Flow Control	1 - 3			
EW-3	Runoff Quality	1 - 3			
EW-4	Stormwater Cost Analysis	1			
EW-5	Site Vegetation	1 - 3			
EW-6	Habitat Restoration	3			
EW-7	Ecological Connectivity	1 - 3			
EW-8	Light Pollution	3			

Access & Equity (AE)		AE Max: 30	Y	?	N
AE-1	Safety Audit	1 - 2			
AE-2	Intelligent Transportation Systems	2 - 5			
AE-3	Context Sensitive Solutions	5			
AE-4	Traffic Emissions Reduction	5			
AE-5	Pedestrian Access	1 - 2			
AE-6	Bicycle Access	1 - 2			
AE-7	Transit & HOV Access	1 - 5			
AE-8	Scenic Views	1 - 2			
AE-9	Cultural Outreach	1 - 2			

Construction Activities (CA)		CA Max: 14			
No.	Title		Y	?	N
CA-1	Quality Management System	2			
CA-2	Environmental Training	1			
CA-3	Site Recycling Plan	1			
CA-4	Fossil Fuel Reduction	1 - 2			
CA-5	Equipment Emission Reduction	1 - 2			
CA-6	Paving Emission Reduction	1			
CA-7	Water Use Tracking	2			
CA-8	Contractor Warranty	3			

Materials & Resources (MR)		MR Max: 23	Y	?	N
MR-1	Lifecycle Assessment	2			
MR-2	Pavement Reuse	1 - 5			
MR-3	Earthwork Balance	1			
MR-4	Recycled Materials	1 - 5			
MR-5	Regional Materials	1 - 5			
MR-6	Energy Efficiency	1 - 5			

Pavement Technologies (PT)		PT Max: 20	Y	?	N
PT-1	Long-Life Pavement	5			
PT-2	Permeable Pavement	3			
PT-3	Warm Mix Asphalt	3			
PT-4	Cool Pavement	5			
PT-5	Quiet Pavement	2 - 3			
PT-6	Pavement Performance Tracking	1			

Custom Credit (CC)		CC Max: 10	Y	?	N
CC-1	____________	1 - 5			
CC-2	____________	1 - 5			
CC-3	____________	1 - 5			

All 11 PR Met?			
Greenroads Total (Max 118)			

Appendix B: GreenLITES Sample Scorecard

GreenLITES Project Environmental Sustainability Rating System Scorecard v 2.1.0 Please fill in all yellow highlighted cells and follow all instructions in red text.				POINTS	
	CATEGORY	ID	DESCRIPTION	Available	Scored
Sustainable Sites (S)	S-1 *Alignment Selection*	S-1a	Avoidance of previously undeveloped lands (open spaces or "greenfields").	2	
		S-1b	Selecting an alignment that establishes a minimum 100-foot buffer zone between the edge of pavement and a natural watercourse or significantly sized natural wetland to serve the purpose of stormwater filtration.	2	
		S-1c	Alignments which minimize overall construction "footprint." Examples: use of retaining walls, selecting design option with minimal footprint.	2	
		S-1d	Design vertical alignments which minimize total earthwork. (Applicable only for projects modifying existing vertical alignments.)	1	
		S-1e	Adjust alignment to avoid or minimize impacts to social/environmental resources (avoidance of parklands, wetlands, historic sites, farmlands, residential and commercial buildings, etc.).	1	
		S-1f	Alignments that optimize benefits among competing constraints. (The goal is not always the minimum-length alignment, but the one with the best benefit overall.)	1	
		S-1g	Micro-adjustments that do not compromise safety or operation but make the difference in providing sufficient clear area for tree planting.	1	
		S-1h	Clear zones seeded with seed mixtures that help to reduce maintenance needs and increase carbon sequestration.	1	
		S-1i	Provide a depressed roadway alignment.	1	
		S-1j	Use of launched soil nails as a more cost effective option to stabilize a slope rather than, for example, closing a road to construct a retaining wall which may negatively affect traffic flow and neighboring properties.	1	
	S-2 *Context Sensitive Solutions*	S-2a	Adjust or incorporate highway features to respond to the unique character or sense of place (both natural and built) of the area ("Unique character" means whatever identifiable elements make a place distinctive, memorable, important to the community, etc. - landmarks, views, historic bridges & buildings, parkways, characteristic use of materials, a notable stand of trees, etc.).	2	
		S-2b	Incorporate local or natural materials for substantial visual elements (e.g., bridge fascia, retaining walls).	2	
		S-2c	Visual enhancements (screening objectionable views, strategic placement of vegetation, enhancing scenic views, burying utilities, etc.).	2	

	S-2d	Period street furniture/lighting/appurtenances.	1	
	S-2e	Inclusion of visually-contrasting (colored and/or textured) pedestrian crosswalk treatments.	1	
	S-2g	Incorporates guidance from *Section 23 - Aesthetics* of the NYS Bridge Manual.	1	
	S-2h	Site materials selection & detailing to reduce overall urban "heat island" effect.	1	
	S-2i	Permanently protect viewsheds via environmental or conservation easements.	1	
	S-2j	Color anodizing of aluminum elements (ITS cabinets, non-decorative light poles, etc.)	1	
	S-2k	Decorative bridge fencing (in lieu of standard chain link).	1	
	S-2l	Use of concrete form liners (for bridge approach barriers, parapet walls, retaining walls, noise walls, bridge piers & abutments, etc.)	1	
	S-2m	Imprinted concrete/asphalt mow strips, gores and/or snow storage areas.	1	
S-3 *Land Use/ Community Planning*	S-3a	Use of more engaging public participation techniques (e.g. charette, task force).	2	
	S-3b	Enhanced outreach efforts (e.g. newsletters, project-specific Web page, communications issued in multiple languages).	2	
	S-3c	Projects better enabling use of public transit (e.g. bus shelters, 'Park &Ride').	2	
	S-3d	Projects applying "Walkable Communities" and/or "Complete Streets" concepts.	2	
	S-3e	Projects that increase transportation efficiencies for moving freight through features such as dedicated rail or intermodal facilities or the use of unit trains to remove trucks from highways and conserve fuel.	2	
	S-3f	Project-specific formal agreement with public or private entities enabling environmental betterment, technological advancement, or financial assistance or relief to the Department.	2	
	S-3g	Project is consistent with local and regional plans beyond those generated by the MPO; (e.g., waterfront revitalization plans, greenway plans, the Scenic Byway program, and other statewide non-transportation plans with regional components) and/or local Smart Growth-based master/comprehensive plans.	2	
	S-3h	Project reports and community outreach materials available online other than the standard project specific web page.	1	

Sustainable Sites (S)		S-3j	Establishment of a new recreational access facility (trailhead parking, car top boat launch, info/map kiosk).	2
		S-3k	Establishment of a new recreational facility (pocket park, roadside overlook, roadside picnic rest area, etc.).	2
		S-3l	Enhancement of an existing recreational facility or enhancement of an existing recreational facility access.	1
	S-4 *Protect, Enhance or Restore Wildlife Habitat*	S-4a	Mitigation of habitat fragmentation through use of significant techniques such as consolidated stream, wetland or ecological mitigation areas, or creation of dedicated "eco viaducts." (Raised roadways that serve to avoid impacts to ecologically important areas such as rare plant communities, diminishing habitats and wildlife migration corridors.).	3
		S-4b	Providing for enhancements to existing wildlife habitat (e.g. bird & bat houses, nesting boxes, osprey poles, turtle nesting areas, avoiding piping plover habitat).	2
		S-4c	Partial mitigation of habitat fragmentation through techniques (United States Army Corp of Engineers (USACE) regional conditions) such as over-sizing culverts to accommodate aquatic and non-aquatic species passage.	2
		S-4d	Use of natural-bottomed culverts.	2
		S-4e	Wildlife crossings that are structures that allow for the safe passage of wildlife across highways without their crossing directly on the roadway. Examples include wildlife overpass/underpass and amphibian tunnels.	2
		S-4f	Wetland restoration, enhancement, or establishment that is above and beyond what is required to obtain a wetland-related permit.	2
		S-4g	Minimize use of lands that are part of a significant contiguous wildlife habitat.	1
		S-4h	Use of wildlife mortality reduction measures such as right-of -way fence, moose signs, etc.	1
		S-4k	Stream restoration/enhancement.	1
		S-4l	Installation of mowing markers to protect natural areas and wetlands.	1
		S-4m	Inclusion of scheduling and logistic requirements to avoid disrupting wildlife nesting or breeding activities.	1
		S-4n	Permanently protects the new or expanded habitat through an environmental or conservation easement.	1

Appendix C: I-LAST Sample Scorecard

CATEGORY		ID	DESCRIPTION		Available Points	Project Points
Planning	P-1 Context Sensitive Solutions	P-1a	Identify Stakeholders and develop Stakeholders Involvement Plan		2	
		P-1b	Engage Stakeholders to conduct Context Audit and develop project purpose		2	
		P-1c	Involve Stakeholders to develop and evaluate alternatives		2	
		P-1d	Employ Stakeholder involvement techniques to achieve consensus for Preferred Project Alternative		2	
	P-2 Land Use/ Community Planning	P-2a	Promote reduction in vehicle trips by accommodating increased use of public transit		2	
		P-2b	Accommodate multi-modal transportation uses (e.g. transit riders, pedestrians, and bicyclists)		2	
		P-2c	Increase transportation efficiencies for moving freight through features such as dedicated rail or intermodal facilities		2	
		P-2d	Partnerships that provide environmental or technological advancements while promoting environmental stewardship		2	
		P-2e	Project is consistent with regional plans and local managed growth-based Master or Comprehensive Plans		2	
		P-2f	Project is compatible with local efforts for Transit Oriented Design		1	
Design	D-1 Alignment Selection	D-1a	Avoid impacts to high quality undeveloped lands			
			D-1a-1	Avoid all impacts	2	
			D-1a-2	Avoid significant impacts	1	
		D-1b	Provide buffer between highway and high quality wetlands/water resources			
			D-1b-1	Provide 100 foot buffer to resources	2	
			D-1b-2	Avoid resource with less than 100 foot buffer	1	
		D-1c	Avoid impacts to environmental resources, such as INAI sites and sites with threatened or endangered species			
			D-1c-1	Avoid all impacts	2	
			D-1c-2	Avoid significant impacts	1	
		D-1d	Avoid impacts to socioeconomic resources			
			D-1d-1	Avoid all impacts	2	

CATEGORY		ID	DESCRIPTION		Available Points	Project Points
Design	D-1 Alignment Selection		D-1d-2	Avoid significant impacts	1	
		D-1e	Cross section minimizes overall construction "footprint" to eliminate R.O.W. takes		2	
		D-1f	Minimize total earthwork by matching proposed vertical alignments as closely as possible to existing grades		1	
		D-1g	Utilize brownfield locations		2	
	D-2 Context Sensitive Design	D-2a	Adjust highway features using design flexibility		2	
		D-2b	Incorporate locally produced or native materials			
			D-2b-1	Over 95% of materials produced from US sources	1	
			D-2b-2	Over 60% of materials produced in metro area	2	
		D-2c	Visual enhancements		2	
		D-2d	Items fit context of surroundings		1	
		D-2e	Bridge aesthetics		1	
		D-2f	Reduce urban "heat island" effect		1-2	
Environmental	E-1 Protect, Enhance or Restore Wildlife and its Habitat	E-1a	Avoid habitat fragmentation		3	
		E-1b	Minimize habitat fragmentation		2	
		E-1c	Mitigate habitat fragmentation		1	
		E-1d	Wetland restoration/mitigation		1 to 3	
		E-1e	Provide nesting locations		2	
		E-1f	Provide wildlife crossings		2	
		E-1g	Provide fish passage		2	
		E-1h	Provide mussel relocation prior to construction		2	
		E-1i	Provide right-of-way wildlife barriers		1	
		E-1j	Provide mowing markers		1	
		E-1k	Schedule construction to avoid wildlife disruption		1	

Environmental	E-2 Trees and Plant Communities	E-2a	Avoidance/protection of individual and contiguous stands of specimen trees and localized areas of established, desirable vegetation		2	
		E-2b	Designs which demonstrate an anticipated ultimate net increase in tree species			
			E-2b-1	Increase tree species through preservation and new planting	2	
			E-2b-2	Coordination with local stakeholders to create a plant palette in context with community	2	
			E-2b-3	Historic native plantings are re-established	1	
		E-2c	Re-establish/expand native vegetation in reclaimed work areas or abandoned old alignments		2	
		E-2d	Use of plant material in lieu of or enhance structural such as living snow fences, sight screens (viburnum, dogwood, etc.)		1	
		E-2e	Use of native species for plugs, seed mixes, perennial and other plantings		2	
		E-2f	Planting trees, shrubs and/or native plant material in highway right-of-way		2	
		E-2g	Tree replacement ratios at greater than 1:1		2	
		E-2h	Minimize potential salt splash impacts through use of berms or vegetative screening		2	
	E-2 Trees and Plant Communities	E-2i	Removal of undesirable plant species, removal of invasive species		1	
		E-2j	Topsoil preservation		2	
	E-3 Noise Abatement	E-3a	Construction of noise barriers			
			E-3a-1	Specialized noise barrier construction	2	
			E-3a-2	Typical noise barrier	1	
		E-3b	Incorporate traffic system management techniques to reduce existing noise levels		2	
		E-3c	Provide a buffer zone for adjacent receptors		2	
		E-3d	Provide sound insulation to public or non-profit institutional structures		1	
		E-3e	Tining of pavement to reduce noise levels		1-2	

Appendix D: Envision Scorecard

TABLE OF POINT VALUES

#	Category	Subcategory	Credit	Improved	Enhanced	Superior	Conserving	Restorative
1	QUALITY OF LIFE	PURPOSE	QL1.1 Improve community quality of life	2	5	10	20	25
2			QL1.2 Stimulate sustainable growth and development	1	2	5	13	16
3			QL1.3 Develop local skills and capabilities	1	2	5	12	15
4		COMMUNITY	QL2.1 Enhance public health and safety	2			16	
5			QL2.2 Minimize noise and vibration	1			8	11
6			QL2.3 Minimize light pollution	1	2	4	8	11
7			QL2.4 Improve community mobility and access	1	4	7	14	
8			QL2.5 Encourage alternative modes of transportation	1	3	6	12	15
9			QL2.6 Improve site accessibility, safety and wayfinding		3	6	12	15
10		WELLBEING	QL3.1 Preserve historic and cultural resources	1		7	13	16
11			QL3.2 Preserve views and local character	1	3	6	11	14
12			QL3.3 Enhance public space	1	3	6	11	13
				13	**27**	**62**	**150**	**151**
13	LEADERSHIP	COLLABORATION	LD1.1 Provide effective leadership and commitment	2	4	9	17	
14			LD1.2 Establish a sustainability management system	1	4	7	14	
15			LD1.3 Foster collaboration and teamwork	1	4	8	15	
16			LD1.4 Provide for stakeholder involvement	1	5	9	14	
17		MNGMT.	LD2.1 Pursue by-product synergy opportunities	1	3	6	12	15
18			LD2.2 Improve infrastructure integration	1	3	7	13	16
19		PLANNING	LD3.1 Plan for long-term monitoring and maintenance	1	3		10	
20			LD3.2 Address conflicting regulations and policies	1	2	4	8	
21			LD3.3 Extend useful life	1	3	6	12	
				10	**31**	**56**	**115**	**31**
22	RESOURCE ALLOCATION	MATERIALS	RA1.1 Reduce net embodied energy	2	6	12	18	
23			RA1.2 Support sustainable procurement practices	2	3	6	9	
24			RA1.3 Use recycled materials	2	5	11	14	
25			RA1.4 Use regional materials	3	6	9	10	
26			RA1.5 Divert waste from landfills	3	6	8	11	
27			RA1.6 Reduce excavated materials taken off site	2	4	5	6	
28			RA1.7 Provide for deconstruction and recycling	1	4	8	12	
29		ENERGY	RA2.1 Reduce energy consumption	3	7	12	18	
30			RA2.2 Use renewable energy	4	6	13	16	20
31			RA2.3 Commission and monitor energy systems		3		11	
32		WATER	RA3.1 Protect fresh water availability	2	4	9	17	21
33			RA3.2 Reduce potable water consumption	4	9	13	17	21
34			RA3.3 Monitor water systems	1	3	6	11	
				29	**66**	**112**	**170**	**62**
35	NATURAL WORLD	SITING	NW1.1 Preserve prime habitat			9	14	18
36			NW1.2 Protect wetlands and surface water	1	4	9	14	18
37			NW1.3 Preserve prime farmland			6	12	15
38			NW1.4 Avoid adverse geology	1	2	3	5	
39			NW1.5 Preserve floodplain functions	2	5	8	14	
40			NW1.6 Avoid unsuitable development on steep slopes	1		4	6	
41			NW1.7 Preserve greenfields	3	6	10	15	23
42		L&W	NW2.1 Manage stormwater		4	9	17	21
43			NW2.2 Reduce pesticide and fertilizer impacts	1	2	5	9	
44			NW2.3 Prevent surface and groundwater contamination	1	4	9	14	18
45		BIODIVERSITY	NW3.1 Preserve species biodiversity	2			13	16
46			NW3.2 Control invasive species			5	9	11
47			NW3.3 Restore disturbed soils				8	10
48			NW3.4 Maintain wetland and surface water functions	3	6	9	15	19
				15	**33**	**86**	**165**	**169**
49	CLIMATE	Emission	CR1.1 Reduce greenhouse gas emissions	4	7	13	18	25
50			CR1.2 Reduce air pollutant emissions	2	6		12	15
51		Resilience	CR2.1 Assess climate threat				15	
52			CR2.2 Avoid traps and vulnerabilities	2	6	12	16	20
53			CR2.3 Prepare for long-term adaptability				16	20
54			CR2.4 Prepare for short-term hazards	3		10	17	21
55			CR2.5 Manage heat islands effects	1	2	4	6	
				12	**21**	**39**	**100**	**101**
				79	**178**	**355**	**700**	**514**

Appendix E: Bridge Sustainability Rating System

Bridge Sustainability Rating System							
		CREDITS		POINTS	DESCRIPTION/CREDIT GOAL	RESTRICTIONS	REFERENCES
		ID	ACTIVITY/WORK-ITEM				
Project Requirements (MANDATORY)	PR-1 Lifecycle Cost Analysis	PR-1.1	Perform a Lifecycle Cost Analysis	2	Perform a life cycle analysis (LCA) to inform project stakeholders of the relative sustainable impacts of various materials/systems/construction practices (i.e. PaLATE software)	Must include LCA to quantify the delay user costs of roadway construction and the air emissions over the life cycle of different modes of freight shipping (if bridge will accommodate freight transportation)	Greenroads, (Muench et al., 2012), (Tupper et al., 2012)
		PR-1.2	Lifecycle Inventory	1	Inventory analysis is based on the lifecycle sub-components that emerge from the various sub-systems considered (i.e. PaLATE software)	Analysis must show energy consumption, resource consumption and emissions for different basic activities, expressed per number of kilometers driven (km) or per amount of materials extracted and/or processed (kg)	Greenroads, (Muench et al., 2012), (Vidal et al., 2013)
	PR-2 Noise Mitigation Plan	PR-2.1	Use of Noise Barriers	2	Reduce construction/traffic noise (i.e soundproof walls)	Use of soundproof devices can be considered for this credit	Greenroads, Envision, I-LAST, (Soderlund et al., 2008), (Zou and Moon, 2014)
		PR-2.2	Provision of a Buffer Zone	2	Reduce construction/traffic noise by providing a buffer zone (i.e ample distance from communities)		GreenLITES, Envision, I-LAST
	PR-3 Waste Management Plan	PR-3.1	Divert Waste from Landfills	2	Reduce the overall waste produced by construction and filter recyclable waste		Greenroads, Envision, GreenLITES, (Soderlund et al., 2008)
		PR-3.2	Implement Site Recycling Plan	1	Implement an on-site recycling plan	Must include in the on-site recycling plan the reuse of waste concrete for backfill materials or coarse aggregate for road construction as well as the setup of designated waste sorting areas	Greenroads, (Soderlund et al., 2008), (Zou and Moon, 2014)
	4 Pavement Management Plan	PR-4.1	Establishing a Detailed Quality Assurance Process	2	Implement an ISO certified quality assurance process to encourage high-quality construction		Greenroads, (Soderlund et al., 2008)
		4.2	Collection and Publication of Large Volumes of Data	1	Reports publication on pavement monitoring and management to the public for future projects and research		GreenLITES

PR-5 Site Maintenance Plan	PR-5.1	Establishing a Frequent Monitoring & Reorting System	1	Establish an on-site operational performance evaluation plan for quick detection and response for maintenance needs		(Zou and Moon, 2014)
	PR-5.2	Long-term Maintenance Plan	2	Project must have a set long-term monitoring and maintenance plan to continue minimizing environmental impacts		Envision
PR-6 Energy Efficiency	PR-6.1	High Efficiency Street Lights	2	Use energy efficient lighting (i.e. LED lights)	Install lights with cut off or full cut off fixtures to minimize energy waste	GreenLITES, I-LAST, (Soderlund et al., 2008)
	PR6-2	High Efficiency Traffic Signals	1	Use energy efficient lighting (i.e. LED lights)		GreenLITES, I-LAST, (Soderlund et al., 2008)
	PR-6.3	Retro Reflective Signs	1	Use retro reflective material to reduce the need for extra roadway lighting		GreenLITES, I-LAST
	PR-6.4	Renewable Energy Sources	3	Establish on-site renewable energy resources (i.e. use of solar panels)		GreenLITES, Envision, I-LAST, (Soderlund et al., 2008)
		Total	23			

Envrionment and Water (VOLUNTARY)	EW-1 Water Control	EW-1.1	Runoff Flow Control	1	Reduce surface runoff volumes and peak flow rates (i.e. interlocking brick for parking spaces)	Must implement runoff control measures if project has land-disturbing activities of 7,000 ft2	Greenroads, GreenLITES, (Soderlund et al., 2008)
		EW-1.2	Runoff Quality	2	Protect waterways from materials entering through runoff, prevent soil erosion and conduct runoff treatment	Must adhere to applicable clauses of the Ontario Clean Water Act and must make a clear effort avoiding the use of fertilizers and herbicides	Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008), (Muench et al., 2012), ("Ontario Clean Water Act", 2014)
		EW-1.3	Stormwater Cost Analysis	1	Perform a stromwater management cost analysis		Greenroads, (Soderlund et al., 2008)
	EW-2 Sustainable Sites Selection	EW-2.1	Improve Infrastructure Integration	2	Site selection encourages easy infrastructure integration with surroundings		Greenroads, Envision, (Soderlund et al., 2008)
		EW-2.2	Encourages Alternative Modes of Transportation	2	Selected site helps promote reduction in vehicle trips by facilitating a potential increase in multi-modal transportation use (e.g. transit riders, pedestrians, and bicyclists)		GreenLITES, Envision, I-LAST
		EW-2.3	Stimulate Sustainable Growth & Development	2	Project must be in line with regional plans to stimulate local sustainable development and economic growth		GreenLITES, Envision
		EW-2.4	Maximize Trucking Efficiency	1	Project site should have easy access and mobility to maximize transportation efficiency and minimize fuel consumption		GreenLITES, I-LAST
		EW-2.5	Improve Community Access and Mobility	2	Project must enhance the access and mobility of surrounding communities		GreenLITES, Envision
	EW-3 Respect for Historic Sites	EW-3.1	Preserve Historic, Cultural and Ecological Sites	2	Avoid sensitive sites such as historical, cultural and ecological areas		Greenroads, GreenLITES, Envision, (Soderlund et al., 2008)
		EW-3.2	Enhance Public Space Around Sites	1	Project must enhance the overall public space and quality of life of communities surrounding the project		Envision
			Total	16			

Access and Equity (VOLUNTARY)	AE-1 Pedestrian/Bicycle Access	AE-1.1	Striped Bike Lanes	2	Provision of dedicated bike lanes		Greenroads, I-LAST, (Soderlund et al., 2008)
		AE-1.2	Widen Sidewalk or Bike Lane	1	Provision of ample width for bike lanes and pedestrian walkways to encourage more multimodal mobility		Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008)
		AE-1.3	Improve Pedestrian Crossing Intersection Design	1	Perform a LOS analysis for intersection pedestrian access to bridge walkways		Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008)
	AE-2 Transit Access	AE-2	Transit Express Lane	3	Provision of transit/high occupancy vehicles express lane		Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008)
	AE-3 Visual Enhancements	AE-3.1	Enhancing Design	1	Encourage appropriate design that fit the context of the project's surroundings and minimizes the construction's overall footprint (i.e. vertical and horizontal curves 3D alignment)		Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008)
		AE-3.2	Enhancing Elements	2	Incorporate visual enhancing and functional roadway elements (i.e. pavement raised markings)		GreenLITES, I-LAST
		AE-3.3	Avoidance of Light Pollution	1	Reduce light pollution produced by roadway lighting	Install lights with cut off or full cut off fixtures to reduce light pollution	Greenroads, Envision, (Soderlund et al., 2008)
		AE-3.4	Scenic View/Bridge Aesthetics	1	Encourage visually pleasing bridge design		Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008)
			Total	12			

Construction Activities (VOLUNTARY)	CA-1 Air Quality Control	CA-1.1	Reduce Air Pollutants	2	Spray the ground with water and install dust barriers to contain and minimize flying dust		Envision, (Zou and Moon, 2014)
		CA-1.2	Reduce Diesel Emissions	3	Non-road diesel engines should install retrofits that reduce exhaust emission and fuel consumption efficiency technology		Greenroads, Envision, (Soderlund et al., 2008)
	CA-2 Vegetation	CA-2.1	Preserve/Plant Vegetation	2	All vegetation that was cleared from the project site must be processed and reused on site or if no vegetation existed/was removed plant new vegetation	Should include the creation of a duff layer (organic material that covers forest soil) if project is within the vicinity of larger areas of vegetation, should maintain a ratio of 1:1 for vegetation reuse/replacement, and suitable vegetation (i.e. Shrub willows) may be used as natural snow fences	GreenLITES, I-LAST, (Muench et al., 2012)
	CA-3 Resources Reduction	CA-3.1	Fossil Fuel Reduction	2	Reduce fossil fuel consumption through the use of biodiesel by off-road equipment		Greenroads, (Muench et al. 2011), (Tupper et al., 2012)
		CA-3.2	Water Use Reduction/Tracking	2	Implement a water consumption tracking and reduction system (i.e. limit water consumption per X ft2 of construction)	All water used should be non-potable effluent obtained from a local waste water treatment plant except for concrete curing	Envision, (Muench et al. 2012)
			Total	11			

Materials and Resources (VOLUNTARY)	MR-1 Recycled Materials Reuse	MR-1.1	Hot Mix Asphalt	2	Recycle HMA as aggregates or within new mix	30% of Hot Mix Asphalt (HMA) or 50% of the total material structure and should be used for the shoulder, subgrade, sub-base, and/or base	Greenroads, Envision, I-LAST, (Soderlund et al., 2008)
		MR-1.2	Portland Cement Concrete	2	Recycle PCC as aggregates or within new mix	30% Portland cement concrete (PCC) layers or 50% of the total material structure and should be used for the shoulder, subgrade, sub-base, and/or base	Greenroads, Envision, I-LAST, (Soderlund et al., 2008)
		MR-1.3	Locally Produced Byproducts	1	Allow the reuse of locally produced byproducts	Reuse locally produced fly ash, microsillica, foundry sand, slag aggregates, and ternary concrete mixtures in new concrete mixtures, embankments, and various structural items (where applicable) [Options not limited to the presented list, credit assessed on an individual basis]	Envision, I-LAST
		MR-1.4	Recycled Asphalt Pavement	2	Reuse recycled asphalt pavement (RAP) in new asphalt mixtures	Preferably combined with warm mix asphalt for optimum results	Envision, I-LAST
		MR-1.5	Timber/Wood	1	Reuse recycled/salvaged lumber	Restricted use for on-site temporary fences and noise barriers/walls; preservative-treated or coated wood cannot be reused	Envision, GreenLITES
		MR-1.6	Major Structural Elements	2	Reuse recycled structural elements of bridges	Only reuse structural elements if appropriate and will not compromise the overall desired integrity and life cycle of the project	Envision, GreenLITES
	MR-2 Earthwork Balance	MR-2.1	Balance Cuts and Fills	1	Minimize earthwork by matching the proposed vertical alignments as closely as possible to existing grades	Balance the cuts and fills within 25-10%	GreenLITES, Envision, I-LAST
		MR-2.2	Reuse Topsoil	2	Reuse or (if possible) the preservation of the topsoil	50-70% of removed topsoil for grading should be reused	GreenLITES, Envision, I-LAST
		MR-2.3	Soil Stabilization with Geo-synthetics/Recycled Material	1	Use geo-synthetics (synthetic products) or recycled cementitious material to stabilize terrain surrounding the project (if required)		GreenLITES, I-LAST
		MR-2.4	Avoid Adverse Geology/Development on Steep Slopes	1	Avoid projects' development on locations with adverse geology or steep slopes to reduce the overall required earthwork		Envision
	MR-3 Regional Materials	MR-3.1	Use Regional Materials	2	Procure regionally available material to minimize effects created by transporting materials from their produced location to the project site	Procured at least 60% of materials from local manufacturers/suppliers	Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008), (Muench et al. 2011), (Tupper et al., 2012)

MR-4 Pavement Technologies	MR-4.1	Long-Term Adaptability/Life Span Extension	3	Extend the pavement life span by specifying the use of 30 or 40 year design life concrete pavement and influence long-term adaptability by specifying the use of pavement preservation processes		Envision, I-LAST
	MR-4.2	Permeable Pavement	2	Reduces surface runoff volumes and peak flow rates and are more efficient at improving the quality of runoff while maintaining infiltration	Permeable areas should be at least more than 20% of the impervious areas If the impacted project area has 2,000 ft2 or more of impervious surfaces and shoulders should be paved with permeable pavement (where practical)	Greenroads, GreenLITES, I-LAST, (Soderlund et al., 2008)
	MR-4.3	Warm Mix Asphalt	2	Reduces the emissions and fossil fuel use from the asphalt mixture plant, improves workability, and potential for increased recycled asphalt pavement (RAP) content	Must use at least 15% RAP in mixture to decrease climate impacts, fossil depletion and total cumulative energy demand by 14%	Greenroads, (Muench et al. 2011), (Tupper et al., 2012), (Vidal et al., 2013)
	MR-4.4	Cool Pavement	1	Reduces the urban heat island effect	Use of a pavement surface that has a minimum albedo of 0.3 or use a porous pavement	Greenroads, GreenLITES, Envision, I-LAST, (Soderlund et al., 2008)
	MR-4.5	Quiet Pavement	1	Reduces the noise generated by the tire-pavement contact		I-LAST
	MR-4.6	Pavement Performance Tracking	2	Establish a plan for continuous pavement monitoring to track pavement performance and improvement/deterioration over time		Greenroads, (Soderlund et al., 2008)
		Total	28			

Potential for Innovations (VOLUNTARY)	PI-1 Intelligent Transportation System	PI-1.1	Implement Remote Intelligent Transportation System (ITS)	3	ITS can improve air quality by reducing emissions and fuel consumption impacts, positively influence drivers' behavior and decision making, and reduce travel times	System must include incident detection, response, and management algorithms and methodology	Greenroads, GreenLITES, I-LAST, (Tupper et al., 2012)
	PI-2 Providing a Bridge User Guide	PI-2.1	Public Website	1	Enhanced public outreach effort to improve community communication, planning, and participation		GreenLITES
		PI-2.2	Interactive Smartphone App	1	Enhanced public outreach effort to improve community communication, planning, and participation		GreenLITES
	PI-3 Innovations	PI-3.1	Innovative Sustainable Practice/Material/System	1-5	Project team has the opportunity of earning credits for additional performance above the requirements set in the rating system (Assessed on an individual basis)	Could earn one or several credits depending upon the innovation's assessed impact	Greenroads, (Soderlund et al., 2008)
			Total	10			
			Overall Total	100			

Appendix F: BrEPSM Collected Data

- Water consumption:
- 2005

	Intake		Recirculation		Recirculation rate [1]	Gross water use [2]		Discharge		Consumption [3]		Consumption rate [4]
	millions of cubic metres	%	millions of cubic metres	%		millions of cubic metres	%	millions of cubic metres	%	millions of cubic metres	%	
Newfoundland and Labrador	85.2 D	1.5	F	F	F	F	F	79.8 D	1.6	5.4	0.8	6.3
Prince Edward Island	F	F	0.0	0.0	F	F	F	F	F	F	F	F
Nova Scotia	136.4 B	2.4	33.3 D	1.1	24.4	169.7	1.9	102.2 A	2.0	34.2	5.3	25.1
New Brunswick	205.2 C	3.6	175.6 A	5.6	85.6	380.9	4.3	200.5 C	4.0	4.8	0.7	2.3
Atlantic	**427.0** B	**7.5**	**217.2** B	**6.9**	**50.9**	**644.1**	**7.3**	**382.6** B	**7.5**	**44.4**	**6.8**	**10.4**
Quebec	1,263.2 B	22.1	786.0 D	24.8	62.2	2,049.2	23.1	1,178.9 B	23.3	84.3	13.0	6.7
Ontario	2,676.5 C	46.8	1,377.9 D	43.5	51.5	4,054.4	45.6	2,345.3 C	46.3	331.2	51.0	12.4
Manitoba	60.2 D	1.1	20.5 E	0.6	34.0	80.7	0.9	50.1 D	1.0	10.1	1.6	16.8
Saskatchewan	60.1 B	1.1	6.4 A	0.2	10.7	66.6	0.7	48.0 C	0.9	12.1	1.9	20.1
Alberta	283.7 B	5.0	380.8 E	12.0	134.2	664.5	7.5	205.7 C	4.1	78.0	12.0	27.5
Prairies	**404.0** B	**7.1**	**407.7** E	**12.9**	**100.9**	**811.7**	**9.1**	**303.8** B	**6.0**	**100.2**	**15.4**	**24.8**
British Columbia	946.6 B	16.6	375.4 C	11.9	39.7	1,322.0	14.9	857.8 B	16.9	88.8	13.7	9.4
Yukon Territory, Northwest Territories and Nunavut	2.2 D	0.0	0.0	0.0	0.0	2.2	0.0	1.0 B	0.0	1.1	0.2	52.6
Canada	**5,719.5** B	**100.0**	**3,164.1** C	**100.0**	**55.3**	**8,883.6**	**100.0**	**5,069.4** B	**100.0**	**650.1**	**100.0**	**11.4**

1. Recirculation rate = Amount of recirculated water as a percent of intake. The same water can leave a sub-system and re-enter it or is used in another sub-system many times, resulting in a recirculation rate > 100%.
2. Gross water use = Intake + Recirculation.
3. Consumption = Intake - Discharge.
4. Consumption rate = Consumption as a percentage of Intake.

Source(s): Statistics Canada, Industrial Water Survey, 2005.

- 2007

	Intake		Recirculation		Recirculation rate[1]	Gross water use[2]		Discharge		Consumption[3]		Consumption rate[4]
	millions of cubic metres	%	millions of cubic metres	%	%	millions of cubic metres	%	millions of cubic metres	%	millions of cubic metres	%	%
Canada	**4,573.1**[A]	**100.0**	**2,665.2**[B]	**100.0**	**58.3**	**7,238.3**	**100.0**	**4,121.5**[A]	**100.0**	**451.6**	**100.0**	**9.9**
Newfoundland and Labrador	63.7[C]	1.4	x	x	x	x	x	63.1[C]	1.5	0.6	0.1	0.9
Prince Edward Island	x	x	x	x	x	x	x	x	x	x	x	x
Nova Scotia	153.3[A]	3.4	79.4[C]	3.0	51.8	232.7	3.2	140.6[B]	3.4	12.7	2.8	8.3
New Brunswick	186.3[A]	4.1	92.1[B]	3.5	49.4	278.4	3.8	169.7[A]	4.1	16.6	3.7	8.9
Quebec	1,027.3[B]	22.5	592.9[C]	22.2	57.7	1,620.2	22.4	996.1[B]	24.2	31.2	6.9	3.0
Ontario	1,799.9[A]	39.4	1,289.0[B]	48.4	71.6	3,088.9	42.7	1,613.9[A]	39.2	186.0	41.2	10.3
Manitoba	118.7[D]	2.6	x	x	x	x	x	109.4[D]	2.7	9.3	2.1	7.8
Saskatchewan	21.8[D]	0.5	x	x	x	x	x	14.1[E]	0.3	7.7	1.7	35.3
Alberta	364.6[B]	8.0	304.8[E]	11.4	83.6	669.4	9.2	270.0[B]	6.6	94.6	20.9	25.9
British Columbia	832.0[B]	18.2	252.3[B]	9.5	30.3	1,084.3	15.0	739.4[B]	17.9	92.6	20.5	11.1
Yukon, Northwest Territories and Nunavut	x	x	x	x	x	x	x	x	x	x	x	x

1. Recirculation rate = Amount of recirculated water as a percent of intake. The same water can leave a sub-system and re-enter it or is used in another sub-system many times, resulting in a recirculation rate > 100%.
2. Gross water use = Intake + Recirculation.
3. Consumption = Intake - Discharge.
4. Consumption rate = Consumption as a percentage of Intake.

Note(s): Figures may not add up to totals due to rounding.
Source(s): Statistics Canada, CANSIM tables 153-0047 and 153-0048.

- 2009

	Intake		Recirculation		Recirculation rate[1]	Gross water use[2]		Discharge		Consumption[3]		Consumption rate[4]
	millions of cubic metres	%	millions of cubic metres	%		millions of cubic metres	%	millions of cubic metres	%	millions of cubic metres	%	
Canada	**3,806.2**[A]	**100.0**	**2,003.3**[B]	**100.0**	**52.6**	**5,809.5**	**100.0**	**3,450.6**[A]	**100.0**	**355.6**	**100.0**	**9.3**
Newfoundland and Labrador	F	F	F	F	F	F	F	F	F	F	F	F
Prince Edward Island	F	F	F	F	F	F	F	F	F	F	F	F
Nova Scotia	181.9[C]	4.8	94.1[E]	4.7	51.7	276.0	4.8	171.3[C]	5.0	10.6	3.0	5.8
New Brunswick	169.2[B]	4.4	69.3[A]	3.5	41.0	238.5	4.1	162.9[B]	4.7	6.3	1.8	3.7
Quebec	974.3[B]	25.6	586.2[C]	29.3	60.2	1,560.5	26.9	925.0[C]	26.8	49.3	13.9	5.1
Ontario	1,478.5[A]	38.8	846.5[A]	42.3	57.3	2,325.0	40.0	1,328.8[A]	38.5	149.7	42.1	10.1
Manitoba	88.2[B]	2.3	161.8[E]	8.1	183.4	250.0	4.3	81.5[B]	2.4	6.7	1.9	7.6
Saskatchewan	17.3[D]	0.5	4.2[B]	0.2	24.3	21.5	0.4	9.3[E]	0.3	8.0	2.2	46.2
Alberta	254.6[B]	6.7	78.9[D]	3.9	31.0	333.5	5.7	196.9[C]	5.7	57.7	16.2	22.7
British Columbia	604.8[D]	15.9	x	x	x	x	x	537.9[D]	15.6	66.9	18.8	11.1
Yukon, Northwest Territories and Nunavut	0.0[A]	0.0	x	x	x	x	x	0.0[A]	0.0	0.0	0.0	0.0

1. Recirculation rate = Amount of recirculated water as a percent of intake. The same water can leave a sub-system and re-enter it or is used in another sub-system many times, resulting in a recirculation rate > 100%.
2. Gross water use = Intake + Recirculation.
3. Consumption = Intake - Discharge.
4. Consumption rate = Consumption as a percentage of Intake.

Note(s): Figures may not add up to totals due to rounding.
Source(s): Statistics Canada, CANSIM tables 153-0047 and 153-0048.

- 2011

	Intake		Recirculation		Recirculation rate[1]	Gross water use[2]		Discharge		Consumption[3]		Consumption rate[4]
	millions of cubic metres	%	millions of cubic metres	%		millions of cubic metres	%	millions of cubic metres	%	millions of cubic metres	%	
Canada	**3,677.5**[A]	**100.0**	**1,870.0**[A]	**100.0**	**50.8**	**5,547.5**	**100.0**	**3,226.8**[A]	**100.0**	**450.7**	**100.0**	**12.3**
Newfoundland and Labrador	16.1[D]	0.4	0.1[E]	0.0	0.6	16.2	0.3	16.1[D]	0.5	0.0	0.0	0.0
Prince Edward Island	9.2[E]	0.3	2.0[D]	0.1	21.7	11.2	0.2	9.0[E]	0.3	0.2	0.0	2.2
Nova Scotia	139.9[C]	3.8	15.0[A]	0.8	10.7	154.9	2.8	123.9[C]	3.8	16.0	3.6	11.4
New Brunswick	191.1[C]	5.2	63.7[A]	3.4	33.3	254.8	4.6	185.7[C]	5.8	5.4	1.2	2.8
Quebec	850.0[B]	23.1	566.6[B]	30.3	66.7	1,416.6	25.5	781.6[A]	24.2	68.4	15.2	8.0
Ontario	1,496.7[A]	40.7	834.5[A]	44.6	55.8	2,331.2	42.0	1,280.4[A]	39.7	216.3	48.0	14.5
Manitoba	95.9[A]	2.6	104.0[A]	5.6	108.4	199.9	3.6	76.2[A]	2.4	19.7	4.4	20.5
Saskatchewan	x	x	7.2[B]	0.4	x	x	x	x	x	x	x	x
Alberta	207.7[A]	5.6	84.7[D]	4.5	40.8	292.4	5.3	147.4[B]	4.6	60.3	13.4	29.0
British Columbia	654.3[A]	17.8	192.3[B]	10.3	29.4	846.6	15.3	600.0[B]	18.6	54.3	12.0	8.3
Yukon, Northwest Territories and Nunavut	x	x	0.0	0.0	x	x	x	x	x	x	x	x

1. Recirculation rate = Amount of recirculated water as a percent of intake. The same water can leave a sub-system and re-enter it or is used in another sub-system many times, resulting in a recirculation rate > 100%.
2. Gross water use = Intake + Recirculation.
3. Consumption = Intake - Discharge.
4. Consumption rate = Consumption as a percentage of Intake.

Note(s): Figures may not add up to totals due to rounding.
Source(s): Statistics Canada, CANSIM tables 153-0047 and 153-0048.

- Water Resource Availability:

AQUASTAT Main Database - United Nations Statistics Division. (2016).

Area	Variable Name	Year	Value (Km3/year)
Canada	Total renewable water resources	1997	2902
Canada	Total renewable water resources per capita	1997	97151
Canada	Total renewable water resources	2002	2902
Canada	Total renewable water resources per capita	2002	92748
Canada	Total renewable water resources	2007	2902
Canada	Total renewable water resources per capita	2007	87987
Canada	Total renewable water resources	2012	2902
Canada	Total renewable water resources per capita	2012	83228
Canada	Total renewable water resources	2014	2902
Canada	Total renewable water resources per capita	2014	80746

- Construction Projects' Carbon Emissions (Statistics Canada):

Carbon Total (Yt)

Year/Province	ON	AB	BC	MB	NB	NL	NS	NU	NWT	PEI	QC
1990	43.89	18.31	16.19	5.50	3.92	2.91	4.72	-	0.52	0.68	26.38
1991	42.53	16.91	16.19	5.38	3.84	2.75	4.55	-	0.38	0.67	25.23
1992	43.49	17.16	16.62	5.42	3.95	2.65	4.54	-	0.40	0.67	25.70
1993	44.40	17.25	16.99	5.44	4.05	2.69	4.66	-	0.48	0.67	26.34
1994	45.39	19.16	17.76	5.77	4.26	2.66	4.83	-	0.52	0.69	27.83
1995	46.12	19.00	18.44	5.93	4.26	2.69	4.90	-	0.60	0.68	28.01
1996	46.85	19.01	18.74	5.95	4.40	2.77	4.82	-	0.54	0.74	28.18
1997	49.39	20.57	19.26	5.90	4.47	2.83	4.92	-	0.54	0.72	29.08
1998	50.38	21.53	19.99	5.84	4.59	2.88	5.07	-	0.59	0.74	30.63
1999	52.75	21.92	20.06	5.94	4.84	2.98	5.43	0.14	0.42	0.78	31.07
2000	53.98	22.91	20.17	5.85	5.00	3.10	5.30	0.19	0.44	0.80	30.81
2001	54.06	24.79	19.76	5.74	4.97	3.03	5.11	0.18	0.54	0.78	30.80
2002	55.14	24.71	20.07	5.69	5.01	3.05	5.16	0.18	0.46	0.78	31.16
2003	56.18	25.26	21.17	5.94	5.03	3.03	5.59	0.20	0.45	0.80	31.99
2004	56.90	26.32	21.88	6.29	5.08	3.06	5.61	0.20	0.50	0.84	32.94
2005	59.60	27.16	21.27	6.15	5.05	3.15	5.64	0.20	0.60	0.83	33.25
2006	58.40	28.73	21.02	6.29	4.90	3.04	5.34	0.20	0.82	0.81	32.93
2007	57.25	30.27	21.34	6.51	4.83	3.52	5.30	0.22	0.81	0.82	34.04
2008	56.03	29.92	21.53	6.25	4.67	3.43	5.14	0.23	0.72	0.79	33.65
2009	56.00	27.46	20.92	6.43	4.35	3.49	4.79	0.20	0.44	0.78	33.81
2010	57.43	29.20	20.97	6.96	4.73	3.67	4.96	0.19	0.42	0.82	33.12
2011	56.69	28.28	20.31	6.83	5.44	3.61	5.37	0.14	0.46	0.76	32.88
2012	54.59	30.13	20.64	7.78	4.86	3.49	5.00	0.15	0.48	0.83	33.04
2013	57.02	31.70	21.03	7.75	4.09	3.14	4.65	0.14	0.44	0.74	32.59
2014	55.55	32.70	20.76	7.84	3.88	3.48	4.26	0.13	0.44	0.76	30.88

- Construction Projects' Electricity Consumption (Statistics Canada):

Electricity Consumption (Terajoules)

Year/Province	ON	AB	BC	MB	NB	NL	NS	NU	NWT	PEI	QC
2010	148000	56400	51800	33700	10600	40500	11700	501	501	461	168000
2011	149000	68200	56300	35100	11200	40300	11400	442	442	492	176000
2012	149000	59100	60200	33200	9700	42500	10800	434	434	482	178000
2013	155000	59700	55000	36300	14500	41800	10500	446	446	507	184000
2014	153000	61700	53900	35500	15700	39800	10400	501	501	603	179000

- Construction Absences rates (Statistics Canada):

Absence rates for full-time employees — Construction (Both Sexes)

Year	Days lost per worker in year	National average days lost per worker
2011	8.5	8.9
2012	9.2	9.0
2013	8.6	8.7
2014	7.2	8.6
2015	8.3	8.6