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

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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 4 modules namely: BrIM module; the first ever Bridge Sustainability Rating System (BrSRS) module; Bridge Environmental Performance Strategy Map (EPSM) 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 an EPSM 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.

Keywords: - Sustainability, Conceptual, Bridges, Information, Modeling

1. INTRODUCTION

Over the past 40 years, the United Nations Ecosystem Assessment revealed that the current rate of natural resources 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. 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" (WCED 1987). 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 resources consumption, minimization of noise production and land use, and composition of recyclable components (Oswald and McNeil 2010). The life cycle of infrastructure must be considered to identify where sustainable practices and alternatives can be incorporated. The earlier the sustainability is integrated in the project's lifecycle, the more efficient and sustainable the project will be (Amekudzi, et al. 2011). Therefore, the conceptual design stage was selected for the purpose of this research due to the versatility it provides project's stakeholders in terms of making major project design related decisions.
Extensive literature review was conducted about the existing infrastructure sustainability rating systems, environmental impact analysis techniques, 3D CAD modeling and Bridge Information Modeling (BrIM) capabilities and characteristics. The 3D CAD modeling, Bridge Sustainability Rating System (BrSRS) and Environmental Performance Strategy Mapping (EPSM) were additional modules integrated within a previously developed model by the second author to provide sustainable bridge design options and BrIM capabilities through rapid information exchange and 3D rendering.

2. LITERATURE REVIEW

2.1 BRIDGE INFORMATION MODELING

Bridge Information Modeling (BrIM) is a concept similar to Building Information Modeling (BIM), but with applications to bridge projects. BIM was 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 "shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle; 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 makers decide on activities during the design and construction phases of a project. In literature, the definition of BrIM as well as its application over various project life cycle phases seem to converge towards commonality between Building and Bridge projects. 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 when they involve the crucial process of environmental management. Thus, BrIM is a shared information resource that supports the capability of 3D visualization of bridge projects at their design stage. 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.

2.2 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 off by identifying the need for a bridge as it encompasses developing a number of design alternatives, comparing them and ultimately selecting the most optimal design solution. The design comparison process involves the consideration of a plethora of factors including environmental impact assessments; feasibility studies; and life cycle analysis. These assessments are conducted in reflection to the constraints a bridge designer could face at the conceptual design stage. The constraints include: constructability; aesthetics; sustainability; economics; structural safety; durability; and environmental compatibility. The conceptual design stage process follows four steps: 1) identifying the project's need, 2) identifying the applicable technology, 3) alternative solutions generation and parameter analysis, and finally 4) alternative conceptual design selection. Designers will follow this process as it helps simplify their role. (Kroll et al. 2011).

2.3 INFRASTRUCTURE SUSTAINABILITY RATING SYSTEMS

Presently, a number of green rating systems exist for various types of projects; however, emphasis was put 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 touching base on some aspects of transportation. Recently, there has been an increased interest and dedication towards the development of sustainability rating systems that solely focus on highway planning, design and construction. Infrastructure sustainability rating systems were selected as bench-lines for this study due to their use and relevance, such as: 1) Greenroads™, 2) GreenLITES (Green Leadership in Transportation and Environmental Sustainability), 3) I-LAST (Illinois Livable and Sustainable Transportation) and, 4) Envision (Clevenger et al. 2013).

Greenroads is a rating system that facilitates tracking the level of sustainability in an infrastructure project by awarding credits for sustainable best practices. This is done by using a holistic approach of evaluating infrastructure sustainability for construction and rehabilitation through a quantitative based decision making methodology (Anderson & Muench 2013).

GreenLITES is an appraisal system that aims to encourage sustainable development, appropriateness of design, construction of low or no cost maintenance infrastructure, and identify areas that need improvement. The system is applicable during the conceptual design stage of a project’s lifecycle while it is mandatory to be used for new infrastructure projects built by NYSDOT (NYSDOT 2012).

The I-LAST sustainability rating system is a self-assessed, paper based and voluntary system 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. Since the system employs self-assessment, there are no calculations but rather yes/no answers assigned by the self-evaluator (IDOT & IJSG 2010).

Envision is a rating system 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 project lifecycle phases (planning, design, construction, and operation). The core focus of the system is on fundamental functions of a community, which include general life improvement and sustainable growth development (Georgoulias 2015).

2.4 INFRASTRUCTURE FOOTPRINT ANALYSIS

2.4.1 Footprint Indicators

The term “footprint” was defined as the “quantitative measurement describing the appropriation of natural resources by humans”; thus, illustrating the imposition and impact of human activity on sustainability (Cucek et al. 2012). In the context of sustainable development, the concept of footprints is present in the sustainable development’s three pillars: environmental protection; economic prosperity; and social dimension. Additionally, the concept of footprints tie-in with the tool Life Cycle Assessment (LCA) as the tool 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). 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). Based on the major footprint categories the suggested indicators are carbon footprint, water footprint, energy footprint, emission footprint (emissions to air, water and soil), work environment footprint (Cucek et al. 2012).

2.4.2 Environmental Performance Strategy Mapping (EPSM)

EPSM was developed to strengthen the analysis of ecological footprint and LCA tools. 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 5 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 footprints estimation is variable depending on each footprint's definition; thus, each indicator has an exclusive quantifiable calculation (De Benedetto and Kleme 2009; Cucek et al. 2012).

3. METHODOLOGY

3.3 MODEL'S 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 heuristic as rules of thumb gathered from conducted interviews with bridge design experts and the second being algorithmic that contains MTO's highway geometric design guidelines, bridge structural codes and the navigational waterway guidelines. The conceptual cost estimating module generates an approximate cost estimate of the conceptual bridge based on the dimensions and bridge type that are outputted from the knowledge-based module. The module utilizes collected cost data from various bridge projects constructed in North America and applies the necessary time and location adjustment factors. To enhance the model with BrIM capabilities and to incorporate sustainable design features, the following modules were developed and integrated with the previous two modules: 1) BrSRS module, 2) EPSM module and 3) a 3D CAD module. The BrSRS and EPSM modules enhance the conceptual design of the bridge project by allowing users to consider sustainable options early on in the project. The BrSRS permits users to customize a bridge with accordance to a developed sustainable rating system while the EPSM provides users with a preliminary EPA with relevance to the project's forecasted footprint. The 3D CAD module was integrated with the knowledge-based system as it relies on the system's output to model the bridge's conceptual design. All the modules are dynamically linked to allow for rapid exchange of information within the developed BrIM model.

3.4 BRSRS SYNTHESIS

Oswald and McNeil (2010) conducted an extensive literature review and identified a methodology that 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:

1. Define criteria for selecting the infrastructure under evaluation;
2. Develop sustainability indicator categories;
3. Develop sustainability indicators;
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 (Oswald & McNeil 2010).

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

3.4.1 Bridge Sustainability Indicator Categories

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 suit the chosen type of infrastructure for evaluation. For example, the materials and resources category was refined to incorporate the superstructural elements of bridges. The following are the developed indicators categories, their respective definitions and their objectives:

1. Project Requirements: This category is established to provide a characteristic baseline as it draws 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 lifecycle cost analysis and lifecycle inventory; moreover, it targets lowering infrastructure development impact.
2. Environment and Water: This category focusses on the physical aspects that surround the bridge project and 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.
3. Access and Equity: This category focusses on the demands of 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.
4. 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.
5. Materials and Resources: This category focusses on the allocation of construction materials and the project's resources and energy demand. The category aims to minimize the consumption of raw materials and reduce energy consumption.
6. Potential for Innovations: This category is referred to as a "catch all" type and aims at promoting sustainability innovation and influence 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.

3.4.2 Indicator Measurement, Points Allocation and Rating Scale

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 list of set indicators stems from existing rating systems, the methods of some indicators' measurement were adjusted to reflect bridge projects' development. Many of the indicators' measurements are based on engineering judgment and thus imitate the existing rating systems requirements format. Credit weight assignment was performed to establish a priority gauge depending on how important the activity/work-item is towards contributing to sustainability. This was done by allocating points according to the importance of the credit's objectives setting a prioritized process. The existing rating systems conducted rigorous studies to develop the priority hierarchy of 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 were the premise that influenced the weight assignment of credits in existing rating systems (Anderson & Muench 2013). 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 aim to design their project with sustainability features that will accumulate enough points between the specified range of the chosen target certification level. To keep the methodology consistent, the same structure as existing sustainability rating systems was implemented and the BrSRS scale was developed with four levels of certification. Because the established total of possible cumulative points for the system is 100, the minimum and maximum thresholds were set as exhibited in Table 1, where "x" is the target accumulated points:

Table 1 - BrSRS Levels of Certification and Domains

Certification Level	Points Domain
Certified	$30 \leq x < 40$
Silver	$41 \leq x < 50$
Gold	$51 \leq x < 60$
Evergreen	$61 \leq x < 100$

3.5 EPSM

The first step of building the EPSM consists of gathering the required data for each variable involved in the calculation of the list of footprints regarded by the technique 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 were identified as the required data: carbon emission rates, water consumption rates, water resource availability, electricity consumption rates, effluent/emission rates into water, air and soil, average worker absence from work due to illness or death, and average number of workers. As most of these variables are in essence measured and their data is collected over a period of time, it was best to search for such data from a reliable and public source such as Statistics Canada. 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 footprints' estimation to the required total area tantamount to provide renewable and non-renewable raw materials, produce energy, installation process needs and products and by-products storage (Ferng 2005). Using the SPI method, equations were derived from each footprint's definition and were used by the EPSM technique to estimate a project's normalized footprints. Once the impact of each footprint is calculated, the EPSM can be built. The map consists of graphing the calculated normalized footprints' percentages on a radar 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 literature (De Benedetto & Kleme 2009).

3.6 3D CAD MODELING

To provide the model with BrIM capabilities, it was decided to integrate 3D modeling of the conceptual bridge design with the existing modules. The entire model was coded in Visual Studio and thus it was best to choose a modeling software that was compatible with the coding. After considering multiple options, AutoCAD was the chosen software due to its flexibility, ease of manipulation and quick response to Visual Studio's commands. The integration process was established in two steps: 1) creation of bridge type templates and 2) Visual Studio coding to link each template with the output of the knowledge-based system. 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 dimensions output are bridge width, bridge length, longest span, bridge's total area, and parapet width. The integration process is based on the "Graphics.DrawLine" (GDL) methodology outlined by Microsoft for VB.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 were already modeled in template AutoCAD files, the method was applied by identifying the pointF structures of each line in the template files and placing them in the visual basic script. The code was 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 can be able to receive any values or modifications users implement on the 3D model of the bridge in AutoCAD and reiterate the conceptual design based on the visual modifications. Therefore, the data flow between the model's knowledge-base system and AutoCAD was developed following an easy, straightforward sequence to establish a user-friendly platform. Figure 1 illustrates the 3D modeling data flow logic.

4. MODEL DEVELOPMENT

The model integrates the 3 new modules, namely, a BrSRS, an EPSM and 3D CAD modeling with the existent knowledge-based system and conceptual cost estimating 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 followed a logical flowchart reflecting the various phases of the conceptual design stage in order to facilitate the development of a user-friendly interface. Figure 2 depicts the model's flowchart. Following the established model's flowchart, the modules were developed to fit in to their respective logical step in the model. The representation of each module was dictated by the amount of information required to display and the available selections the users could perform.

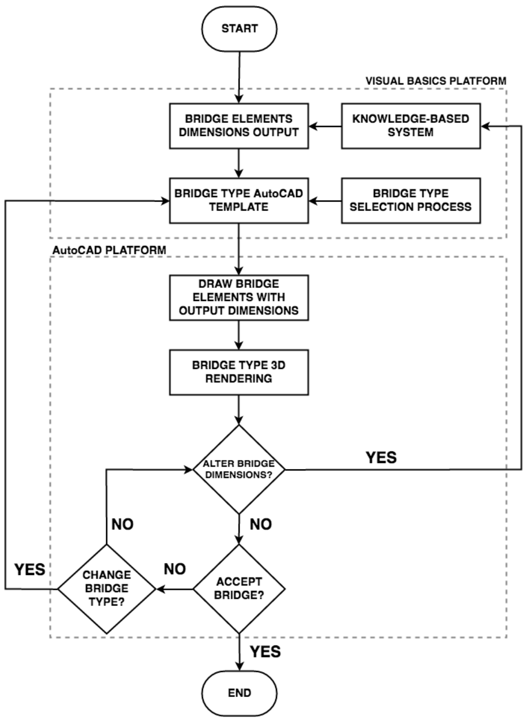

Figure 1 - Data Flow between the Model and AutoCAD

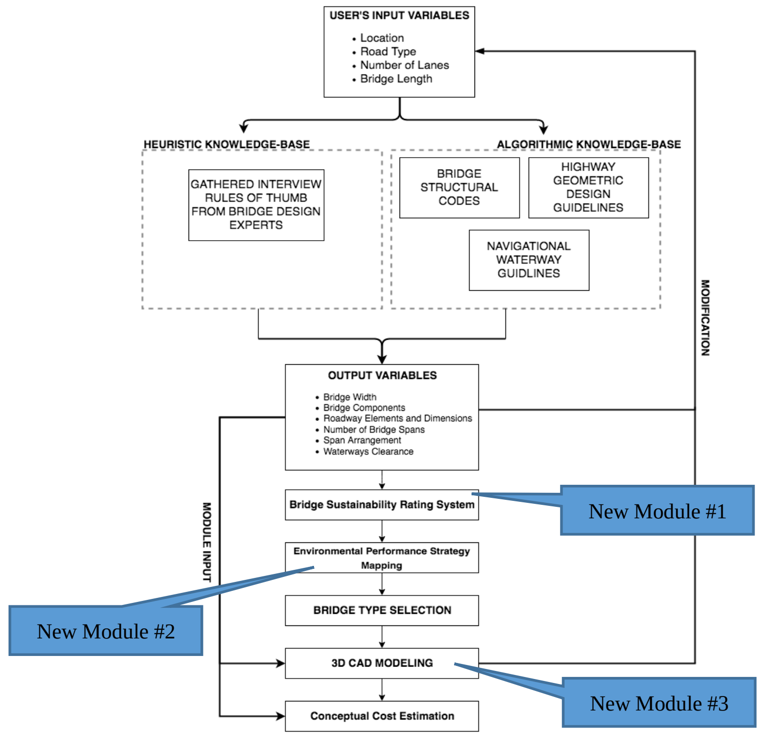

Figure 2 - Model's Flowchart

The BrSRS was exhibited via an expanding tree diagram so that users could view the tier levels of the indicator categories and credits. Once a user highlighted a credit, it's description and restrictions would be displayed. To accumulate points, users click the check boxes assigned to each individual credit, sub-category group, or indicator category group and a tally with the certification level are automatically computed and displayed. Figure 3 illustrates the BrSRS step in the model. The EPSM relies on two inputs, the intended project's province and the selection of the forecasted year (which is only up to 2018). The model runs the programmed database and equations to calculate the normalized percentages of a conventional and a sustainable bridge. The percentages are then plotted on the radar graph for comparison. Figure 4 illustrates the EPSM step in the model. When users have selected a recommended bridge type, suggested by the knowledge-based system, they can click on the AutoCAD option to view the 3D wireframe rendering of the chosen bridge type. In AutoCAD, users have the ability to change the dimensions of the bridge and then click the "Length Take-Off" button for the model to retrieve the new dimensions from AutoCAD for the knowledge-based system to reiterate the calculations and recommend a new conceptual bridge design based on the new inputs. Figure 5 illustrates the 3D model of an exemplary bridge type in AutoCAD being altered.

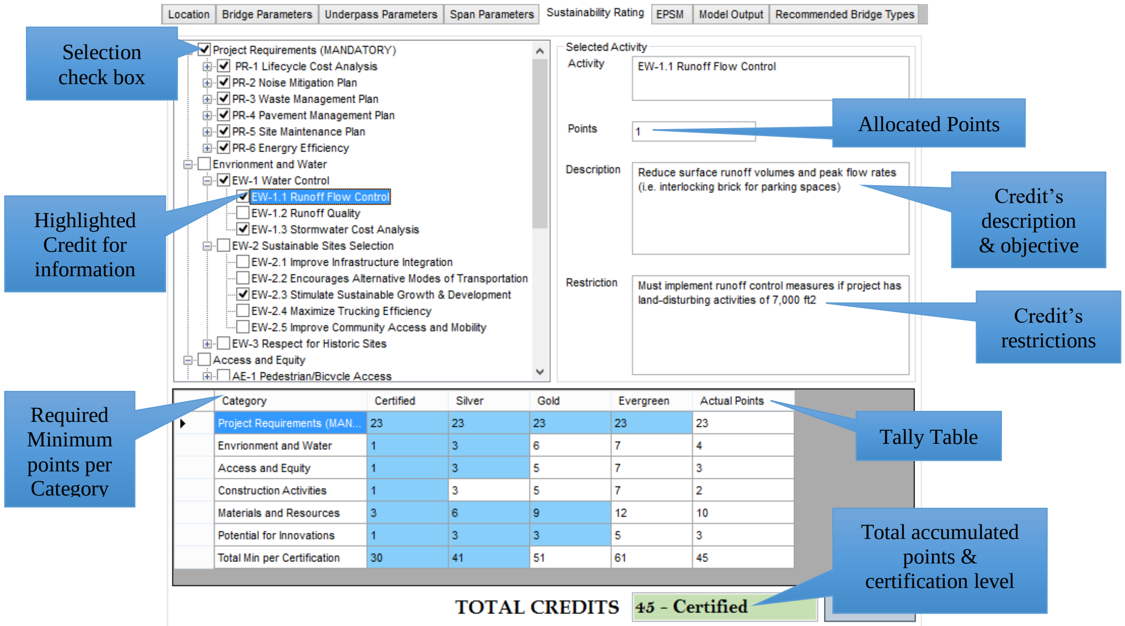

Figure 3 – BrSRS Module

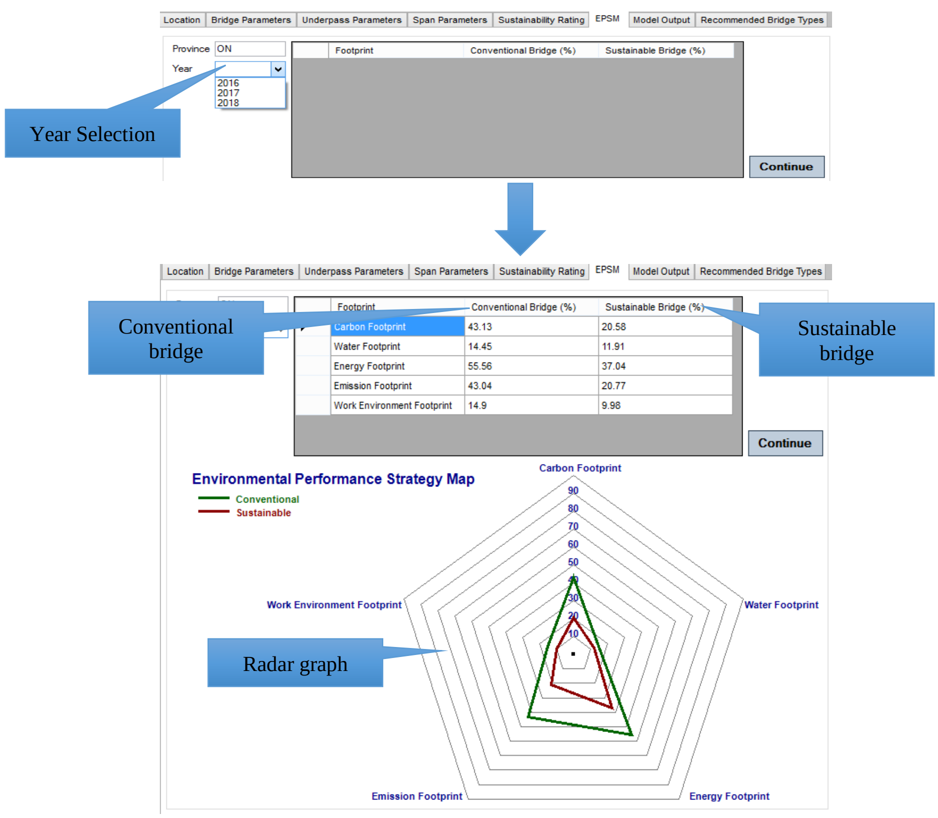

Figure 4 – EPSM Module Results

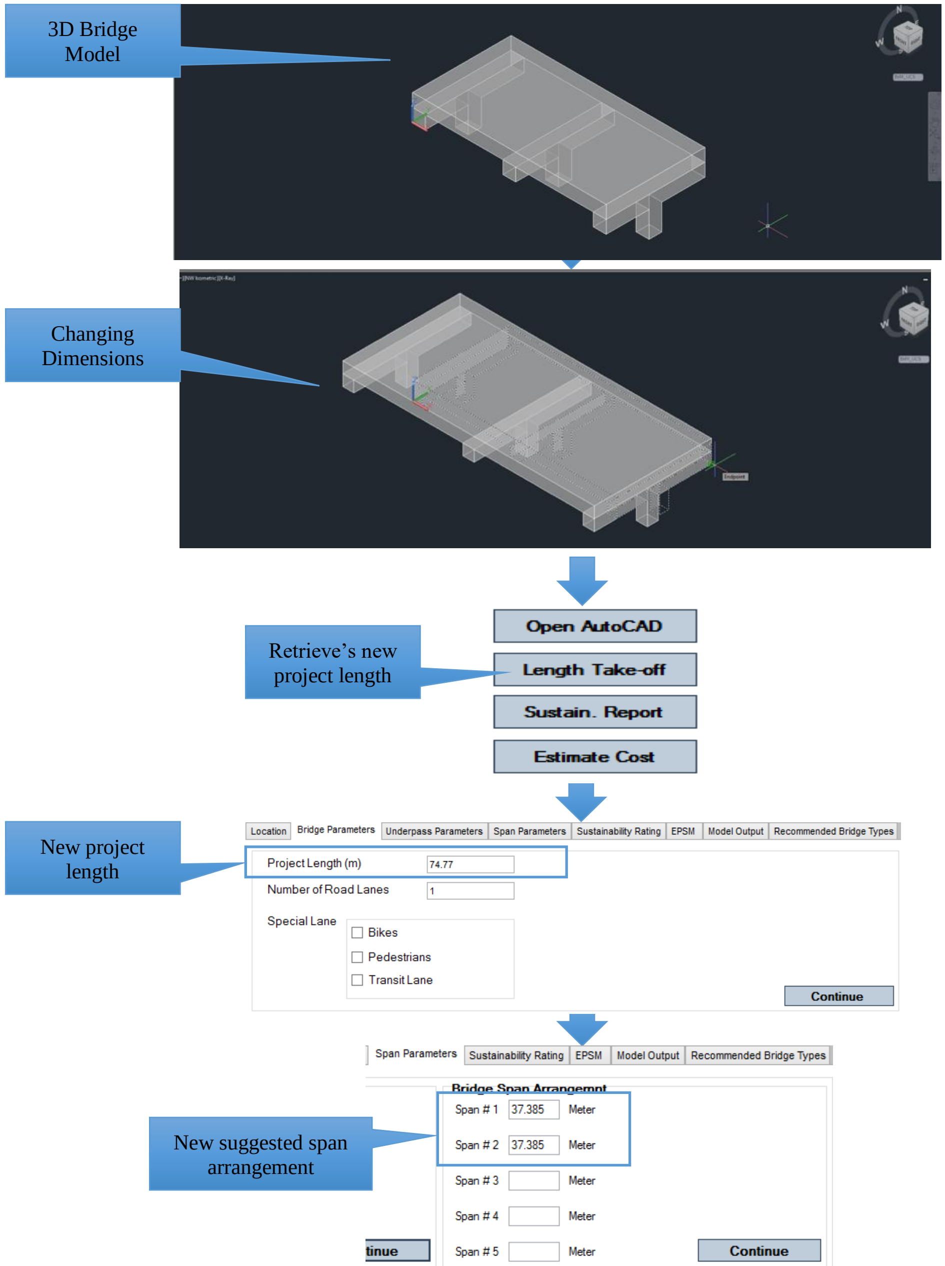

Figure 5 – 3D Model of Beam/Girder Bridge Type with Dimensions Alteration

5. CONCLUSION

A model was developed to encompass the integration of 5 modules: a knowledge-based system, conceptual cost estimating, a BrSRS, an EPSM and 3D CAD modeling. A BrSRS was synthesized by the amalgamation of existing rating systems and integrated into the model to expose users to the concepts of sustainable bridge design as early as the conceptual stage. The EPSM is a technique that is used to evaluate multiple options based on the estimation of their impacts on the environment using footprints as indicators. A database was compiled from Statistics Canada's public files and the module was integrated into the model to calculate the normalized percentages of the footprint indicators and present the results of both a conventional and sustainable bridge on a radar graph to emphasis the reduced impact of a sustainable bridge design option. In order to give the model BrIM capabilities, the model had to facilitate rapid exchange of information and model the conceptual bridges. This was accomplished by integrating

AutoCAD with the model via Visual Studio coding to establish a two-way communication conduit between the model and software. AutoCAD renders the bridges in 3D utilising the dimensions output by the knowledge-based system and transmits changes to the dimensions done on the 3D model so that the knowledge-based system can trigger a calculation reiteration based on the changes done to the design. The model has room for further development as the databases for the EPSM can be updated and expanded to include North America as a whole rather than just Canada. Moreover, updating the data to include more data points can strengthen the forecasting model and can be extended to predict future years past 2018. The 3D modeling can be improved by working on the bridge types templates to model further details beyond a simple wireframe rendering. Further research and development is underway to enhance the model.

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