CRITERIA FOR THE EVALUATION OF LIFE CYCLE ASSESSMENT SOFTWARE PACKAGES WITH APPLICATION TO CONCRETE

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Abstract:

Life cycle assessment (LCA) is defined as "the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040 1997). With such a broad scope of and timeframe for potential impacts, a LCA perspective is useful for assessing the environmental performance of various cementing material types. Prior to conducting a comparative LCA study on different concrete materials it is necessary to examine a variety of software packages for this specific focus. The paper evaluates three LCA tools in the context of the LCA of four mix designs (conventional concrete and concrete with fly ash, slag, or limestone as cement replacement). Three key evaluation criteria required to assess the quality of analysis are: adequate flexibility, sophistication and complexity of analysis, and usefulness of outputs.

1 INTRODUCTION

Life cycle assessment (LCA) enables analysis of all activities that occur during a product's life cycle, including raw materials extraction, transportation, production, use, maintenance and end of life. With such a broad scope of potential impacts, a LCA perspective is useful for assessing the environmental performance of these materials.

As the field of LCA continues to develop, an increasing number of software packages designed specifically for conducting LCAs have become available. These software packages enable quick LCA calculations even when systems and databases are very large, as they are for a typical LCA study. LCA practitioners must be able to evaluate these products critically in order to determine which product is suitable for their study. This paper, therefore, proposes a methodology for evaluating software packages using preliminary LCA data and assumptions based on a broader Ontario Ministry of Transportation (MTO)-funded research project. After the evaluation and selection process, LCA parameters can be further refined and a full study can be undertaken with the chosen software package.

2 LITERATURE REVIEW

2.1 Life Cycle Assessment

LCA is defined as "the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040 1997). ISO 14040 is a framework that serves as a guide to the four main stages of life cycle assessment, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation (Scientific Applications International Corporation (SAIC) 2006).

2.2 LCA Software Packages

LCA software packages have evolved significantly in the last 20 years, from calculations using spreadsheets or general mathematical modeling software, to highly functional applications developed specifically for LCA studies. There is currently a multitude of products on the market, with different levels of functionality and specificity, and at a variety of price points. Ciroth (2012) identifies some main characteristics of LCA software systems, which are summarized in Table 1.

Table 1 Main characteristics of LCA software systems (summarized from Ciroth (2012))

Platform	Web tools vs. desktop tools
Pricing Model	Commercial tools vs. freeware
Development Model	Open source vs. closed source
Purpose	General LCA vs. specialized tools vs. add-ons

Most of these software packages also include access to databases that can be the basis for building a strong Life Cycle Inventory (LCI), the dataset that forms the foundation of any LCA. Some software packages offer specific features such as Monte Carlo simulations or scenario analysis, or are designed for specific real-world applications. LCA practitioners must be able to critically assess which product meets the unique needs of each research project.

The capabilities of a software package cannot be fully assessed unless the evaluator actually uses the software. Similarly, evaluation should be done within the context of a specific research project, as the capabilities of the software package must align with the parameters and objectives of the project. It is impractical, however, that a LCA practitioner should fully develop models using multiple software packages solely for the purposes of comparison. In this paper preliminary LCA parameters and assumptions are established to perform a comparative study to evaluate three software packages.

2.3 Various Cementing Materials

The environmental benefits of cement replacement with ground granulated blast furnace slag, fly ash, or Portland limestone cement stem from the reduction in cement use and/or the use of a waste material. LCA is an appropriate tool to assess the potential environmental impacts of using these materials as measured throughout the life cycle of the concrete. LCA can be used to study the interplay between concrete strength, durability, and environmental impact.

Ground granulated blast furnace slag is a by-product of the steel industry, where rapid cooling of blast furnace slag results in fine, glassy particles that can be used as a direct replacement for Portland cement (Siddique and Khan 2011). Typical replacement rates range from 15-45%, and generally the strength development of slag cement concrete is similar to that of conventional concrete (Kosmatka et al. 2011 p. 78). The MTO replacement rate limits range from 25 to 50% for cast-in-place concrete and sulphate resistant foundations respectively (Konecny, 2005). Over its life cycle, slag cement concrete has been shown to have improved durability, even in aggressive environments similar to those experienced by Canadian infrastructure (Xu et al. 2008 p. 131).

Fly ash is a by-product of coal-fired power stations. Since the 1930s fly ash has been used in concrete due to its durability and structural benefits, including low permeability, good sulfate and chloride ingress resistance, low long-term shrinkage and creep, and effective mitigation of ASR (Marsh 2003). It is typically used as 15-30% by mass of the total cement content, but recent development of high-volume fly ash concrete (HVFAC) has allowed for replacement levels of more than 50% for use in structural applications (Marsh 2003). The MTO limits replacement to 10% for cast-in-place concrete and 25% for high performance concrete (Konecny, 2005). O'Brien, Menache and O'Moore (2009) have shown that replacing cement with fly ash is environmentally beneficial from a greenhouse gas emissions perspective even when very large transportation distances are required. As with slag, the improved durability of concrete containing fly ash may also influence the service life of the concrete in certain applications.

Portland limestone cement (PLC) is produced by partially replacing Portland cement (PC) clinker with ground limestone; the replacement level is typically greater than 5% (Thomas et al. 2013). In Canada, the objective is that with further research PLC may be able to replace PC in all applications and achieve adequate technical performance (Thomas et al. 2013). Generally, limestone is ground to a higher fineness than typical PC, which improves the gradation of the cement and can improve workability and increase strength (Tennis et al. 2011).

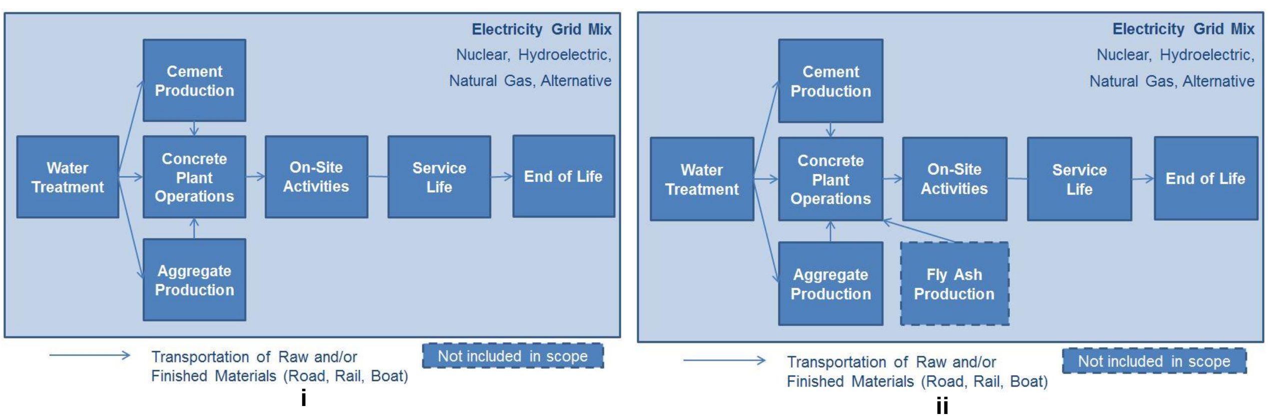
3 OBJECTIVE AND SCOPE

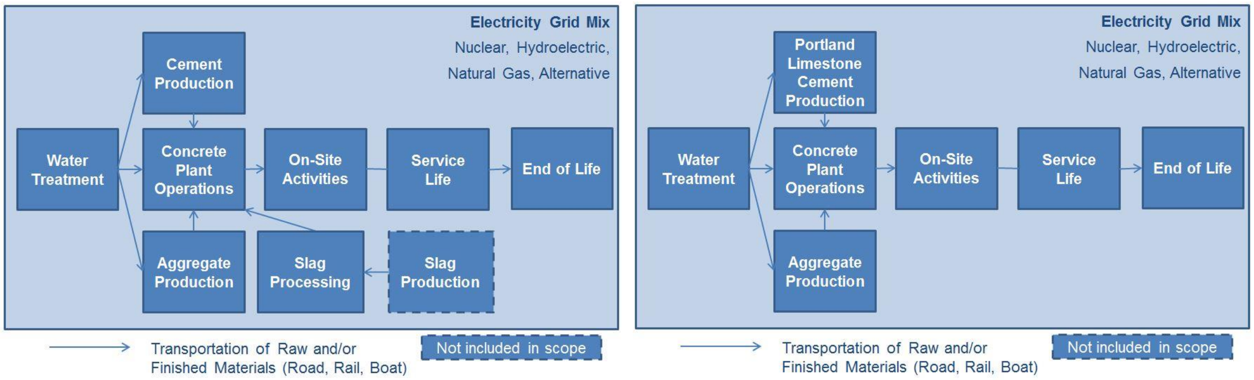
The objective of this paper is to conduct a critical and comparative review of LCA software packages for use in LCA studies of concrete products in Canada. Three software packages are included in this review, and they are identified as SP-A, SP-B, and SP-C as shown in Table 2. SP-A and SP-B, developed for highway and building elements respectively, were selected for this review as they correlate well to the geographical scope of this project. SP-C was chosen as it is one of the more popular commercially available LCA software packages.

Table 2 Software packages included in the critical and comparative review.

	Software Package (Version)	Developer (Country)	Description
SP-A	Athena Impact Estimator for Highways (1)	Athena Institute (Canada)	Free, closed source desktop tool developed specifically for LCA studies of highway and road elements and projects
SP-B	BEES (4)	NIST Engineering Laboratory (USA)	Free, closed source web tool developed specifically for LCA studies of building products
SP-C	GaBi (6)	PE International (Germany)	Commercial, closed source desktop tool for general LCA studies

It is imperative that a software package is selected within the context of a specific research project, to ensure that the final selection is truly adequate for the project. SP-A, SP-B and SP-C will be assessed in the context of a MTO-funded project. The objective of this MTO project is to evaluate and compare the environmental impact of various concrete mix designs which are often described as being more sustainable, including concrete with fly ash, slag, or limestone as cement replacement. The study presented in this paper, a critical examination of software suitability, is the first step in this overall LCA project. For this study, the functional unit is a target design strength of 35 MPa at 28 days. A functional unit is a parameter that enables analysis based on functional equivalency, and 28-day strength is a common functional requirement for concrete structural applications. The scope of this study includes the entire life cycle, including raw material extraction, production, maintenance, use and end-of-life reuse. The system boundaries for the LCA of each type of concrete are shown in Figure 1.





iii **iv**

Figure 1 System boundaries for the LCA of i) conventional concrete, ii) fly ash concrete, iii) slag concrete, and iv) Portland limestone cement concrete

The system boundaries were designed to align with the logical flow of materials and energy through each system; the diagrams presented in Figure 1 present a high level view of what activities are and are not included in the analysis. A critical factor in determining whether a software package is appropriate for this research will be whether the system boundary can be modelled accurately. Data for all the processes in Figure 1 must be available, or the software package must support the import of data from other sources.

For this comparative study, several assumptions were made to simplify the study and reduce the level of effort required at this stage, to facilitate the selection of a software package:

- The upstream production of slag and fly ash are not included in the analysis, as they are waste products that would be produced regardless of whether they are used in concrete. Using them in concrete is environmentally beneficial compared to landfilling these wastes and so not including these upstream activities, therefore, is a conservative assumption.
- For Portland limestone cement production, transportation of raw materials is not included. This is because cement production facilities are typically located at limestone quarries, and so there is no transportation requirement for these materials (CANMET and Radian Canada 1993).
- All four concrete types were included in the modeling for each software package. This was done in order to determine data availability, as this is a critical characteristic of the software packages.
- The selected functional unit (target design strength of 35 MPa at 28 days) was consistently used to the extent that this was possible given the capabilities of the software packages.
- LCI data was kept consistent across software packages wherever possible given the capabilities of the software packages.
- All chemical admixtures were excluded from the analysis. This is a common assumption due to the low relative contribution of these materials to the concrete environmental impact (Damineli et al. 2010; Nisbet et al. 2002).
- Maintenance was not included in the analysis. This is an assumption employed in LCA literature that focuses on ‘cradle to gate’ analysis (e.g. Anderson and Silman 2009).
- No weighting scheme was applied to the results

4 METHODOLOGY

4.1 General Procedure

The general methodology for this study is illustrated in Figure 2. The first task was to establish evaluation criteria. The next task was to identify whether software packages have the LCI data required for this analysis, have a selection of well-known impact assessment methods, and/or have the ability to add in LCI data or life cycle impact assessment (LCIA) methods as required. The four concrete mixes were then modelled using each software package, and outputs were evaluated for their utility, clarity, and modifiability. Throughout this process, observations about the software packages were recorded and compared with the evaluation criteria. The result of this process is the selection of a software package.

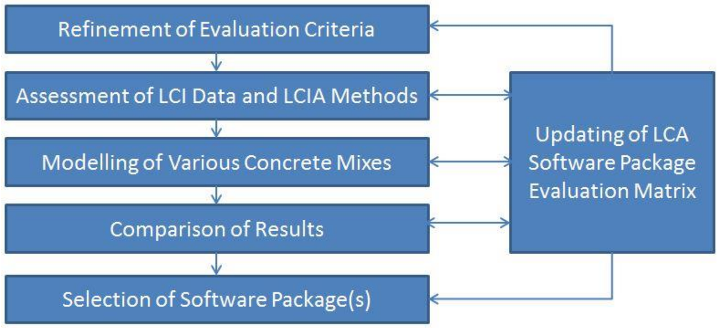


Figure 2 Selection process used during comparative study of LCA software packages.

4.2 Evaluation Matrix

The evaluation criteria should be defined such that the selection of the software package is aligned with the overall objective of the research. This evaluation matrix is generally categorized according to the stages of a LCA as follows: 1) Goal and Scope Definition, 2) Life Cycle Inventory Analysis, 3) Life Cycle Impact Assessment, 4) Interpretation, and 5) General Usability.

The questions used in the evaluation matrix have been selected to address flexibility, complexity, and outputs. This is to ensure that the selected software package will have the functionality to meet the objectives of the overall research project. The most desirable criteria are described as follows:

- Adequate **flexibility**: the ability to define custom functional units, system boundaries, and impact assessment methods; the ability to import and modify LCI data
- Sophistication and **complexity** of analysis: the presence of relevant LCI data and powerful LCIA methods; the ability to model all life cycle stages; the ability to perform sensitivity analysis; the transparency of the processes used
- Useful **outputs**: the utility, clarity, and modifiability of the outputs; in particular, the ability to extract raw output data

A numerical rating system was developed to compare the software packages. The rating legend is shown in Table 3, and the detailed questions pertaining to the five categories of the evaluation matrix and the corresponding results are shown in Figure 6. The maximum score is 48 points.

Table 3 Rating legend for numerical comparison of software packages.

Rating	Meaning
0	No/ Not at all
1	Somewhat/ Indirectly
2	Yes/ Very

5 RESULTS

5.1.1 Flexibility

In the context of LCA software packages, flexibility refers to the extent to which the user can define and modify the parameters of the study, including the system boundary, functional unit, and weighting of results. Flexibility also refers to the extent to which the system can be expanded by adding data or impact assessment methods.

The flexibility of SP-A is somewhat limited by the fact that it is developed specifically for roadway applications. The functional unit is a section of road, and it is difficult to model any other functional unit. By setting the lane length to 0.001 km, the thickness to 1000 mm and the width to 1 m, a 1 m^3 functional unit can be approximated. Similarly, the system boundary is fairly rigid, although the user can select the lifespan, type of concrete, transportation distances for raw materials, and construction and maintenance activities from pre-programmed options. For this research, it was not possible to create models for all four types of concrete using the functional unit of 35 MPa design strength, due to the limited existing options. Custom products can be created, but only if they are composed of raw materials that are already pre-defined in SP-A's database. This means that the LCI is quite limited to only data that is already provided. Similarly, the characteristics of the construction equipment in the library (ex. fuel consumption) can be modified, but no new construction equipment can be input. It should be noted that the developer of SP-A does indicate on its website that parties interested in adding a material or system to the databases should contact the developer directly. SP-A results are not weighted or normalized by the software package.

SP-B is the least flexible of the three software packages considered in this study. Like SP-A, it is limited by the fact that it was developed for a specific purpose, in this case building products, and so the database is appropriate only for projects that align with that purpose. Additionally, it is an online web application that operates based on drop-down lists of options that the user can select. This format means that users cannot input data or methods that are not built in to SP-B. Functional units are also pre-defined based on the building elements selected, and it may not be directly clear to the user what functional unit applies to which building element until the user reviews the online documentation that accompanies the web application due to a lack of transparency. Users also cannot modify the system boundary at a process level- either an element is selected and included, or it is not. Default weightings can be modified based on pre-defined or user-defined schemes. It is easy to run the software on any web browser; however results cannot be saved by the program and users must print or screenshot their results.

SP-C is the most flexible of the three options considered in this study. The software is meant to enable any LCA study, and is not limited to a specific industry or set of materials. The user defines the system boundary as they add processes to the system. For the modelling of concrete, SP-C allows for the indirect selection of functional unit through the specification of a mix design. The database that is packaged with the software is extensive, and new processes can be easily added if required. Many impact assessment methods are available for the user to select from, and users can also customize impact assessment methods.

5.1.2 Complexity

In this study, complexity refers to the level of detail at which the LCA is done, and also the transparency of the calculations to the user. It is critical that researchers be able to easily understand the software package calculations, in order to accurately interpret the results.

SP-A contains LCI data that is suitable for road infrastructure (including the types of concrete being studied) and is specific to Canada (subdivided into 9 Canadian regions); in the context of the data quality indicators discussed above it has a moderate technological correlation and a high geographic correlation to the research project. The data appears to be updated semi-regularly; the oldest data is from 1997. SP-A has a fairly detailed user interface that allows for the modelling of activities that occur over the infrastructure's lifespan, including maintenance activities, operating energy and pavement-vehicle interaction. There are two options for the end-of-life stage, including demolition and landfill. There is one impact assessment method that was developed for this tool, but is based on the US EPA's TRACI methodology. The results cannot be weighted directly. The user interface is somewhat difficult to navigate, and the calculation process is not very transparent.

SP-B has a database built specifically for this tool, and as such it consists of only building construction and maintenance materials. The data is collected from the industry in the United States, and so it has a moderate level of geographical correlation and a fairly high level of technological correlation given similarities between the industries in Canada and the United States (Marceau et al. 2006 p. 28). One potential issue with using SP-B for Canadian applications is that the electricity profiles of different regions of the two countries may be very different, and as electricity is typically another major source of environmental impact after cement production, this could significantly affect the results. In the calculation of environmental impact, the weightings can be modified. The drop-down structure of the tool, while it has the limitations mentioned above, also creates a highly intuitive user interface. The calculations, however, are not very transparent as it is unclear how the results are generated. In addition, during the preparation of the comparative study the web applications experienced errors on several occasions that required the user to restart work.

SP-C has a large database with multiple additional databases specific to certain industries or regions, which can be purchased. In addition, the user can also import or add data to their system. The types of concrete being included in this study are all contained in these databases. SP-C contains most major impact assessment methods, and also allows users to input their own methods. The software can be used to perform sensitivity analysis and compare alternatives. The data entry is intuitive as it consists of building a network diagram of processes, with logical connections and movements of materials and energy between them. The strength of SP-C is the transparency of the tool, which is due to the extensive and easily available documentation of all activities, and the high level of control that users can exercise over the details of their projects. SP-C also provides the most useful support for users of the software, in the form of a detailed online Learning Centre, and live chat with experts online.

5.1.3 Outputs

Comparative study modeling of the concrete types was done for the purpose of testing the software packages and exploring potential outputs. Note that the results of the modeling are not directly comparable and the absolute values of these numbers are not at all finalized. These have not been reviewed, optimized or evaluated for sensitivity. Due to the limitations of the software packages, it was not possible to ensure consistent LCI data and functional units.

Calculations were done for all four types of concrete within the scope of this research in order to ensure that they could be modelled by each software package; results for concrete containing 20% fly ash replacement are shown as output samples in Figure 3, Figure 4, and Figure 5. Note that for SP-A it was not possible to model the functional unit of 35 MPa strength, as only 30 MPa strength was available for selection. Results for a single impact category, global warming potential, are included here to demonstrate what types of outputs are produced by the software packages.

In addition to examining raw graphical outputs, for the purposes of research and the presentation of results, it is also critical to determine whether the numerical raw outputs are available. Free access to this data is necessary for processing of the data including normalization, weighting and sensitivity analysis; these are all activities that commonly occur in LCA.

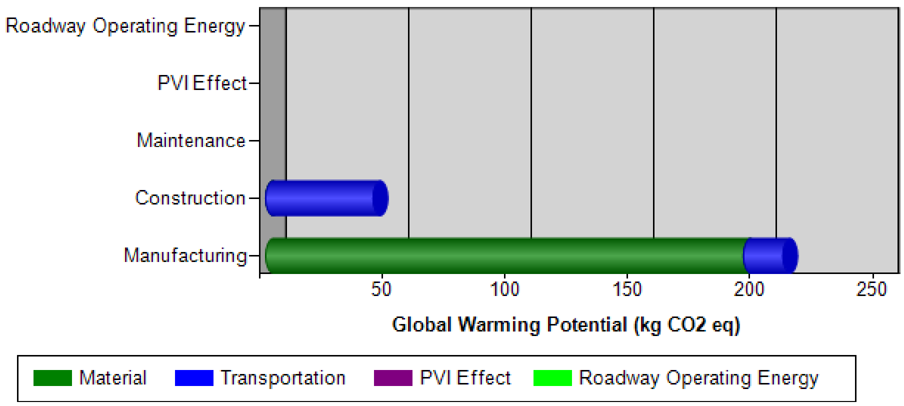


Figure 3 Software Package A: LCIA Result for 30 MPa Concrete with 25% Fly Ash Replacement

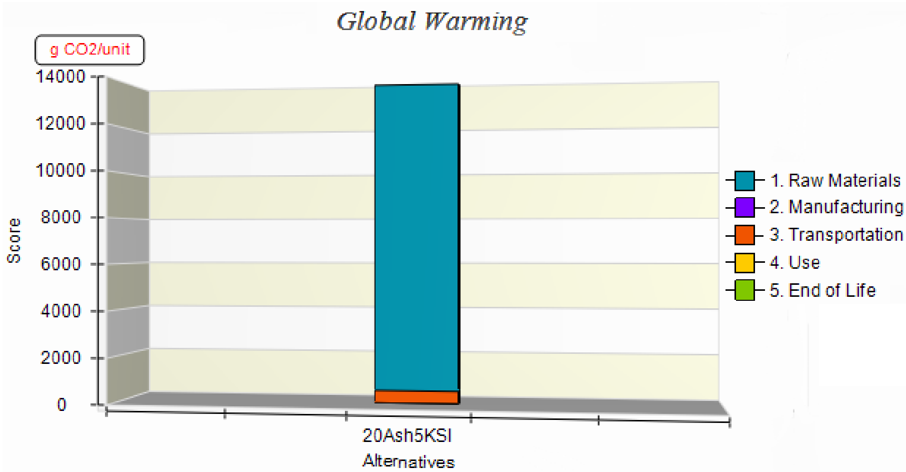


Figure 4 Software Package B: LCIA Result for 35 MPa Concrete with 20% Fly Ash Replacement

SP-A produces very simple results that can be aggregated or separated by impact category. Absolute value results are also available. A somewhat confusing aspect of the outputs from this software is that categories that were not included in this comparative study (ex. maintenance, pavement vehicle interaction) are still shown on the y-axis of the graph, giving the impression that they might have a '0' rather than 'N/A' value. Quantitative data outputs can be extracted from the software, either aggregated or separated by impact category. Results can be exported to Microsoft Excel, Microsoft Word, or PDF.

SP-B produces simple and clear graphs that can be displayed in aggregated form or by impact category. Results can be shown divided by life stage, by environmental flow, or by embodied energy. A strength of SP-B is that it allows for easy comparison of multiple products and displays these comparative results in a variety of different charts. Results from SP-B are simultaneously displayed as graphs and as charts. The weakness of SP-B is that as it is purely a web application, results cannot be saved easily. Charts and tables must be printed or copied for future reference. The parameters of the graphs, such as the axis titles, labels, legend, etc. cannot be modified. The graphs can be saved as images or copied into another program.

SP-C produces charts that are separated by impact assessment method and impact category. The charts show the breakdown of each impact category by each process modelled. The user can modify all of the parameters of the graph, including titles, axes, colours etc.. Quantitative data tables can be organized in several different ways. Users can select the exact parameter that they want to study in detail, and can organize the results based on absolute value or relative contribution. The software can also perform a weak point analysis, identifying processes and flows with a high relative contribution to the environmental impact of the system. The graphs and tables can be easily exported or copied into another program.

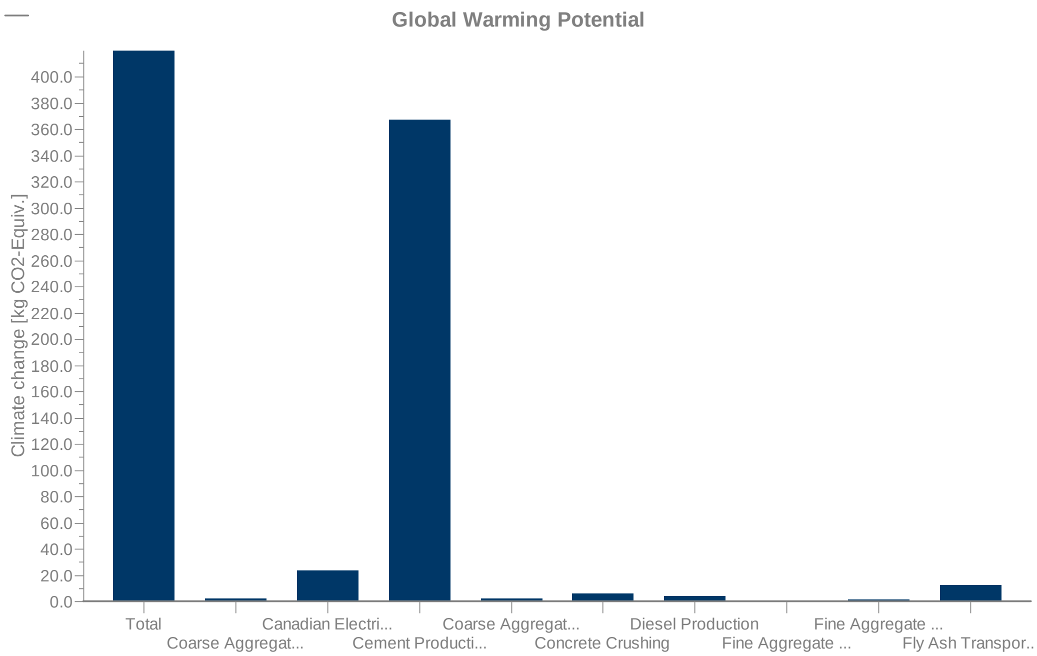


Figure 5 Software Package C: LCIA Result for 35 MPa Concrete with 20% Fly Ash Replacement

6 CONCLUSIONS

The results of this comparative study are shown in Figure 6. The software package with the highest score is SP-C, with 45 out of a possible 48 points. Its main advantage is that it allows for the user to have a high level of control over the system being modelled and the calculation methods used. Based on these findings, this evaluation methodology will be applied to other software packages that potentially have these characteristics in order to finalize the selection of a package. The selected software package will then be used to complete a full LCA study, including the creation of a detailed LCI, the selection and application of impact assessment methods, and interpretation of the results within the specific context of the evaluation and comparison of the environmental impact of various sustainable concrete mix designs for MTO concrete infrastructure.

This comparative study highlights the importance of selecting a software package that is appropriate for a specific research project. Note that the software packages reviewed for this study represent a sample of available products, and other products should be evaluated for other applications. The ability to accurately model the chosen functional unit and system boundary is an important selection criterion. Three key criteria are defined and explored: adequate flexibility, sophisticated and complex analysis, and useful outputs.

This study also demonstrates a method to select a software package while reducing the level of effort required at the preliminary stage of a LCA. By prioritizing the most important selection criteria, and making some preliminary assumptions to simplify models, LCA practitioners can assess the advantages and disadvantages of different tools without having to fully develop and optimize their models in multiple software packages. This can enable a critical and rigorous comparison without excessive and redundant duplication of efforts. The selected software package is then the basis for further development of a LCA.

No.	Primary Criteria Addressed	Questions and Sub-Questions	SP-A	SP-B	SP-C
1.0		**Goal and Scope Definition**			
1.1	Flexibility	Can system boundaries be defined by the user?	1	0	2
1.2	Flexibility	Can users input any functional unit that they want?	0	0	1
2.0		**Life Cycle Inventory Analysis**			
2.1	Complexity	Does the software include a database of inventory information for life cycle processes?	2	2	2
2.1.1	Flexibility	Can additional databases be added?	0	0	2
2.1.2	Complexity	Are the databases relevant to Canada?	2	1	1
2.1.3	Complexity	Is the available data relevant to the concrete industry?	2	2	2
2.1.4	Complexity	Is the data updated regularly?	1	1	1
2.1.5	Complexity	Are the concrete types to be studied included in the database already?	2	2	2
2.2	Complexity	Can the use stage of a product be modeled?	2	0	2
2.3	Complexity	Can the disposal phase of a product be modeled?	1	1	2
3.0		**Life Cycle Impact Assessment**			
3.1	Complexity	Does the tool include impact assessment methods?	1	2	2
3.1.1	Complexity	Do the impact assessment methods support weighting?	0	2	2
3.1.2	Flexibility	Can the default weightings be modified?	0	2	2
3.1.3	Flexibility	Can you set a 'cut off' point for what impacts are included?	0	2	2
3.2	Complexity	Can you incorporate other impacts besides environmental ones?	2	2	2
4.0		**Interpretation**			
4.1	Output	Does the software generate graphical representation of results?	2	2	2
4.2	Output	Are the quantitative or physical data outputs readily available?	1	2	2
4.3	Complexity	Can the software be used to perform sensitivity analysis?	1	1	2
4.4	Output	Can the software be used to compare alternatives?	2	2	2
5.0		**General User-Friendliness**			
5.1	Complexity	How intuitive is the data entry?	1	2	2
5.2	Complexity	How transparent is the process?	0	0	2
5.3	Complexity	Does the software have a good user interface?	0	2	2
5.4	Output/ Flexibility	How easy is it to compare alternatives by making small changes?	1	2	2
5.5	Complexity	Is support provided for users of the software?	0	1	2
TOTAL (MAXIMUM POSSIBLE SCORE = 48 POINTS)			**24**	**33**	**45**

Figure 6 Questionnaire and evaluation matrix results for the comparison of three software packages.

7 Acknowledgement

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