Preliminary sensitivity study on an life cycle assessment (LCA) tool via assessing a hybrid timber building

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Abstract

In order to address concerns related to global warming and increased atmospheric carbon content, the life cycle assessment (LCA) tool has demonstrated usefulness in the building and construction sector. The LCA is used to evaluate environmental impacts concerning all stages of the building process from “cradle” to “grave”. The LCA helps promote sustainable development by considering environmental indicators such as stratospheric ozone depletion, eutrophication, global warming potential, and many more. It is of interest to know the degree of impact on a given environmental indicator if an input is changed in terms of the type or amount of the materials used. The LCA software Athena IE4B was employed to analyze data of a selected timber building. This study was aimed at evaluating the sensitivity of LCA analysis on a hybrid timber building, which was done via two case studies. Case 1 focused on changes in the volume of wood materials, meanwhile Case 2 focused on simultaneous changes in the volume of materials for wood, steel, and concrete. In Case 1, it was observed increasing wood materials increased environmental indicators, with stratospheric ozone depletion being the most sensitive and global warming potential as the least sensitive. Case 2 discovered that proportionally increasing wood materials in relation to steel and concrete materials decreased environmental indicators, with eutrophication being the most sensitive and stratospheric ozone depletion as the least sensitive. This study helped support the feasibility of using Athena IE4B for LCA analysis in the initial assessment of a building.

1. Introduction

It is reported that the combustion of fossil fuels generated an emission of more than 32.5 gigatonne (GT) of CO₂ in 2017 (Abergel et al., 2017). Fuel combustion results in a continuous increase of CO₂, which may eventually lead to environmental problems such as global warming. Decreasing atmospheric carbon content has become an international hot topic, increasing worldwide interest in a low carbon economy. The building and construction sector alone consumes 36% of the final global energy use and produces 39% of energy-related carbon dioxide emissions (Abergel et al., 2017). Since 2010, CO₂ emissions have continued to increase by about 1% annually, while household air pollution causes more than 4 million deaths each year (Abergel et al., 2017). As indicated by the United Nations Environment Program, the estimated amount of emissions will be doubled by 2050 if there are zero new and innovative technologies developed in construction in the meantime (Howe, 2010).

In the construction sector, sustainability has increasingly become an important factor (Ritter et al., 2011). Sustainability is defined as the study of balance retention concerning natural system functions, diversity retention, and production focused on minimal damage to the environment. Sustainability has primary environmental goals of reducing the effects of climate change, pollution, and other
environmental factors (Pisano et al., 2015). With an increase in awareness towards the living environment, wood has been used to replace steel and concrete as a main building material in the 21st century (Frearson, 2016). The issues of natural resource depletion and environmental degradation have also been considered. These environmental issues can be resolved to a large degree by considering environmental impacts and improving performances of products and processes to support “greener” initiatives such as using wood and wood-based products as building materials.

To approach these environmental issues and provide insight towards possible solutions, the life cycle assessment (LCA) has been developed and used to evaluate the environmental impacts for all the stages of a product, such as a building from its “cradle” to “grave” (Margni and Curran, 2012). The LCA starts with a “cradle” by gathering raw materials from the earth, creating the product, and then returning all materials back to the earth, i.e., “grave” (Margni and Curran, 2012). The unit process of the LCA is defined and used to assess the impact of each material and process to systematically synthesize a complete LCA study for the product (Sharma et al., 2011).

The LCA enables the estimation of all environmental impacts on the life cycle of a product. Typically, it involves raw material extraction, material transportation, product manufacturing and distribution, product use and disposal, etc., which does not take traditional analyses into account. Using the LCA to access a product helps provide a comprehensive view of the processes of the product alongside environmental factors of all the materials used. The user will consider trade-offs for a more convenient selection (Margni and Curran, 2012). For the construction industry, the LCA can be an effective tool to help investors determine trade-offs early on in the building design process (Han and Srebric, 2011).

It is of interest to know the degree of impact on a given environmental indicator if an input is changed in terms of the type or amount of the materials used. Thus, an in-depth understanding of selecting the most important inputs when using an LCA software can be gained. This study was aimed at evaluating the sensitivity of the LCA analysis on a hybrid timber building via the LCA software Athena IE4B.

2. Methods

2.1. The LCA analysis

To conduct a LCA study, ISO 14,040 series standards should be complied with. The ISO 14,040 series standards for the LCA address quantitative methods for assessing the environmental aspects of a product or service in its entire life cycle phases. The ISO 14,040 is an overarching standard encompassing all four phases of the LCA (ISO, 2006), including: 1) ISO 14,041 deals with defining the goal and scope phase, and life cycle inventory methods; 2) ISO 14,042 deals with life cycle impact assessment methods; and 3) ISO 14,043 deals with life cycle interpretation methods. The relationship between these four phases stipulated in ISO 14,040 series standards are illustrated in Fig. 1 (Margni and Curran, 2012).

Definition of goal and scope is the first step of the LCA. In this step, the Functional Equivalent, system boundaries, and quality criteria for inventory data will be defined (Sharma et al., 2011). The goal and scope should be defined clearly enough to make sure that the breadth, depth, and detail of the study are addressed sufficiently (ISO, 2006).

Inventory analysis is the second step of the LCA. It includes data collection and calculation procedures (ISO, 2006). Life cycle inventory (LCI) is the data collection portion of the LCA (Athena Sustainable Materials Institute, 2018b). It tracks material and energy flows in and out of the product system. The elements of inventory include raw materials, energy by type, water use, and emissions to air, water, and land by specific substance. The process of analysis can be very complex and may involve many individual unit processes in one supply chain, as well as tracking different substances for hundreds of times (Athena Sustainable Materials Institute, 2018b).

Life cycle impact assessment (LCIA) is the third step of the LCA, which is used to make connections between the inventory of basic flows for the system of the product and its potential environmental impacts (Hauschild and Huijbregts, 2015). In the LCIA, different environmental impacts are assigned to different environmental impact categories (Sharma et al., 2011). The environmental impact categories refer to abiotic and biotic resource depletion, global warming, ozone depletion, etc. Globally, there are various calculating methods of environmental impact. In North America, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) methods are normally used. These methods focus on the following impact categories: ozone depletion, climate change, acidification, eutrophication, smog formation, and non-renewable energy consumption (Bare et al., 2012). The life cycle impact of the flows to and from the environment will be categorized and characterized by those methods. Complications may arise during the comparability of different LCA studies. Variables that may affect the LCIA include the system boundary, the functional equivalent, and specific LCIA methods chosen. When comparing two LCA studies, these factors are important to understand if the comparison is feasible (Athena Sustainable Materials Institute, 2018b).

Life cycle interpretation is the last step of the LCA. Life cycle interpretation includes the identification of significant issues and the evaluation of results. It deals with the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment (Sharma et al., 2011).
2.2. Research base

In this study, Athena Impact Estimator for Building (IE4B) was used as the research base for the ISO 14,040 series. The IE4B is a Canadian software for conducting an LCA assessment on a building, which is an open source software (Athena Sustainable Materials Institute, 2018a). It is applicable towards any types of new construction, renovations, and additions projects in North America. It can model over 1200 structural and envelope assembly combinations and allows for quick and easy comparisons of multiple design options. The IE4B provides the inventory profile for a whole building over its entire life cycle, i.e., from product stage to construction process stage, to use stage and finally, to the end of life stage. Such an inventory includes the flows from and to nature, emissions by energy, and raw materials to air, water and land. Athena becomes a leader in environmental declarations, including pioneered environmental building declarations (EBDs) to produce whole building life cycle declarations with a real commitment to accountability and transparency in sustainable design for building owners.

Another important section of Athena IE4B is its database and environmental impact assessment tool. Athena IE4B has its own life cycle inventory called Athena database. The TRACI 2.1 (tool for reduction and assessment of chemicals and other environmental impacts) was selected as the environmental impact assessment tool. It provides characterization factors for the LCIA for the analysis results. The environmental factors include ozone depletion, climate change, acidification, eutrophication, smog formation, human health impacts, and ecotoxicity (Bare et al., 2012). The level of sensitivity of a given factor to the LCIA results are different from one another at any given situation.

2.3. Sensitivity analysis

The sensitivity study was conducted by using Athena IE4B. The John W. Olver Design Building of the University of Massachusetts (USA) was selected as the reference building. This building is the largest and most technologically advanced academic contemporary wood structure. It is also the first building in the USA. that uses a wood-concrete composite floor system (Building and Construction Technology, 2017). This building has already been assessed using the first environmental building declaration (EBD) for a U.S. building by Athena Sustainable Materials Institute and published by United States Department of Agriculture (USDA) Forest Service, Forest Products Laboratory (FPL) (Gu and Bergman, 2018).

In this study, the research was based on the data acquired from the open source report from USDA FPL and was permitted by the Project Leader. In order to conduct the study, all the materials of different units were converted into the same unit. Then, all the material density values as provided by Athena IE4B could be used to convert their mass to volume. The volume of each material used in the representative building is given in Table 1. Concrete and wood were the main building materials that were used in the representative building, taking up 32.0% and 31.1%, respectively (Table 1). Thus, concrete and wood were considered as variables in the sensitivity study. Since steel is a main structural building material in construction, steel materials were also considered in the sensitivity study. Other construction materials were not considered due to their low quantity, which did not, therefore, influence the total volume to a significant degree.

Two case studies were conducted in this study, and one corresponding to the percentage of wood volume and the other corresponding to the proportional percentage of wood volume in relation to steel and concrete. The data of the raw materials and annual operational energy used from each step were used as inputs in Athena IE4B. Meanwhile, the total environmental impact results were compared with the published results for the baseline building.

In Case 1, the volume of wood materials was changed, meanwhile the volumes of all other materials, such as steel and concrete, were kept unchanged. The changes were made by increasing (+) or decreasing (−) the volumetric percentages of wood materials, such as by: −20%, −10%, +10%, +20%, and +50%. After estimating the environmental impact for each plan, the results were compared with the results of the baseline building. Thus, the sensitivity level of each environmental indicator could be understood by changing the total volume of wood materials. Athena IE4B was run by imputing the data for the raw materials and annual operational energy used from each step.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Materials inventory of representative building.</td>
</tr>
<tr>
<td>Material type</td>
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<tr>
<td>Aggregate</td>
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<tr>
<td>Concrete</td>
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<tr>
<td>Gypsum</td>
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<tr>
<td>Insulation</td>
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<tr>
<td>Roofing</td>
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<tr>
<td>Steel</td>
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<tr>
<td>Wood</td>
</tr>
<tr>
<td>Other materials</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Source: Gu and Bergman, 2018.
In Case 2, the volume of wood materials was changed by −20%, −10%, +10%, +20%, and +50%, while the volumes of steel and concrete materials were also changed accordingly by +20%, +10%, −10%, −20%, and −50%. In this case, the total volume of building materials used could be considered the same. The volumetric changes in wood, concrete, and steel materials could be considered as an alternative analysis. The results were also compared with those of the baseline building. The volumes of wood, steel, and concrete were input into Athena IE4B by considering the raw materials and annual operational energy used from each step.

### 3. Results and discussion

In Case 1, only the wood materials were volumetrically changed in the reference hybrid timber building, in which every environmental impact result was divided by baseline results. The results from Case 1 for each step are shown in Table 2 and Fig. 2. As illustrated in Fig. 2, the trends of data of Case 1 are very clear. All the environmental indicators no doubt continuously increased with increasing wood materials. Based on the slope of each curve, it can be observed that the most sensitive indicator in this case was stratospheric ozone depletion, followed by tropospheric ozone formation, acidification of land and water, eutrophication, depletion of non-renewable energy resources, and finally global warming potential as the least sensitive indicator.

In Case 2, the volumetric percentage of each major building material (i.e., wood, steel or concrete) used in the reference building was changed proportionally, meanwhile, the total volume of building materials was kept the same. The environmental impact results from each step for the Case 2 are shown in Table 3. Every environmental impact result was divided by baseline results and presented in Fig. 3. In Fig. 3, the trends of data from the Case 2 are different from the Case 1. Simultaneously changing the volumes of wood, steel, and concrete materials demonstrated a decrease in the environmental effect results. Eutrophication became the most sensitive indicator in this study, followed by global warming potential, depletion of non-renewable energy resources, acidification of land and water, tropospheric ozone formation, and stratospheric ozone depletion as the least sensitive indicator.

The environmental impact results were compared with the published results for the baseline building (Table 4). The data were converted to a logarithmic scale for a better comparison. It can clearly found that there are some differences in results between the data of this study and those published, suggesting the calculation errors from Athena IE4B between the authors’ and the published results. This could be due to the fact Athena IE4B is a kind of “black box” software, the operational errors can not be amended.
Table 4
Comparison of baseline building between author’s and published results.

<table>
<thead>
<tr>
<th>Summary measure</th>
<th>Author’s baseline building result</th>
<th>Published baseline building result</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential</td>
<td>4.83E+06</td>
<td>4.61E+06</td>
<td>-4.40%</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>4.28E-02</td>
<td>8.53E-02</td>
<td>99.23%</td>
</tr>
<tr>
<td>Acidification of land and water</td>
<td>2.80E+04</td>
<td>2.39E+04</td>
<td>-14.83%</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>2.51E+03</td>
<td>1.38E+03</td>
<td>-45.12%</td>
</tr>
<tr>
<td>Tropospheric ozone formation</td>
<td>4.46E+05</td>
<td>3.82E+05</td>
<td>-14.38%</td>
</tr>
<tr>
<td>Depletion of non-renewable energy resources</td>
<td>5.79E+07</td>
<td>5.65E+07</td>
<td>-2.47%</td>
</tr>
</tbody>
</table>

Fig. 3. Sensitivity study of environmental impacts in relation to simultaneous changes in all three main building materials.

Fig. 4. Comparison of environmental impact of baseline building between author’s and published results.

Fig. 4 compares the authors and published results, suggesting a strong difference of 99.23% can be observed for stratospheric ozone depletion. Meanwhile, the lowest difference of -2.47% can be observed for the depletion of non-renewable energy resources.

Conclusions

Based on the results and above discussion, the following conclusions could be drawn.

(1) Only increasing the volume of wood materials used in the reference hybrid timber building no doubt increased the values of environmental indicators. The most sensitive indicator in this case was stratospheric ozone depletion and the least sensitive one was global warming potential.

(2) By changing the volume of each major building material (i.e., wood, steel or concrete) used in the reference building in a proportional way and meanwhile keeping the total volume of building materials the same, it was found eutrophication was the most sensitive indicator and stratospheric ozone depletion was the least sensitive one.

(3) There were some differences in the results between the authors’ and published data, suggesting the existence of calculation errors from Athena IE4B, which was difficult to fix due to the fact Athena IE4B is a kind of “black box” software. Thus, Athena IE4B can be used as a tool for architects and engineers to conduct an initial and quick environmental analysis.
Taking the various sensitivity of environmental indicators into consideration, it could be reasonably speculated that an optimized use of all building materials should be made with an aim to reduce the potential environmental impact.

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References


Bare, J., Young, D., Qam, S., Hopton, M., Chief, S., 2012. Tool For the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). US Environmental Protection Agency, Washington DC, USA.


