TOOLKIT TO CAPTURE ENVIRONMENTAL EMISSIONS IN CONSTRUCTION PHASE OF BUILDINGS IN THE AUSTRALIAN CONTEXT

Malindu Sandanayake, Guomin Zhang and Sujeeva Setunge
Department of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia

Buildings consume a large amount of natural resources and generate high volumes of environmental emissions. A number of studies have attempted to quantify these life cycle emissions of buildings. Unlike other phases, emissions at the construction phase of a building include both greenhouse and non-greenhouse gas emissions. Most of the emission studies on buildings have either overlooked or concentrated only on greenhouse gas emissions when considering emissions at the construction phase. On the other hand, the majority of the commercially available software either lacks reliable inventory or involves complex modelling processes to quantify emissions at the construction phase. Many industry personnel and researchers observe the requirement of a simple toolkit which can accurately evaluate emissions at construction phase with minimum effort. Thus the main focus of the study is to develop a toolkit which can estimate and compare emissions due to materials, equipment usage and transportation at construction phase of the building. The emission factors published by United States Environmental Protection Agency, Australian National inventory report and Inventory of Carbon and Energy were adopted to develop the mathematical models in the toolkit to estimate greenhouse and non-greenhouse gas emissions due to equipment usage, transportation vehicles and materials, respectively. The main functions of the toolkit also include comparison of emissions between two construction methods and activities of the project. A case study was utilized to justify the validity and implementation of the toolkit. This developed toolkit will aid researchers and construction contractors to estimate and compare emissions of different construction techniques with minimum effort.

Keywords: greenhouse gas emissions, construction phase, toolkit.

INTRODUCTION

Buildings are known to be a major contributor of natural resources consumption and environmental emissions with studies showing that it contributes 30% of the greenhouse gas (GHG) emissions (Mao et al., 2013). Apart from GHG emissions, buildings may indirectly contribute towards non-GHG emissions due to its heavy equipment utilization at construction stage. Both these emissions may have adverse environmental and health effects in both short run and long run. Therefore a slight opportunity to reduce these emissions would attract significant emission reduction prospects. At initial stages of the building construction industry, the main research focus was to introduce cost efficient buildings with little interest given to the environment. But the introduction of sustainable construction has changed the fundamental research focus towards energy-efficient buildings. These energy-efficient...
building designs typically focus on the use phase of the building in order to provide improved comfort level to its inhabitants. Apart from use phase, a typical building is also associated with emissions due to materials, construction and end-of-life. Although emission studies have outlined the significance of emissions at use phase, the emissions at other phases cannot be neglected (Guggemos and Horvath, 2005). Focusing only on use phase will not only eradicate the possibilities of reduction of emissions at other phases, but also will eliminate the possibility of the analysing total environmental impact of a building.

Life-cycle assessment (LCA) is a technique that measure environmental impacts of a product or a process over its life cycle (Diakaki and Kolokotsa, 2009). Selection of materials, equipment and construction techniques may influence the total emissions of a building considerably at an aggregated level. Therefore emissions at construction stage should be given more attention. However, Research studies seldom focus on analysing environmental emissions at construction stage due to many complications (Guggemos, 2003). Collection of accurate and reliable on-site data and constant disturbances at the construction site are few of the major issues at the data collection stage that would force researchers to give less consideration on construction stage. Apart from data collection issues, lack of reliable software which can estimate emissions at construction phase is another major issue for studies to approximate or neglect the emissions at construction stage. Thus contractors and designers find the necessity of a toolkit that is able to evaluate and compare emissions at construction phase with minimum effort.

The objective of this paper is to develop a toolkit that is able to estimate and compare environmental emissions at construction stage of a building. A framework was initially developed to identify the functions of the toolkit. The toolkit is able to separately analyse the emissions due to materials, equipment usage and transportation. Knowing the emissions at a lower level will enable the designers and contractors to introduce emission reduction methods during the execution phase. A previous case study from a literature is used to check the accuracy and functions of the toolkit.

TOOLKIT DESIGN AND DEVELOPMENT

Functions and scope of the toolkit

The aim of the study is to include the following functions in the toolkit.

- Analysis of emissions at construction stage with minimum effort
- Assessment of the emission patterns of the construction equipment used
- Emission evaluation between two construction techniques
- Comparison of emissions among the activities of construction stage

The next design step is to specify the scope and system boundary for the defined functions. The system boundary is selected to incorporate all the major activities related to environmental emissions. Emissions due to materials, equipment usage and transportation are considered as the emission sources at construction stage. The emissions from these sources are further divided in to GHG and non-GHG emissions. Non-GHG emissions are pre-dominant in equipment usage and transportation stage due to partial combustion of fuel whereas GHG emissions are significant in materials stage. Previous studies point out that CO\textsubscript{2} emission governs the GHG emissions (AGGA, July 2013; Seo and Hwang, 2001). Therefore the study limits GHG emissions to CO\textsubscript{2} emissions. Figure 1 shows the scope and the system boundary for the toolkit. The scope also classifies the construction stage of a building into
foundation, structure and whole building construction. Foundation and structure construction are given separate consideration because it covers majority of the construction.

**Development of the toolkit**

Development of the toolkit is based on two key considerations. The first was to decide the user inputs for the toolkit. Three important factors had to be taken into consideration when deciding these inputs. Firstly, the inputs should not be complicated, secondly it should be user friendly and finally the inputs should make a comprehensive analysis. The second stage was to decide system specific data and inputs steps to deliver the desired outputs in a simplified manner. Figure 3 describes the calculation steps of the toolkit with clearly specifying the user input data, system generated data and information on calculation steps. Explanation of the working flow of the inputs is given in the following sections.

![Figure 1 Scope and system boundary of the study (Toolkit)](image)

**Mathematical models/ emission factor inventories used**

The mathematical models are developed based on the emission factor inventories selected. Emission factors published by United States Environmental Protection Agency (US EPA) are used to determine non-GHG emissions from equipment usage (Exhaust, 2002) whereas emission factors published by Australian Greenhouse Gas Accounts are used for calculation of GHG emissions from transportation and equipment usage (AGGA, July 2013; Exhaust, 2002). US EPA factors were found to be a comprehensive set of emission factors to evaluate non-GHG emissions (Jung et al., 2009). Emission factors for materials were obtained from Inventory of Carbon and Energy (ICE) as it was one of the most commonly used comprehensive database for material emission factors (Hammond and Jones, 2008).

**Initial development using excel-based spread sheet**

The mathematical models and design steps of the toolkit were first employed in an excel spread sheet to understand the execution and complication issues of the toolkit. Macro settings and mathematical functions available in excel were used to develop the working flow of the toolkit. Figure 4 shows the working flow for the intended toolkit. The first three steps are project specific inputs whereas the final two steps are analysis based inputs. The first step is to enter the project specific details into the system.

Step 1a) Scope of the analysis – The user has the option of considering either foundation, building structure or the whole building construction for the emission study.
Step 1b) Project information – General project information such as building use, height and location of the building, number of floors are requested from the user. This information is later utilised in the comparative analysis.

Step 1c) Building information – In this step the user is invited to input building specific information such as construction type, total floor area, plan area, contractor name, foundation and structure construction type and soil type. Contractor name is an optional input and the others are compulsory inputs.

The next step is to input the machines, materials and vehicles used during construction stage.

Step 2a) Machine and equipment details – Total usage hours of every machine used at site should be entered in this step. Machine specific details such as machine type, make, model number, power (in hp), technology and cumulative usage are also required to carry out the analysis. A machine’s emission pattern is different from one another and therefore every machine will have a unique emission factor for each emission substance. Thus a database is created to incorporate all the unique emission factors (HC, CO, NOx, SO2, CO2 and PM) of the different construction equipment. These emission factors and the corresponding machine characteristics are sorted based on the model number of the machine. The user has the privilege of loading the corresponding machine details once the model number is entered if it is already in the database. If not available, the user can create a new machine profile using a new entry by typing the machine type, model number, power and technology. Technology refereed here is an emission standard (usually tier 1, 2, etc.) which can be obtained from the technical statement. A view of the database for construction equipment emission factors is shown in Figure 2.

Step 2b) Transportation details – The user is required to input all the details of transportation vehicles used during the construction. Vehicle specific details such as type of vehicle, model year, category, fuel type and project specific details such as cumulative km’s travelled, fuel consumption and the distance travelled are the required inputs for calculating emissions from transportation.

Step 2c) Material details – Under material details, the total quantity of the materials used (in kgs) should be entered. The user has the option of selecting a material category which is already in the database. If the material is not available it is required to manually enter the concerned material.

The third step is to record the activities corresponding to the materials, machines and transport vehicles entered in the preceding step. If emission comparison is not required at activity level, the user has the option of skipping this step.

Step 3 a) Activity details – Activities in construction and the corresponding duration in hours needs to be entered in this step.

Step 3 b) Assign input data to activities – Assign machines and materials (entered in Step 2) to the activities entered in the previous step.

Step 3 c) Add quantities – Add quantities to the assigned materials and machines for each activity introduced in the previous step.

Once the required information is entered, the toolkit will calculate the emission rates for materials in g/kg, for equipment in g/hr and for transportation vehicles in g/km. When assigning machines to activities in Step 3b, the toolkit will suggest selecting the equipment or vehicle with the minimum emission rate wherever possible. At this stage
the user is given the option to choose the combination suggested by the toolkit or the option according to the user’s preference.

Step 4 a) Select the required analysis options – This step enables the users to select the required analysis options. At this step the user is given the option to compare emissions completely, at activity level, at equipment level and between two different construction techniques.

Step 4 b) Comparison required – This step is required if the user intends to compare the current emissions with another construction project of similar kind.

The final step is to interpret and validate the results obtained.

Step 5 a) Results interpretation – The obtained results are then directed towards impact categories by introducing characterising, normalisation and weighting factors. Five major impact categories, Global warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP), Photochemical Oxidant formation potential (POFP) and Human Toxicity potential (HTP) are used in the analysis. The weighting factors are developed to understand the significance of the impact categories based on three perspectives, global, regional and local level. These perspectives represent different geographic levels and the significance of emissions at construction on the three levels will be compared.

Step 5 b) Results validation – Sensitivity analysis will be carried out to check the impacts of the inputs on the output. First the user is given the option to choose a minimum and maximum range of the inputs that are likely to change the outputs. Then recalculation is done for 2500 randomly generated inputs between the ranges specified by the user. The resulting output is then utilised to draw conclusion on which inputs have more impact on the output. Uncertainty analysis will be carried out by using Monte-Carlo simulation. The results obtained are then to be verified by standard software (@ RISK).

The interpretation and validation processes involve broader analysis which is out of the scope of this paper and will be discussed in a different publication.

**TOOLKIT FUNCTIONS AND IMPLEMENTATION**

A case study of a previous published literature study on horizontal directional drilling (HDD) is used to check the functions and the consistency of the toolkit (Sihabuddin and Ariaratnam, 2009). The project specific details of the case study are given in Table 1. Only emissions from equipment are considered to explicate the working flow of the toolkit. An ID number is generated for equipment and activities as shown in Table 1 to be used for comparison purposes. The results obtained by the toolkit and the original results are then compared to check the consistency of the toolkit.

<table>
<thead>
<tr>
<th>MACHINE TYPE</th>
<th>MAKE</th>
<th>MODEL</th>
<th>Fuel Type</th>
<th>POWER (hp)</th>
<th>LIFE SPAN</th>
<th>LF</th>
<th>BSFC</th>
<th>HC</th>
<th>HC</th>
<th>HC</th>
<th>CD</th>
<th>CO</th>
<th>NOx</th>
<th>NO2</th>
<th>NOx</th>
<th>POFP</th>
<th>HTP</th>
<th>GWP</th>
<th>AP</th>
<th>EP</th>
<th>POFP</th>
<th>HTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavator A</td>
<td>Hitachi</td>
<td>ZX50LC-3</td>
<td>Diesel</td>
<td>164</td>
<td>6000</td>
<td>0.59</td>
<td>0.367</td>
<td>0.027</td>
<td>1.05</td>
<td>0.164</td>
<td>0.155</td>
<td>1.53</td>
<td>0.867</td>
<td>0.008</td>
<td>1.64</td>
<td>2.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.23</td>
<td>2.01</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Excavator B</td>
<td>Hitachi</td>
<td>ZX100H-3</td>
<td>Diesel</td>
<td>164</td>
<td>6000</td>
<td>0.59</td>
<td>0.367</td>
<td>0.027</td>
<td>1.05</td>
<td>0.164</td>
<td>0.155</td>
<td>1.53</td>
<td>0.867</td>
<td>0.008</td>
<td>1.64</td>
<td>2.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.23</td>
<td>2.01</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Excavator C</td>
<td>Hitachi</td>
<td>ZX210LCH-3</td>
<td>Diesel</td>
<td>164</td>
<td>6000</td>
<td>0.59</td>
<td>0.367</td>
<td>0.027</td>
<td>1.05</td>
<td>0.164</td>
<td>0.155</td>
<td>1.53</td>
<td>0.867</td>
<td>0.008</td>
<td>1.64</td>
<td>2.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.23</td>
<td>2.01</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Excavator D</td>
<td>Hitachi</td>
<td>ZX210K-3</td>
<td>Diesel</td>
<td>164</td>
<td>6000</td>
<td>0.59</td>
<td>0.367</td>
<td>0.027</td>
<td>1.05</td>
<td>0.164</td>
<td>0.155</td>
<td>1.53</td>
<td>0.867</td>
<td>0.008</td>
<td>1.64</td>
<td>2.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.23</td>
<td>2.01</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Excavator E</td>
<td>Hitachi</td>
<td>ZX210K-3</td>
<td>Diesel</td>
<td>164</td>
<td>6000</td>
<td>0.59</td>
<td>0.367</td>
<td>0.027</td>
<td>1.05</td>
<td>0.164</td>
<td>0.155</td>
<td>1.53</td>
<td>0.867</td>
<td>0.008</td>
<td>1.64</td>
<td>2.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.23</td>
<td>2.01</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Excavator F</td>
<td>Hitachi</td>
<td>ZX370LCH-5</td>
<td>Diesel</td>
<td>164</td>
<td>6000</td>
<td>0.59</td>
<td>0.367</td>
<td>0.027</td>
<td>1.05</td>
<td>0.164</td>
<td>0.155</td>
<td>1.53</td>
<td>0.867</td>
<td>0.008</td>
<td>1.64</td>
<td>2.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.23</td>
<td>2.01</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 2 Database created for construction equipment emission factors*
The case study was chosen because it replicates the emission substances similar to the toolkit and could effectively be used to emphasize the functions of the toolkit.

**Web based toolkit development**

Excel based toolkit is expected to be further developed into an online web- based toolkit which will provide easy access. This web based toolkit is still under development and will be uploaded in the near future.

**Figure 3: A general layout on the calculation flow of the toolkit**

The developed toolkit is able to capture emissions at all stages of construction in a building. At this stage toolkit limits the emissions evaluation to major construction stages of a high-rise building. The authors intend to further develop it into a toolkit which is able to capture emissions all the construction stages. A total up to 1000 equipment, materials, transport vehicles and activities can be analysed from the toolkit.

These project details are entered into the toolkit according to the steps shown in Figure 7. The comparative results shown in Table 2 illustrate that apart from CO$_2$ the deviation of results are less than 5%. The reason is that since CO$_2$ emissions are dependent only on the fuel consumption, the toolkit use fuel based emission factors whereas the original study uses a default fuel consumption factor which depends on the power of the machine. This deviation is comparatively high because the total emissions are much smaller (in grams) and becomes negligible when the amount of emissions becomes larger.
Table 1 Equipment data of HDD case study

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Engine model</th>
<th>Model year</th>
<th>Rate d hp</th>
<th>Cumulative usage (hrs)</th>
<th>ID</th>
<th>Name</th>
<th>Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Backhoe</td>
<td>Tier 2</td>
<td>2007</td>
<td>90</td>
<td>12</td>
<td>A1</td>
<td>Excavation of pits</td>
<td>15</td>
</tr>
<tr>
<td>E2</td>
<td>Vacuum truck</td>
<td>Tier 2</td>
<td>2006</td>
<td>36</td>
<td>906</td>
<td>A2</td>
<td>Potholing for utilities</td>
<td>20</td>
</tr>
<tr>
<td>E3</td>
<td>Drill rig</td>
<td>Tier 1</td>
<td>2000</td>
<td>165</td>
<td>2200</td>
<td>A3</td>
<td>Pilot hole</td>
<td>40</td>
</tr>
<tr>
<td>E4</td>
<td>Fluid mixer</td>
<td>Tier 1</td>
<td>2003</td>
<td>8</td>
<td>112</td>
<td>A4</td>
<td>Pre-ram</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A5</td>
<td>Pull back</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A6</td>
<td>Supply of drilling fluid</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 2 Comparative results of the toolkit with the original results

<table>
<thead>
<tr>
<th></th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>CO2</th>
<th>PM</th>
<th>SO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original results (in g)</td>
<td>56.6</td>
<td>305.8</td>
<td>638.1</td>
<td>49900</td>
<td>37.65</td>
<td>68</td>
</tr>
<tr>
<td>Toolkit results (in g)</td>
<td>57.31</td>
<td>306.72</td>
<td>650.60</td>
<td>66700</td>
<td>39.24</td>
<td>67.86</td>
</tr>
<tr>
<td>Deviation (%)</td>
<td>1.3%</td>
<td>0.3%</td>
<td>1.95%</td>
<td>34.2%</td>
<td>1.6%</td>
<td>-3.15%</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

One of the potentials of the toolkit is that the results obtained can be analysed in different perspectives. The analysis shown in Figure 5 shows the emission analysis based on the activities and Figure 6 illustrates the comparison of emissions between the equipment used at site.
The results obtained by the toolkit draw several important observations on emission analysis perspectives. A close inspection on the results at Figure 6 shows although E3 has the highest emissions in almost all the emission substances, E1 records the highest emission rates for all the emission substances. This is because E3 is used more at site compared to E1. When a number of same types of machines are used, the emission rates comparison provides a useful mode for effective allocation of work for each machine. The emission comparison at activity level shown in Figure 5 provides a detailed breakdown of emission distribution in different activities. The results show that activity A1 has the highest emissions for most of the emission types. This is because machine E1 with the highest emission factor is utilised for activity A1. It can also be observed that although having maximum emissions, activity A1 has the least operation hours. This clearly shows that the duration is not the only factor that decides the amount of emissions and careful allocation of machines into critical activities can reduce the emissions considerably. This machine allocation becomes critical when the whole construction of the building is considered where several machines are used in one activity.

CONCLUSIONS

Construction phase may release substantial amount of GHG emissions as well as non-GHG emissions. Different construction techniques may have different levels of emissions based on the selection of materials, equipment and transportation. A comparative tool which is able to estimate and evaluate the emissions before the execution phase would enable the designers and the contractors to adopt energy reduction options. The study focus was to develop a toolkit which enables the users to compare the emissions at construction phase effectively with minimum effort. The developed toolkit is able to estimate and compare GHG and non-GHG emissions between two construction techniques. It can either evaluate the emissions of a completed project or estimate the emissions of a future scheduled project. It also can compare emissions between construction equipment which will aid in understanding emission reduction possibilities. The case study results confirmed the capacity of the
toolkit to estimate and compare emissions at different construction techniques, activity level and at different emission stages. The toolkit can be further developed which can be used by designers and contractors to reduce emissions before commencing the construction.

Figure 7: Working flow of the toolkit

FUTURE RESEARCH

The intended objective of the paper is to introduce a toolkit that is able to evaluate and compare emissions at construction stage. The next stage will be to introduce
weighting criteria for emission substances to compare them from different impact categories. Further studies will be carried out to increase the accuracy and reliability of the toolkit using case study results and statistical analysis methods. The toolkit will be further developed to evaluate the complete activities at construction phase with having more user input options. Future research and studies are also encouraged on carrying out optimization between the cost and the emissions to identify the ideal selection of construction materials and equipment for different construction techniques.

REFERENCES


