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# COMPARISON OF EMBODIED CARBON ESTIMATING METHODS

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## *ABSTRACT*

*The Australian building sector contributes up to 36% of carbon emissions emphasising the importance of carbon management. Embodied Carbon (EC) and Operational Carbon (OC) are classified as two main types of carbon emissions in buildings. Zero carbon projects have gained popularity nowadays where OC is reduced to zero, which enables EC to increase. The focus should have been to reduce overall emissions. The current EC estimating databases and tools could result in inaccurate EC estimates due to various reasons, such as different system boundaries, different geographical locations, lack of standardisation and so forth. To address prevailing shortfalls, a new methodology, Supply Chain based Embodied carbon Estimating Method (SCEEM), has been introduced. This study aims at comparing EC estimates prepared using SCEEM against existing carbon estimating databases/tools. A case study was selected to collect data and estimate EC using SCEEM as well as selected database, Blackbook, and tool, eToolLCD. The results indicated that the EC estimates prepared for the case study was quite high in the selected database/tool compared to the EC values of SCEEM. The percentage difference between SCEEM vs Blackbook and SCEEM vs eToolLCD, was more than 50% for most of the items within the collected data set. The first principles-based methodology considered in SCEEM ensures the accuracy and consistency of estimates prepared using SCEEM.*

**Keywords:** *Carbon Databases/Tools; Carbon Estimating; Supply Chain; Supply Chain-based Embodied Carbon Estimating Method (SCEEM).*

## 1. INTRODUCTION

Climatic changes have caused a significant impact on the global community resulting in increased temperatures, rises in sea levels, increased water vapours in the atmosphere, and melting of glaciers (Kaluarachchi, 2017; Karl et al., 2009). It is widely believed that climatic changes occur as a result of human activity (Shukla et al., 2019; United Nations Environment Programme, 2009). As the Australian building sector accounts for about 36% of the overall carbon emissions (Huang et al., 2017), it is extremely important to reduce Life Cycle Carbon (LCC) emissions. LCC emissions in buildings can be classified into two main types - Embodied Carbon (EC) and Operational Carbon (OC). Royal

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Institution of Chartered Surveyors (2014) investigated the overall carbon footprint during the operational stage of various kinds of buildings, such as supermarkets, offices and others, to discover that the emissions of OC are comparatively higher than EC. The latest trend is to create zero-carbon projects (Bui et al., 2021), which intend to reduce OC to zero, making the remaining component, EC, more significant (Royal Institution of Chartered Surveyors, 2014; Yokoo et al., 2013). Ashworth and Perera (2015) suggest that in order to reduce the OC component, new materials should be introduced, such as additional layers of insulation, increasing EC. Some buildings possess a short life span and at the same time account for a high percentage of EC emissions when the total environmental impact of the building is assessed (Wolf et al., 2016). EC emissions during material extraction, production, transportation, construction and demolition are irreversible (Wolf et al., 2018). Hence, it is important to reduce net carbon emissions. Green Building Councils worldwide are focusing on introducing roadmaps to improve the focus on achieving net-zero EC (Green Building Council Australia, 2018; World Green Building Council, 2019).

There are various EC estimating databases for early-stage and detailed stage estimating (Victoria et al., 2016). The University of Bath's Inventory of Carbon and Energy (ICE), Waste Reduction Action Plan (WRAP) and Hutchins UK Building Blackbook are quite acknowledged and popular, amongst others. Due to the existence of a different number of EC estimating tools and different system boundaries, comparison of EC calculations is relatively difficult and even within the same system boundary, calculations may differ. Therefore, the accuracy and reliability of these estimating methods are questionable, giving rise to the necessity of developing a methodology to calculate EC accurately and consistently. A new methodology identified as SCEEM has been introduced to estimate EC accurately and consistently (Rodrigo et al., 2021), which is elaborated in Section 2.2.

This study aims at comparing EC estimates prepared using SCEEM against existing carbon estimating databases/tools. In order to achieve this aim, the following objectives were established:

1. To select suitable carbon databases/tools to compare against SCEEM, and
2. To compare EC estimates prepared using SCEEM and selected databases/tools.

Section 2 discusses the literature review carried out while the research methodology followed in this study is shown in Section 3. The findings are presented in Section 4 followed by the conclusions of this research.

## 2. LITERATURE REVIEW

Construction-related activities contribute to climate change and global warming immensely highlighting the importance of carbon estimating in the construction industry (Baldasano & Reguart, 2014). Therefore, it is necessary to estimate carbon, ultimately to reduce construction industry-related carbon emissions. Currently, there are various carbon databases/tools developed to estimate EC.

### 2.1 CARBON ESTIMATING DATABASES AND TOOLS

Various carbon databases and tools have been developed by various parties in different countries to estimate carbon (Refer to Table 1). Databases provide carbon coefficients/ factors that could be used for carbon estimating, while tools provide an application that has incorporated carbon datasets and a method to estimate EC.

*Table 1: Summary of the EC estimating databases and tools*

| Type | EC estimating tool | System Boundary | Details | Estimating Method | Type of Application | Publicly Available | Free | Location | Last Updated | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Databases | ICE | cradle-to-gate | EC | Process | Excel Sheet | Yes | Yes | UK | August 2019 | Hammond and Jones (2008) |
| | Hutchins UK Building Blackbook | cradle-to-gate | EC | Process | Book | Yes | No | UK | 2010 | Franklin and Andrews (2010) |
| | WRAP | | EC | Process | Web Application | For registered users | Yes | UK | | WRAP (2018) |
| | Ecoinvent | cradle-to-gate | LCA | Process | Web Application | Yes | No | Switzerland | Oct 2017 | Frischknecht and Rebitzer (2005) |
| | AusLCI | cradle-to-gate | EPD | Process | Excel Sheets/ XML Format | Yes | Yes | Australia | 2016 | The Australian National Life Cycle Inventory Database. (2020) |
| | EPiC | cradle-to-gate | EE and EC | Hybrid | Book | Yes | Yes | Australia | 2019 | Crawford et al. (2019) |
| | The GreenBook 2020 | cradle-to-end of construction | EC | Process | Book | Yes | No | Australia | Nov 2019 | The GreenBook (2020) |
| Tools | CapIT Online Carbon and Cost Estimator | cradle-to-gate | EC | Process | Published as Hutchins UK Building Blackbook | Yes | No | UK | 2011 | Mott MacDonald (2018) |
| | BRE Green Guide Calculator | | EC | Process | Web Application | For licensed BREEAM/ EcoHomes | No | UK | Jan 2015 | Building Research Establishment (2020) |

| Type | EC estimating tool | System Boundary | Details | Estimating Method | Type of Application | Publicly Available | Free | Location | Last Updated | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Tools (Cont'd) | BEES | cradle-to-grave | $CO_2$ cost in $/ton | Process | Web Application | Yes | Yes | US | 2010 | Fu et al. (2014) |
| | GaBi Education Software | cradle-to-grave | LCA | Process | Desktop Application | Yes | Yes | Germany | 2017 | Gabi Software (2019) |
| | Tally | cradle-to-grave | LCA | Process | Add-on Software to Revit | Yes | No | US | 2021 | Tally (2021) |
| | Athena Impact Estimator for Buildings | cradle-to-gate/grave | LCA | Process | Desktop Application | Yes | Yes | US | Feb 2017 | Athena Sustainable Materials Institute (2018) |
| | SimaPro | cradle-to-grave | LCA | Process | Desktop Application | Yes | No | Netherlands | 2017 | SimaPro (2008) |
| | EC3 | Cradle-to-gate | EPD | Process | Web Application - Beta version | Yes | Yes | US | 2019 | Building Transparency (2021) |
| | eToolLCD | cradle-to-grave | LCA | Process | Web Application | Yes | No | Australia | 2010 | eTool (2018) |
| | ECE Tool | cradle-to-gate | EC | EEIOA | Web Application | Yes | No | Australia | 2019 | The University of New South Wales (2019) |
| | The Footprint Calculator | cradle-to-grave | LCA | Process | Web Application | Yes | No | Australia | 2019 | The Footprint Company (2019) |
| | LCAQuick | cradle-to-grave | LCA | Process | Desktop Application | Yes | Yes | New Zealand | 2021 | LCAQuick (2022) |

*Source: After Rodrigo et al. (2021)*

Table 1 provides a summary of the various databases/tools developed by various researchers and organisations that are popular among practitioners and academics. Though there are several databases/tools introduced for carbon accounting, there are several issues when estimating EC using them. EC estimating databases and tools at present are lacking in transparency, simplicity and accuracy, especially in the way that data are collected (Wolf et al., 2016). As a result, some organisations have begun developing their own in-house EC assessment tools (Wolf et al., 2017). For example, Thornton Tomasetti (2016) developed a tool to estimate EC. Arup developed their in-house EC database, Project Embodied Carbon Database (Wolf et al., 2018), Carbon Leadership Forum has compiled the Embodied Carbon Benchmark database (Simonen et al., 2017), and so forth. Haynes (2010) noted that it is difficult to estimate carbon emissions accurately, and that the calculations are subject to variability. In addition, differences in system boundaries and geographical locations, lack of standardisation, incomplete or outdated data, static nature of data, and assumptions could result in inaccuracies and inconsistencies in carbon estimates prepared using these databases/tools (Rodrigo et al., 2019). Hence, a new methodology was introduced to estimate EC accurately and consistently as discussed next.

### 2.2 SUPPLY CHAIN-BASED EMBODIED CARBON ESTIMATING METHOD (SCEEM)

SCEEM is a new methodology introduced to estimate EC in Construction Supply Chains (CSCs) by incorporating the value chain concept and blockchain technology (Rodrigo et al., 2021). There are several activities carried out within a construction project involving multiple CSCs. Each activity adds value to the CSC while contributing to EC. SCEEM considers this philosophy and captures EC emissions of each contributor within the CSC and stores in a blockchain (database) to improve transparency, security, trust and accountability among users. SCEEM captures EC emissions considering a first principles-based methodology. For example, it collects data related to fuel usage and electricity usage to account EC emissions of each EC contributor in CSCs. This method provides a more accurate EC estimate as it captures raw data without relying on existing databases/tools which are lacking of transparency, using incomplete or outdated data and many other issues as discussed in the previous section.

## 3. RESEARCH METHODOLOGY

This research aimed at comparing EC estimates prepared using SCEEM against existing carbon estimating databases/tools. To achieve the objectives and the aim of the study, the methodology demonstrated in Figure 1 was followed.

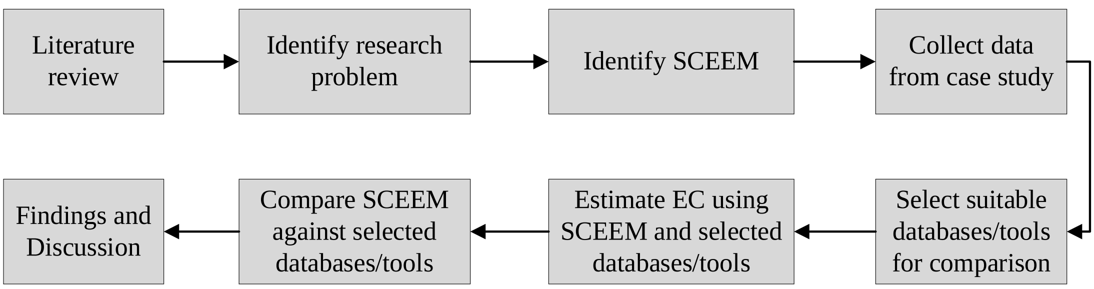


*Figure 1: Research Methodology Framework*

This study followed the steps shown in Figure 1. Initially, a literature review was carried out to identify the research problem related to inaccuracies/inconsistencies when estimating EC using existing databases/tools (Section 2.1). A more accurate methodology, SCEEM, was identified to resolve this issue (Section 2.2.). It was required to collect data from an actual project due to the calculation steps to estimate EC using SCEEM and other databases/tools, and also to carry out fair comparisons. Therefore, a case study in Sydney, Australia was selected to collect data. Fuel quantities related to a few items within the case study was collected. The next step was to select suitable databases/tools for the comparison. Hence, the currently available carbon databases/tools (Table 1) were evaluated and the results are presented in Section 4.1. Subsequently, the fuel quantities were used to estimate EC using SCEEM and the BOQ quantities were used to estimate EC using selected database/tool. Finally, the comparison between SCEEM and selected database/tool was carried out (Section 4.2).

# 4. FINDINGS AND DISCUSSION

This section presents the findings of the study.

## 4.1 SELECTION OF DATABASES AND TOOLS FOR THE COMPARISON

There are various EC databases and tools, as illustrated in Table 1, that can be used to estimate EC in construction projects. A comparison was carried out between the Australian databases, Australian Life Cycle Inventory (AusLCI) database, Environmental Performance in Construction (EPiC), and GreenBook 2020; Australian tools, eToolLCD and Embodied Carbon Explorer (ECE) Tool; and the most popular UK-based databases, Blackbook and Inventory of Carbon and Energy (ICE), to select the most suitable databases and tools for the study. Table 2 presents a justification on the tools that were evaluated and selected.

*Table 2: Evaluation of reasons for selection of EC databases or tools*

| Reason | | Selected | | Non-Selected | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Database | Tool | Database | | | | Tool |
| | | **Blackbook** | **eToolLCD** | **AusLCI** | **EPiC** | **GreenBook 2020** | **ICE** | **ECE Tool** |
| A | Availability of EC emission factors suitable for the data set | Yes | Yes | No | No | No | No | No |
| b | Ease of calculations | Yes | Yes | No | No | Yes | No | No |
| c | Clear and detailed descriptions | Yes | Yes | No | No | Yes | No | No |
| d | An Australian database/tool | No | Yes | Yes | Yes | Yes | No | Yes |
| e | Standalone database/tool | Yes | Yes | No | Yes | Yes | Yes | Yes |
| f | Use of database/tool by previous studies and practitioners | Yes | Yes | Yes | No | No | Yes | No |
| g | Hybrid Approach | No | No | No | Yes | Yes | No | Yes |

*Source: Adapted from Rodrigo et al. (2021)*

The database, Blackbook, and the tool, eToolLCD, were selected for this study to estimate EC and carry out the comparisons. The other databases and tools have not been considered due to various limitations and issues existent in them. This section elaborates the reasons and justification for the selection or non-selection of databases and tools for carrying out comparisons with the EC values estimated using SCEEM.

*a. Availability of EC emission factors suitable for the data set*

Blackbook and eToolLCD consisted of EC emission factors applicable for the data set considered in this study. The data collected from the case study was related to civil construction works of a housing development project. The main reason for not selecting other databases and tools to estimate EC in this study is due to non-availability of EC coefficients for the items in the data set. The key items in the data set include excavation of topsoil, stockpile, cut and fill, excavation of trenches, backfill and so forth. However, the databases, AusLCI, EPiC, GreenBook 2020, and ICE, and the tool, ECE Tool, did not have suitable EC emission factors for the items in the data set. Therefore, they were not considered for estimating EC in this study.

*b. Ease of calculations*

Blackbook, eToolLCD and GreenBook 2020 provide EC values for a variety of items given in the format of a Bill of Quantities (BOQ) related to a building construction project. Therefore, it is extremely easy to estimate EC using Blackbook, eToolLCD and GreenBook 2020. On the other hand, the databases, AusLCI, EPIC, and ICE, and tool, ECE Tool, provide EC emission factors for various materials. Hence, if these databases or tools are to be used, initially the BOQ has to be converted to a bill of material. Subsequently, EC emissions could be calculated. Compared to these databases and tools, it's easier to use Blackbook, eToolLCD and GreenBook 2020.

*c. Clear and detailed descriptions*

Blackbook, eToolLCD and GreenBook 2020 provide detailed descriptions for each of the items given in the format of a BOQ. Therefore, a user can easily understand the scope of the item with a clear indication of inclusions and exclusions. This allows the user to accurately calculate EC by using the exact item or else the most suitable item if the exact item is unavailable. However, the databases, AusLCI, EPIC, and ICE, and tool, ECE Tool, provide EC emission factors for various materials. Therefore, it is difficult to consider these databases or tools for the comparison in this study.

*d. An Australian database/tool*

AusLCI, EPiC, and GreenBook 2020 are Australian EC databases while eToolLCD and ECE tool are Australian EC tools. It is more suitable to use Australian databases or tools to carry out comparisons as data was collected from Sydney, Australia. However, although Blackbook is a UK-based database, it includes location factors that can be used to convert the EC emission factors to Australian values. Therefore, if all other criteria are fulfilled by Blackbook, it can easily be used in the study to carry out comparisons.

*e. Standalone database/tool*

All the databases or tools, except AusLCI, are standalone. Therefore, they can be independently used for EC estimating in this study. However, AusLCI is still in its development stage, therefore, the developers have enabled the AusLCI database to be accessed through SimaPro or Ecoinvent ( The Australian National Life Cycle Inventory

Database., 2020). SimaPro and Ecoinvent have been developed based on the Netherlands and Swiss data, respectively. Therefore, it is difficult to extract Australian-based data through SimaPro or Ecoinvent. Hence, as AusLCI is not a standalone database, it would not be suitable for this study.

*f. Use of database/tool by previous studies and practitioners*

The EC databases, Blackbook, AusLCI, and ICE, as well as tools, EC tool, eToolLCD, have been used in previous studies. Darby et al. (2011); Fernando et al. (2018); Menzies (2011); and Victoria et al. (2015), have used Blackbook in their research to estimate EC. Teh et al. (2018) have used AusLCI to develop and evaluate a hybrid life cycle assessment framework for recycled materials. Atmaca (2016); Benton et al. (2017); and Din and Brotas (2016), have used ICE to estimate EC. eToolLCD is quite popular among the construction industry practitioners of Australia. A survey carried out by Fouche and Crawford (2015) identified that eToolLCD is the second most popular tool in Australia, being only 4% behind the most popular tool, SimaPro. These databases and tools provide validity and confidence when considering them to be used in the study. However, EPiC, GreenBook 2020 and ECE Tool, being launched only recently, have not yet been used in previous studies.

*g. Hybrid Approach*

SCEEM uses a process-based bottom-up approach to estimate EC. Hence, it is important to select databases/tools that have followed a process-based method to develop EC emission factors. EPiC, GreenBook 2020 and ECE Tool have each followed a hybrid approach, considering both process-based and Environmentally-Extended Input-Output Analysis (EEIOA) methods. The EEIOA method includes the input-output model of the national economy, where the entire supply chain of material is covered, across the economy, while using detailed and relevant process data as much as possible. This could create double-counting related issues, as some data could overlap one another. Due to these reasons, EPiC, GreenBook 2020 and ECE Tool cannot be used for the comparisons in this research. However, the other databases/tools have used a process-based method, hence, they can be considered.

In summary, Blackbook and eToolLCD were selected to carry out comparisons with EC values calculated using SCEEM. The reasons for selecting Blackbook and eToolLCD are: availability of EC emission factors suitable for the items in the data sets; ease of calculations; including clear and detailed descriptions; being a standalone database/tool; being used by previous studies and practitioners; and, utilising a process-based method.

## 4.2 COMPARISON OF SCEEM AGAINST SELECTED DATABASE AND TOOL

This section compares EC values calculated for a data set, using SCEEM against Blackbook and eToolLCD. EC values calculated using SCEEM, Blackbook and eToolLCD are illustrated in Table 3.

*Table 3: Difference of EC values of the case study estimated using SCEEM, Blackbook and eToolLCD*

| Item | Item - Description | Quantity | Unit | EC ($kgCO_2e$) | | | Difference % of SCEEM vs | |
|---|---|---|---|---|---|---|---|---|
| | | | | SCEEM | Blackbook | eToolLCD | Blackbook | eToolLCD |
| A | Strip topsoil (200mm) and stockpile on site | 401,724 | $m^2$ | 77,556 | 142,794 | 390,815 | 84 | 402 |
| B | Cart from stockpile and spread topsoil (200mm) | 314,022 | $m^2$ | 71,463 | 35,616 | 132,684 | -50 | 86 |
| C | Cart from stockpile and spread topsoil (100mm) | 29,695 | $m^2$ | 9,295 | 3,368 | 6,274 | -64 | -33 |
| D | Cut to onsite fill | 189,105 | $m^3$ | 452,004 | 487,297 | 919,848 | 8 | 104 |
| E | Cut and stockpile onsite | 158,384 | $m^3$ | 159,969 | 337,453 | 770,415 | 111 | 382 |
| F | Excavate, backfill and compact trenches | 16,714 | $m^3$ | 76,980 | 96,061 | 229,765 | 25 | 198 |
| G | Cart surplus materials to stockpile | 7,713 | $m^3$ | 18,480 | 22,459 | 37,518 | 22 | 103 |

According to Table 3, considering all calculations, the highest EC values were reported from the item, ‘cut to onsite fill’. Similarly, the lowest EC values were resulted from the item, ‘cart from stockpile and spread topsoil (100mm)’. Comparing the percentage difference between SCEEM vs Blackbook, for most of the items, the percentage difference was 50% or more. In almost all of the items, the percentage difference between SCEEM and eToolLCD was more than 50%, except for item C, ‘Cart from stockpile and spread topsoil (100mm)’, which indicated a percentage difference of 33%.

Table 3 clearly demonstrates that Blackbook and eToolLCD provide comparatively higher EC estimates while SCEEM that uses a first principles-based method produces accurate estimates as explained in detail in Section 2.2.

# 5. CONCLUSIONS

This study aimed at comparing EC estimates prepared using SCEEM against existing carbon estimating databases/tools. There were 2 objectives established to achieve the aim as presented in Section 1. The 1st objective was achieved by identifying and evaluating the available carbon estimating databases (Table 1 and Section 4.1). The EC database, Blackbook, and the tool, eToolLCD, were selected for the comparison. The 2nd objective was achieved by comparing EC estimates calculated using SCEEM against Blackbook and eToolLCD. A case study in Sydney, Australia was selected to collect data related to a few items and carry out the comparisons. The results indicated that the EC estimates prepared for the case study was quite high in the selected database/tool compared to the EC values of SCEEM. The percentage difference between SCEEM vs Blackbook and SCEEM vs eToolLCD, was more than 50% for most of the items within the collected data set. However, the first principles-based methodology considered in SCEEM ensures the accuracy and consistency of estimates prepared using SCEEM. The key limitations of the study were the size and nature of the data set due to the difficulty to collect fuel quantities for various items/activities separately as well as time and resource limitations. The study contributed to establishing the proof of concept, which could be later on tested with more complex CSCs in any type of project. SCEEM is recognised as a better methodology to be used for accounting carbon emissions in CSCs.

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