Material quantities in building structures and their environmental impact

by

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“It is [...] important to remember that unlike operational carbon emissions the embodied carbon cannot be reversed”

Craig Jones, Circular Ecology
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Title Supervisor: Professor of Architecture and Civil and Environmental Engineering

Abstract

Improved operational energy efficiency has increased the percentage of embodied energy in the total life cycle of building structures. Despite a growing interest in this field, practitioners lack a comprehensive survey of material quantities and embodied carbon in building structures. This thesis answers the key question: “What is the embodied carbon of different structures?”

Three primary techniques are used: (1) a review of existing tools and literature; (2) a collaboration with a worldwide network of design firms through conversations with experts and (3) the creation of a growing interactive database containing the material efficiency and embodied carbon of thousands of buildings.

The first contribution of this thesis is to define challenges and opportunities in estimating greenhouse gas emissions of structures, expressed in carbon dioxide equivalent (CO₂e). Two key variables are analyzed: material quantities (kg_material/m² or kg_material/m²) and Embodied Carbon Coefficients (ECC, expressed in kg_CO₂e/kg_material). The main challenges consist of creating incentives for sharing data, identifying accurate ECCs and resolving transparency while protecting intellectual ownership. The main opportunities include using Building Information Models to generate data, proposing regional ECCs and outlining a unified carbon assessment method.

The second contribution is the development of an interactive online tool, called deQo (database of embodied Quantity outputs), to provide reliable data about the Global Warming Potential of buildings (GWP, measured in kg_CO₂e/m² and obtained by multiplying the two key variables). Given the need for a long-term initiative, a framework is offered to create an interactive, growing online database allowing architects, engineers and researchers to input and compare their projects.

The third contribution is the survey of 200 existing buildings obtained through deQo. Two general conclusions result from this survey of building structures: material quantities typically range from 500 to 1500 kg/m² and the GWP typically ranges between 200 and 700 kg_CO₂e/m². Conclusions from this survey include that healthcare buildings use more materials whereas office buildings have a lower impact. Additionally, specific case studies on stadia, bridges and skyscrapers demonstrate that the design approach can have a significant impact on the embodied carbon of building structures.

Ultimately, this thesis enables benchmarking of the environmental impact of building structures.

Key words: Embodied Carbon/Energy; Life Cycle Analysis; Database; Materials; Structures
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1. Introduction

1.1. Motivation

Life cycle energy in buildings includes operational energy for heating, cooling, hot water, ventilation, lighting on one hand and embodied energy for material supply, production, transport, construction and disassembly on the other. The terms “embodied carbon” and “Global Warming Potential” (GWP) refer to the equivalent in carbon dioxide of all lifecycle greenhouse gas emissions and is expressed in weight of carbon dioxide equivalents (CO$_2$e). Many leading structural engineering and design firms are currently developing in-house embodied carbon estimators to answer the following question: what is the embodied carbon for different structures?

Craig Jones, co-founder of the Inventory of Carbon & Energy (Hammond & Jones, 2010), highlights the importance “to remember that unlike operational carbon emissions the embodied carbon cannot be reversed” (Circular Ecology, 2014). The key question of this thesis examines embodied carbon for several reasons.

First, carbon reduction is needed now. As mentioned in the latest Intergovernmental Panel on Climate Change (IPCC) report, substantial carbon reductions need to occur in the near future in order to avoid extreme climate disruptions (IPCC, 2014). Embodied carbon savings in building structures are an obvious opportunity to reduce the impacts in the short term. Next, some buildings have a short lifetime, which results in a high percentage of embodied carbon in the total environmental impact of a building. This is true for a diverse range of buildings, even those most prized and lauded as architectural exemplars at the time of their construction. For example, the Folk Art museum (Figure 1.1), built in 2001, will be torn down for an extension of the MOMA after a lifespan of less than 15 years (New York Times, 2014).

Moreover, with the effective reduction of the operational carbon of buildings in future decades, embodied carbon will become a more significant percentage of greenhouse gas emissions caused by buildings. Furthermore, research in this field will help structural engineers and architects to understand how to lower embodied carbon and fill this gap in literature (Dixit et al., 2012). Finally, rating schemes such as LEED (USGBC, 2013) have begun including embodied carbon in their credit system, though without defining baselines for benchmarking (Yang, 2014).
It should be noted that this thesis is limited to structural material quantities. Cladding and other non-structural materials are not considered for two reasons. First, structure accounts for the greatest weight in buildings and contributes to about half of the total carbon emissions due to materials (Webster et al., 2012). With a breakdown of embodied carbon for the different elements in offices, hospitals and schools, Kaethner and Burridge (2012) demonstrate that the super- and substructure together represent more than 50% of the total embodied carbon emissions of buildings (Figure 1.2). Second, this helps to focus attention on a well-defined quantity while still having a significant impact.

![Figure 1.2: Average breakdown in building elements of embodied carbon in offices, hospitals and schools, after (Kaethner and Burridge, 2012)](image)

### 1.2. Definitions of concepts

Several key concepts are used regularly throughout this thesis. Since misunderstandings exist around concepts such as “carbon”, “Embodied Carbon Coefficients” or “carbon equivalent”, this section defines how they are interpreted in this work. Precise definitions can be found in the nomenclature in appendix A.

The value for “embodied energy” is not the same as the value for “embodied carbon”. The same amount of embodied energy can emit different intensities of greenhouse gases (GHG) depending on the fuel used and the carbon emitted or absorbed by the materials processed. For example, emissions occur in the chemical processing of cement, whereas carbon is sequestered in wood. It is useful to account in terms of embodied carbon instead of embodied energy, as CO₂ contributes considerably to climate change. Also, measuring specifically in carbon helps to compare the embodied with operational emissions. Carbon accounting therefore facilitates the assessment of the whole life cycle impacts of buildings (Kaethner and Burridge, 2012).

The total embodied carbon of a building is often referred to as “Global Warming Potential” (GWP). The GWP is expressed in kilograms of carbon dioxide equivalent per functional unit. The carbon dioxide equivalent is noted “CO₂e” and represents the equivalent in carbon dioxide of the GHGs produced during the manufacturing and transportation of materials. The other GHGs such as CH₄, N₂O, SF₆, PFC and HFC can hence be converted to CO₂ using conversion factors in order to obtain a common unit for the environmental impact (IPCC, 2014), i.e. the “carbon dioxide equivalent”.

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A “functional unit” is a specified metric used to normalize the carbon footprint of buildings, in order to compare ‘apples to apples’. For example, the useable floor area can be the functional unit. The GWP is then measured in kg\textsubscript{CO2e}/m\textsuperscript{2}. The number of occupants is another example of a functional unit. The GWP is then measured in kg\textsubscript{CO2e}/occupant.

Two key variables are analyzed in this thesis: Structural Material Quantities (SMQ), expressed in kg of material (kg\textsubscript{material} or kg\textsubscript{m}) per functional unit (often m\textsuperscript{2}), and Embodied Carbon Coefficients (ECC), expressed in kg of CO\textsubscript{2}e (kg\textsubscript{CO2e}) per kg of material (kg\textsubscript{m}). Presently, there is no clear standard for accurate ECC values and information on SMQ values for buildings is scarce.

As illustrated in equation [1], the GWP (kg\textsubscript{CO2e}/m\textsuperscript{2}) is obtained by multiplying the two key variables: SMQ (kg\textsubscript{m}/m\textsuperscript{2}) and ECC (kg\textsubscript{CO2e}/kg\textsubscript{m}), together.

\[ \text{GWP (kg}\textsubscript{CO2e}/m\textsuperscript{2}) = \text{SMQ (kg}\textsubscript{m}/m\textsuperscript{2}) \cdot \text{ECC (kg}\textsubscript{CO2e}/kg\textsubscript{m}) \]  

[1]

Figure 1.3 illustrates how the GWP of different materials can be added up for building projects to define the embodied carbon.

![Figure 1.3](image)

**Figure 1.3**: GWP divided into the composing materials of different building projects

In this thesis, “structure” refers to the structure of a building and implies the loadbearing part of something built or constructed. When talking about a pattern, relation or organization, other words, such as “framework”, are used.
1.3. Problem statement

This thesis aims to build literacy on the embodied carbon for different structures. Data is collected in collaboration with a network of worldwide design firms. The research is conducted in three primary streams:

1) Collect data from recently published literature on Life Cycle Assessments (LCA);
2) Collaborate with design and construction firms to build a useful database of their projects;
3) Create an interactive growing database where participants can input projects to include thousands of buildings worldwide.

Two necessary variables are introduced in section 1.2: SMQ (kgm/m²) conveys the amounts of steel, concrete, wood, etc. and ECC (kgCO2e/kgm) expresses the carbon equivalent of these materials. The former is sought from industry participants; the latter is computed with existing LCA software and current literature. Developing confidence in the numbers for embodied carbon of structures (GWP in kgCO2e/m²) requires a large amount of data. No framework or reliable database exists yet assessing material efficiency and embodied carbon in structures. This lack of information results in buildings using materials in a wasteful way with impunity.

However, to be able to rationally compare and assess projects, a wider set of input parameters is needed beyond the two key variables. The first set of input parameters consists of general project information such as the building location, typology and geometry. The second are structural parameters such as material choices and quantities, structural systems, soil types and loads. Outputs include ranges of GWP, illustrated in graphics comparing building projects or categories (Figure 1.3). An intermediate result is better information on material efficiency.

This thesis has three main contributions. The first contribution is to define the challenges and opportunities in obtaining the material quantities and estimating the embodied carbon of structural materials. To obtain the key variables SMQ and ECC, many challenges occur in existing tools and literature. However, by listing the challenges and offering possible solutions and opportunities, this thesis clarifies which paths can be followed to reduce the embodied carbon of building structures.

The second contribution of this thesis is the development of an interactive online tool to give confidence in the GWP measurement of buildings. A framework is presented for a relational database collecting both the embodied carbon of buildings, and their material quantities. The idea is to create a worldwide online tool, which allows architects, engineers and researchers to input their projects and compare it with others.

The third contribution is the survey of two hundred actual buildings taken from the database. Additionally, a new unified embodied carbon assessment method is applied to specific case studies, such as stadia, historic bridges and recent skyscrapers in order to critically analyze and refine the process. Ultimately, this will enable benchmarking and comparisons of the environmental impact of a wide range of projects.
1.4. Organization of thesis

The following chapter (Chapter 2) discusses the state of the art on material quantities, ECC values and implementing the calculation of the GWP. Chapter 3 elaborates on the methodology.

The Chapters 4 to 6 expand on the contributions and results of this thesis. First, Chapter 4 reviews the challenges and opportunities in obtaining material quantities and ECCs. Chapter 5 then develops a framework for an interactive database collecting data on existing building projects. Finally, Chapter 6 surveys 200 actual buildings from industry and applies the defined approach for estimating the embodied carbon of structures to three case studies: sport stadia, historic bridges and tall office buildings.

Finally, Chapter 7 discusses the key contributions, takes conclusions and proposes paths for future research.
2. State of the art

This chapter summarizes the state of the art on material quantities, ECCs and environmental impact analysis tools. Gaps and challenges are highlighted in this chapter and will be addressed in the following chapters. Chapter 2 is divided into three parts. The first two parts discuss the literature on the two key variables: SMQ and ECC. The last part addresses existing tools to implement the calculation of the GWP of buildings.

Figure 2.1 shows the wide range of results for embodied energy and carbon, illustrating the need for an agreement on an accurate way to estimate the embodied energy and embodied carbon of buildings. Cole and Kernan (1996) estimated the embodied energy is 4 to 9% of a 50 year life-cycle energy, whereas the Athena Institute of Sustainable Materials (2009) mentions 9 to 12% of a 60 year lifespan and Webster et al (2012) talk about 2 to 22% over 50 year. For the embodied carbon, the numbers vary widely as well, from 11 to 80% depending on the source (Simpson et al., 2010).

Figure 2.1: Wide-ranging results for embodied carbon, after (Simpson et al., 2010)
2.1. Material quantities

In the 1890s, a tower design competition in London asked for material weight as one of the criteria (Figure 2.2) and in the 1920s, Buckminster Fuller asked: “how much does your house weigh?” (Lynde, 1890; Braham and Hale, 2013). However, material efficiency does not always drive building design today. Indeed, as no framework yet exists to assess the embodied carbon of a structure, many buildings may be consuming materials in a wasteful way with impunity.

![Figure 2.2](image1.png)

**Figure 2.2**: Particulars of the design competition for the London tower in 1890 (Lynde, 1890).

Recently, other studies have attempted to map material efficiency of tall buildings considering the number of floors and structural systems (Cho et al., 2004; Elnimeiri and Gupta, 2009; Ali and Moon, 2007). Data on material quantities from leading structural design firms such as Arup and Thornton Tomasetti have been collected in the material quantity and the database of embodied Quantity outputs (deQo), developed at the Structural Design Lab within the Building Technology program at MIT (De Wolf and Ochsendorf, 2014; deQo, 2014).

Cho et al. (2004) express unit material quantities in volume (m³ per m²) for concrete and in mass (kg per m²) for rebar and steel. In Figure 2.3, they compare the structural steel quantities for various story heights. As Elnimeiri and Gupta (2009) express it, “good structural engineering revolves around achieving efficiency and minimization of material”.

![Figure 2.3](image2.png)

**Figure 2.3**: Structural steel quantities by number of stories (Cho et al., 2004)
Fazlur Khan (1980) introduced the notion of “premium for height” (Figure 2.4). With a growing number of stories, the weight of steel in kg/m² is not only increasing due to columns and bracing walls, but also due to the increasing lateral wind loads. Ali and Moon (2007) and Rizk (2010) give weights of steel in pounds per square feet (psf) versus the number of floors for steel framed tall buildings. The Council on Tall Buildings and Urban Habitat (CTBUH) points out it is often difficult to compare these material quantities, as some studies may include or exclude the foundations, mezzanine floors, etc. (CTBUH Journal, 2010).

![Figure 2.4](Image)

**Figure 2.4**: Weights of steel per numbers of stories, after (Khan, 1980; Ali and Moon, 2007)

The scope of current studies tends to be narrowed down to a specific type of structure (e.g. skyscrapers) or program (e.g. offices) (Amato and Eaton, 1998). Literature is lacking about the ranges of material weights in typical buildings.

### 2.2. Embodied Carbon Coefficients (ECCs)

Similar uncertainty and gaps in data also characterize the literature that examines Embodied Energy and Embodied Carbon. Moncaster and Symons (2013) describe the general lack of data in the field of embodied carbon. Alcorn (1996) discusses the “Embodied Energy Coefficients” (EEC, in MJ/kg\textsubscript{material}) of building materials, while Dias and Pooliyadda (2004) define “Embodied Carbon Coefficients” (ECC, in kg\textsubscript{CO2e}/kg\textsubscript{material}). The phrase “Carbon Intensity Factors” (CIF) is sometimes used interchangeably for the “Embodied Carbon Coefficients” (ECC).

Various reports have analyzed the environmental impact of concrete (Vares and Häkkinen, 1998; Lagerblad, 2005; Collins, 2010; Struble and Godfrey, 1999; NRMCA, 2014), as well as the impact of cement (Young, Turnbull and Russel, 2002). Other articles describe the embodied energy of metals (Chapman and Roberts, 1983) and in particular steel (ISSF, 2013; IISI, 2013; Eurofer, 2000; Stubbles, 2007; World Steel, 2014). Next to concrete and steel, discussions exist on the embodied energy and carbon of other construction materials such as timber (Pullen, 2000; Corrim, 2014). However, there is a significant variability in the results for both EEC and ECC values.
There is a need for material manufacturers, such as the concrete, steel and timber industry, to make the ECC data of their products more transparent and consistent (The Concrete Centre, 2013; Moynihan et al., 2012; Weight, 2011). However, each manufacturer puts forth a set of assumptions, such as which life cycle stages to include. For example, taking into account the carbon sequestration may be beneficial for the ECC value of timber, while taking into account the end of life recycled content may be beneficial for the ECC value of steel (Weight, 2011).

Efforts exist to summarize the ECCs of common construction materials. In the United Kingdom, the Inventory of Carbon and Energy (ICE) report from the University of Bath is one of the most complete open source databases for ECCs (Hammond and Jones, 2010). Figure 2.5 illustrates the variability of the available data on the embodied energy of steel. The wide range of available EEC/ECC values undermines useful comparisons of the environmental impact of different buildings. The ICE report selects the best available embodied energy and carbon data. However, there is still a need for values per country or region. The same concrete mix used in a big city in China or a small town in the United States will not have the same coefficients if factors such as transport are included (Ochsendorf, et al., 2011). In addition, the embodied carbon in the ICE report is often underestimated by considering only the initial stage (‘cradle to gate’) instead of the whole life cycle (‘cradle to grave’ or ‘cradle to cradle’). The life cycle stages are defined in the TC350 European standards (Moncaster and Symons, 2013). In the Unites States, the Carbon Working Group discusses the embodied carbon of common construction materials. However, the group highlights the uncertainty and variability of available data quality (Webster et al., 2012).

Several Life Cycle Inventory (LCI) and LCA tools exist to calculate impacts of single projects or materials. The commercial software Gabi, EcoInvent and SimaPro are common practice for LCA calculations, but can lack transparency due to protection of intellectual property (GaBi, 2013; EcoInvent, 2013; SimaPro, 2013). Furthermore, the Athena Institute of Sustainable Materials has integrated LCI data at the building scale (Athena, 2009).
2.3. Examples of existing implementations

The following paragraphs illustrate several existing databases and tools for estimating embodied carbon. The Athena Institute is a non-profit organization based in Canada that has integrated LCI data into building industry specific tools: the Athena Eco Calculator (free) and the Athena Impact Estimator (Athena, 2009). Also, EcoInvent provides thousands of LCI datasets in various fields from agriculture to electronics (EcoInvent, 2013).

Furthermore, various companies have developed in-house tools focused on estimating the embodied carbon of their projects. In 2013, Kieran Timberlake and PE International released the Tally environmental impact tool (Tally, 2013) extracting data from Revit models (Revit, 2014). The SOM Environmental Analysis tool is a user-friendly embodied carbon calculator for design projects (SOM, 2013).

In the United Kingdom, the non-profit Waste Reduction Action Program (WRAP) recently launched a project-based database of embodied carbon (WRAP, 2014). WRAP asks users of the web-interface to clearly mark building life cycle stages and to reference the LCA software used, without asking specifically for material quantities (Charlson, 2012). The Royal Institution of Chartered Surveyors (RICS) has started developing a range of benchmarks based on the available data on embodied carbon in buildings (RICS, 2014).

Many leading structural engineering firms have also started the development of in-house databases of structural material quantities or embodied carbon for their own projects. One thoroughly developed example is the Arup Project Embodied Carbon and Energy Database (PECD) mainly consisting of Arup buildings or projects from literature (PECD, 2013; Kaethner and Burridge, 2012; Yang, 2013). Although PECD contains approximately 600 projects, the data scarcity, scattering and wide ranges of data still hinders the definition of a baseline. Other companies, such as Thornton Tomasetti, have also developed a database of the material quantities, extracted via a Revit plug-in, and the embodied carbon in their projects.

Studies demonstrate the need to inform not only designers and clients, but also governments and the public of the need to develop solutions for carbon savings (Clark, 2013).

Table 2.1 gives a brief overview of companies and institutes working on similar problems. As can be discerned from this table, the existing initiatives only look at one or two of the parameters to estimate the embodied carbon of buildings. This thesis aims to bridge the gap between the various influences.
Despite a growing interest in this field, designers and clients still lack a global embodied carbon estimator (De Wolf et al., 2014).

Studies have attempted to map material efficiency of tall buildings considering the number of floors and structural systems (Khan, 1980; Cho et al., 2004; Ali and Moon, 2007; Elnimeiri and Gupta, 2009). Leading structural design firms such as Arup and Thornton Tomasetti collected data on material quantities in their projects in-house.

Other studies are assembling data on ECCs, such as the ICE database of the University of Bath in the United Kingdom (Hammond and Jones, 2010) or the Carbon Working Group in the United States of America (Webster et al., 2013). There is a need for material manufacturers, such as the concrete, steel and timber industry, to make the ECC data of their products more transparent and consistent.

Several LCI/LCA software exist on the material and product scale, such as GaBi (GaBi, 2013), EcoInvent (EcoInvent, 2013) and SimaPro (SimaPro, 2013), or on the building scale, such as the Athena Institute of Sustainable Materials (Athena, 2009). The WRAP embodied carbon

Table 2.1: Leading efforts in material quantity collection, ECC values, database implementation

<table>
<thead>
<tr>
<th>Reports</th>
<th>ECC Implementation</th>
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<tr>
<td>Inventory of Carbon &amp; Energy (ICE)</td>
<td>✓</td>
</tr>
<tr>
<td>Structure and Carbon (Carbon working group)</td>
<td>✓</td>
</tr>
<tr>
<td>Cole and Kernan, 1996</td>
<td>✓</td>
</tr>
<tr>
<td>Eaton and Amato, 1998</td>
<td>✓</td>
</tr>
<tr>
<td>Council of Tall Buildings and Urban Habitat (CTBUH)</td>
<td>✓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Software</th>
<th>ECC Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athena</td>
<td>✓</td>
</tr>
<tr>
<td>GaBi, SimaPro</td>
<td>✓</td>
</tr>
<tr>
<td>SOM Environmental Analysis Tool</td>
<td>✓</td>
</tr>
<tr>
<td>Tally beta tool</td>
<td>✓</td>
</tr>
<tr>
<td>Build Carbon Neutral, 2007</td>
<td>✓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Databases</th>
<th>ECC Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arup PECD</td>
<td>✓</td>
</tr>
<tr>
<td>Thornton Tomasetti</td>
<td>✓</td>
</tr>
<tr>
<td>WRAP</td>
<td>✓</td>
</tr>
</tbody>
</table>

2.4. Summary
database collects total carbon footprints of buildings, without asking for the material quantities in the projects still (De Wolf and Ochsendorf, 2014; WRAP, 2014). The RICS hopes to develop new benchmarks for embodied carbon based on these new data-points (RICS, 2014).

Overall, estimating the embodied carbon of building structures is data-intensive. However, the available data on material quantities or ECCs are scarce and often unreliable. A general lack of transparency hinders the usage ECC values available in the literature. Also, no baseline has been defined for benchmarking material efficiency and embodied carbon in buildings. This thesis will address these issues, by looking at the opportunities within the challenges. A framework for an interactive database a survey of several hundreds of existing buildings will follow.
3. Methodology

The study of publicly available carbon data in Chapter 2 (Figure 2.1) illustrates the variability in assumptions from different organizations. The existing literature is synthesized and the published numbers on both key variables – the material quantities and the ECCs – are compared in order to advise a unified method of estimating the GWP of buildings.

The methodology for estimating material quantities and the environmental impact of building structures is threefold. First, one-on-one conversations with leading structural engineering and design firms leads to a description of the current common practice and existing challenges in estimating embodied carbon of their building projects. Further, existing literature and tools for estimating the environmental impact of buildings are reviewed. Finally, the implementation of an interactive interface and a relational database will unify the collection and processing of data.

3.1. Personal conversations with practitioners

To start, conferences and discussions with experts provide feedback from the professional sectors of building design, engineering and construction. These interactions are held in the form of personal conversations, presentations at conferences or open discussions in offices.

The design firms and experienced practitioners give a critical review of what should be queried in a new database in order to legitimately compare the environmental impact of building structures. These conversations with experts pave the way to accurate baselines for embodied carbon while keeping the results easily accessible for the stakeholders.

Next to this critical review of the field, these interactions with practitioners also play a crucial part in the gathering of data. These contacts with professionals deliver a significant amount of data on material quantities in building projects. Leading structural engineering firms such as Arup and Thornton Tomasetti have shared hundreds of projects with this research to analyze, compare and validate the embodied carbon assessment method in their offices.

3.2. Assessment of existing literature and tools

As mentioned above, the available data are variable and often unreliable. It is therefore important to thoroughly and critically review the challenges and opportunities arising from the literature and existing tools. On one hand, (scarce) published numbers on material quantities in buildings are listed. On the other hand, the different numbers for ECCs are compared and evaluated. Finally, the current implementation of the actual estimation of the embodied carbon of whole building structures is assessed.

In particular, this thesis uses and compares various existing embodied carbon estimating tools. Various software or databases have been assessed (Table 3.1): the Athena Impact Estimator for Buildings, the GaBi LCA software, the Tally tool developed by Kieran Timberlake and PE
International, the SOM Environmental Analysis Tool, the WRAP embodied carbon database, etc. Very little has been written on the comparison of the available tools.

<table>
<thead>
<tr>
<th>Company</th>
<th>EC estimating tool</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athena Sustainable Materials Institute</td>
<td>Impact estimator</td>
<td>Athena, 2009</td>
</tr>
<tr>
<td>PE International</td>
<td>GaBi Software</td>
<td>GaBi, 2013</td>
</tr>
<tr>
<td>Kieran Timberlake &amp; PE international</td>
<td>Tally</td>
<td>Tally, 2013</td>
</tr>
<tr>
<td>Skidmore, Owings &amp; Merrill</td>
<td>SOM Environmental Analysis Tool</td>
<td>SOM, 2013</td>
</tr>
<tr>
<td>WRAP</td>
<td>WRAP Embodied Carbon Database</td>
<td>WRAP, 2014</td>
</tr>
</tbody>
</table>

Table 3.1: Existing reviewed embodied carbon estimating tools

3.3. A new interactive database

Recognizing the need for a uniform method of assessing embodied carbon in buildings, this research undertakes a long-term initiative to create an interactive, growing database of building projects. The online interface allows architects, engineers and researchers to input data on the material quantities and embodied impact of their projects.

The interactive web-based interface, where practitioners from industry can input data on their projects from all around the world in a transparent way, is connected to a growing relational database. While controlling the quality of the entered data, contribution of all industries is encouraged. A “Wiki” approach with multiple participants facilitates the communication with companies. The relational database is coded in MySQL, the interactive web-based interfaced in html and php scripts make the connection between both.

The following example illustrates the working of the interactive database. A user inputs the structural material quantities of an office building in London. Then, the participant can opt for the default ECC value offered by the database or enter his/her own customized value. The result will give the GWP of the project compared to other similar structures. Figure 3.1 shows the current interface and database developed for the purpose of this thesis.

A transparent database composed of thousands of projects, will give participants a greater confidence in the numbers for the GWP of buildings. Visualizing and comparing results will increase the understanding of the environmental impact of various building types and structural systems. Ultimately, the analysis of material quantities and embodied carbon will direct architects and engineers towards designs with a lower embodied carbon.
Figure 3.1: Part of the interactive interface of the database

The following chapters will expand on the three main contributions of this thesis. Chapter 4 reviews the challenges and opportunities in the field of embodied carbon. Chapter 5 proposes a framework for the interactive database. Chapter 6 illustrates the survey of over 200 existing buildings. The results will be summarized, discussed and will lead to conclusions in Chapter 7.

3.4. Summary

The methodology can be summarized in three techniques: personal conversations with leading experts, a review of the existing tools and literature and the development of a new interactive database. The experts are structural engineers, architects, researchers and consultants. The existing tools are databases such as WRAP, assessment tools such as Athena or LCA software such as GaBi. The interactive database is composed of a web-based interface and a relational database and will be discussed in more detail in Chapter 5. As a whole, these three techniques led to the development of the challenges and opportunities in obtaining material quantities and ECCs (Chapter 4), the framework for a new database (Chapter 5) and the survey of over 200 existing buildings (Chapter 6).
4. Challenges and opportunities in obtaining embodied quantities

4.1. Introduction

While individual companies and researchers are developing their own in-house databases, it is important to understand the challenges arising from carbon accounting. For an accurate, complete and reliable database, it is essential to know the obstacles before it is possible to overcome them. The thesis therefore addresses the lack of methodology or regulation divided among three topics:

1. The first task is to collect material quantity data and assess their quality. This can allow for comparisons across building types and structural systems.
2. The second goal is to propose standards for ECCs that are reasonably accurate but at the same time do not require a complicated calculation from a complete LCA for each material and each project.
3. The third topic addresses the implementation of the database. It includes unifying the different methodologies in a transparent way while respecting intellectual property.

For each of the three problems identified, this thesis defines opportunities as well as challenges. The opportunities illustrate the possibilities of the environmental impact database and can solve part of the tasks in each topic, but challenges remain to be undertaken.

4.2. Getting material quantities

The first challenges consist in obtaining accurate material quantities and generating as much data as possible. For accurate data, the scope of what is included should be very well defined (for example, should the sub-structure be included?). Generating large amounts of data requires incentives for architecture, engineering and construction firms to share their project information. Indeed, hundreds of projects are needed to create a representative sample pool.

The opportunity in getting structural material quantities arise from Building Information Models (BIM) such as Revit (Revit, 2014). Connecting Revit models to a database of material quantities will generate data quickly in an automated way. Architecture and structural design firms now almost always use BIM models for their projects. These 3D model based data consequently makes a significant amount of data on material quantities in buildings available. New design projects have a digital version of the amount of steel, concrete, timber or other materials used in the building structure.

With the right incentives, these design firms can share the information on their project in a fast and automated way with BIM, facilitating the collection of data on material choice and material quantities in the building projects. Accordingly, a considerable amount of quantitative data is already available in design firms and a user-friendly interactive web-interface should help populate the database.
4.3. Accurate ECCs

4.3.1. Literature on ECCs

The definition of ECCs is an important and complex matter. Typically these data are obtained from Life Cycle Inventory (LCI) databases. Many databases are available such as Bath University’s ICE report (Hammond and Jones, 2010), Athena (Athena, 2009) and EcoInvent (EcoInvent, 2013). In particular, the ICE presents ‘cradle-to-gate’ data for carbon and energy impacts of building materials mainly in the United Kingdom. Athena integrates average transportation distances (results customizable for different regions of the United States of America) as well as impacts from construction, maintenance and demolition (Athena, 2009). The tool helps designers evaluate environmental impacts without developing detailed material quantity takeoffs. The EcoInvent datasets are based on industrial data. The tool is compatible with most LCA and eco-design software tools (EcoInvent, 2013).

In order to understand the variability of ECCs among different databases, the values for cement and concrete obtained by ICE and Athena are reported in Table 4.1. For concrete in particular, the ECC can vary in a significant way depending on strength (Table 4.1, Figure 4.1 and Figure 4.2), cement quantity, percentage of fly ash (Figure 4.1) and blast furnace content. Moreover, in the case of reinforced concrete the environmental impact of reinforcing bar (rebar) has to be considered: the ICE suggests adding 0.77 for each 100kg of rebar per m$^3$. With different concrete strengths and rebar contents, the results vary widely per m$^3$ (240 kg versus 788 kg, Figure 4.2). A critical study is needed to interpret this extreme variability to establish reliability in the available concrete ECCs.

<table>
<thead>
<tr>
<th></th>
<th>ICE</th>
<th>Athena</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.74</td>
<td>0.776</td>
</tr>
<tr>
<td>Concrete 16/20</td>
<td>0.100</td>
<td>0.091</td>
</tr>
<tr>
<td>Concrete 25/30</td>
<td>0.113</td>
<td>0.128</td>
</tr>
</tbody>
</table>

Table 4.1: ECC for cement and concrete, data after (Hammond and Jones, 2010) and (Athena, 2009)

![ECC for concrete](image)

Figure 4.1: ECC for concrete, varying strengths and percentages of fly ash, data after (Hammond and Jones, 2010)
Figure 4.2: Embodied carbon for a 1m$^3$ of concrete at varying strengths and percentages of rebar, data after (Hammond and Jones, 2010).

Next to concrete, the ECC values for steel products also present an important variation, as illustrated in Figure 4.3 for various steel products and different recycled contents.

Figure 4.3: ECC for steel products at varying recycling contents, data after (Hammond and Jones, 2010)
Table 4.2 proposes average ECC values after the ICE database (Hammond and Jones, 2010) and EcoInvent (EcoInvent, 2013). The opportunity lies in the definitions of average numbers per location. If the database can propose an agreement for ECC standards, it can allow practitioners to use both average and more sophisticated customized values.

<table>
<thead>
<tr>
<th>Material</th>
<th>ECC in $\text{kg}_{{\text{CO}_2}/\text{kg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete¹</td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.11*</td>
</tr>
<tr>
<td>High Strength</td>
<td>0.13*</td>
</tr>
<tr>
<td>Steel²</td>
<td></td>
</tr>
<tr>
<td>Sections (beams, columns)</td>
<td>1.1</td>
</tr>
<tr>
<td>Sheeting</td>
<td>2.6</td>
</tr>
<tr>
<td>Studs</td>
<td>1.2</td>
</tr>
<tr>
<td>Plates</td>
<td>2.5</td>
</tr>
</tbody>
</table>
| Rebar³         | 65% recycled content                      | 1.7

¹ The Carbon coefficients for concrete can vary in a significant way depending on strength, cement quantity, percentage of fly ash and blast furnace content, in this table two values are provided that can be applied respectively for normal concrete (C20/25 - C28/35 and 30% fly ash) and high strength concrete (C32/40 - C40/50 and 30% fly ash). This does not include reinforcing steel in the concrete.

²after (Hammond and Jones, 2010);
³after (EcoInvent, 2014).

³after (GaBi, 2013)

Table 4.2: Evaluation of ECCs for a set of structural materials, in collaboration with Ornella Iuorio

### 4.3.2. Applied ranges for ECCs

This section discusses a choice of default ECCs, based on a critical review of databases, software and design scheme guides of leading companies. Figure 4.4 illustrates the results for unreinforced concrete, from different sources such as the ICE database, GaBi, Athena, The Concrete Centre. The deQo database follows the most reliable source or an average of the most reliable numbers.

![Figure 4.4: ECC of low, medium and high strength concrete from various sources](image)

30
Not only do these amounts depend on location (transport from extraction site to construction site), but also vary as a function of material composition. For example, for an ECC of reinforced concrete, numbers depend significantly on the mixes. Indeed, different cement contents, fly ash replacements, or rebar contents will have a considerable impact on the value of the ECC. However, to simplify the approach to estimating the GWP of buildings, an average ECC range can be determined. Figure 4.5 proposes average values for the ECC of reinforced concrete from low to high strength concrete and from 0 to 5% of rebar.

The same analysis is conducted for steel values (Figure 4.6), differentiating hotrolled steel and rebar. The ICE database gives the value for steel in the United Kingdom; Athena is applied to North America; SimaPro gives a general value for both hotrolled and rebar steel; and GaBi incorporates different global values. As can be discerned from Figure 4.6, the values are very different from one source to another.
A similar comparison was established for timber as a structural material. Figure 4.7 gives a summary of the ECC values for timber (Arup, 2008).

![Figure 4.7: ECC of glued laminated timber from various sources](image)

Having made this overview of material quantities and ECCs, a more critical evaluation is possible for the GWP results for building projects in section 4.4.

### 4.4. Implementation of a unified method

The last topic in this chapter is the implementation of a database with material quantities and embodied carbon. To define the challenges in this field, the first step is to analyze existing embodied carbon estimator tools (Table 4.3). Current developments are mainly design-oriented. Usually, tools do not give a specific indication of a baseline for benchmarking. A database-oriented tool is needed to shift away from the design process towards disclosure of projects after construction, in order to give an idea how the embodied carbon of a new design will compare to a typical building of the same typology and structural system.

<table>
<thead>
<tr>
<th>Tools</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>TALLY beta version</td>
<td>• Uses BIM output</td>
<td>• Control what BIM includes?</td>
</tr>
<tr>
<td></td>
<td>• Design oriented</td>
<td>• Transparency</td>
</tr>
<tr>
<td>SOM Environmental</td>
<td>• Basic default assumptions</td>
<td>• No Normalized metrics (kg/m²)</td>
</tr>
<tr>
<td>Analysis Tool</td>
<td>• Option for customized details</td>
<td>• Linear modeling of ECCs</td>
</tr>
<tr>
<td>Athena Carbon Estimator</td>
<td>• Established estimator</td>
<td>• No BIM connection</td>
</tr>
<tr>
<td></td>
<td>• No LCA expertise required</td>
<td>• Transparency</td>
</tr>
<tr>
<td>ARUP PECD</td>
<td>• Uses BIM output</td>
<td>• Control what BIM includes?</td>
</tr>
<tr>
<td></td>
<td>• Hundreds of projects available</td>
<td>• Transparency</td>
</tr>
</tbody>
</table>

Table 4.3: Review of used and tested tools

Two important aspects contradict one another: the need for transparency and the protection of intellectual property. Indeed, if a comparative database divulges all projects, the risk exists that companies will use it to demonstrate “lower” embodied carbon compared to their competitors, which could result in skewed data-points. Also ownership of data should be taken into account. An option would be to allow anonymous data input, which then undermines the transparency.
Also, the implementation has to make sure the input method is unified, so that apples are compared with apples.

Therefore, a uniform method is necessary. If the same two variables (SMQ in kg/m² and ECC in kg CO₂/kg m) are used for all project entries, with a clear definition of what is included (sub/superstructure), it will be possible to compare similar building types (office, residential, healthcare, stadia, etc.), structural systems, or locations. A unified and transparent database, with clear standards on ECCs and populated with thousands of projects, would give a greater confidence in the Global Warming Potential (kg CO₂/m²) of building structures and result in a baseline for comparison in the field of material weight and embodied carbon.

Examples of potential outcomes of the database are given in Figure 4.8 and Figure 4.9. These express the preliminary results of the GWP of real projects. The user can filter by different parameters, such as building type (Figure 4.8) or structural system (Figure 4.9). The preliminary results of available data have shown that average values range from 200 to 500 kg CO₂/m².

![Figure 4.8: Example of graphic showing GWP ranges for varying building types](image1.jpg)

![Figure 4.9: Example of graphic showing GWP ranges for varying structural systems](image2.jpg)
The main challenges discussed in this chapter are the following.

- The creation of incentives for companies to share data on their building projects.
- The identification of accurate default ECC values considering various locations.
- The resolution of data transparency while protecting intellectual ownership.

Nevertheless, these challenges also lead to following opportunities.

- The compatibility of data collection with Building Information Modeling tools allows for the generation of hundreds to thousands of datapoints.
- The proposal for an agreement on accurate ECC values will facilitate the calculation of the embodied carbon of buildings.
- A unified methodology for calculating the GWP of buildings will define reference buildings for assessing the embodied carbon of building structures.

Moreover, this chapter offered default ECCs based on the existing literature. Results for concrete range between 0.1 and 0.2 kg\(_{CO_2e}/kg\). With 2% of rebar, it can range between 0.13 and 0.23. With 2% of reinforcement, the value ranges between 0.18 and 0.28. For steel, a distinction is made between rebar (around 1.7 kg\(_{CO_2e}/kg\)) and hotrolled steel (around 0.8 kg\(_{CO_2e}/kg\)). Note that these values are used mostly in projects in the United States, but can vary with the location or material specification. Glued laminated timber has an ECC ranging between 0.1 and 0.8 kg\(_{CO_2e}/kg\).
5. Framework for a database

5.1. Introduction

The second contribution of this thesis is to create a framework for a database of building projects. Indeed, efforts exist to create an embodied carbon database of materials, such as the Inventory of Carbon & Energy (Hammond and Jones, 2010). However, until very recently, no database of buildings existed. This research proposes a framework for a worldwide, transparent and interactive database where architects, engineers and other stakeholders can input data about their building projects, more precisely about the material quantities and embodied carbon in their building structures.

In 2014, WRAP launched a database collecting embodied carbon in buildings (WRAP, 2014). However, they do not collect material quantities. This method requires a priori knowledge of the embodied carbon in a building project. Also, the collected carbon results in the WRAP database originate from various studies, making different assumptions. The embodied carbon calculated with different tools can therefore not always be compared equally. Therefore, this chapter will propose a framework for a complete database including material quantities together with the embodied carbon of building structures. The database elaborated in this Chapter is named “deQo” or “database of embodied Quantity outputs”.

The input and output parameters should be compatible with other databases such as WRAP, Project Embodied Carbon Database (PECD), etc. and use existing, international listings, classes and standards. The database should contain a significant amount of data entered with comparable assumptions.

Figure 5.1 illustrates the framework for an interactive database. On one side (Figure 5.1, left), the web-based interface is created to collect data on material quantities in building projects. Architects and engineers can input data on their projects on this interactive interface (deQo, 2014). The user can access this part online and can make different queries.

On the other side (Figure 5.1, right), a relational database, inaccessible to the user, stores the project data. This database in MySQL is connected to the HTML web-interface through a PHP script (Figure 5.1, center), processing the data back and forth.
The main aims of the relational database are the following:

- Build literacy on typical embodied carbon of structures;
- Offer a large data population beyond a single company;
- Compare project options (material choice, structural system, etc.) transparently;
- Shape a baseline for benchmarking in embodied carbon;
- Ultimately allow designers, industry and education to optimize design solutions.

This chapter contains six sections and a summary. In section 5.2, the database specifications are elaborated: what should be included in the in- and output parameters? In addition, section 5.3 details a framework for the relational database itself. In section 5.4, the interactive web-interface and tool to query results are illustrated. Furthermore, section 5.5 suggests the collaboration with industry and possibilities for connections with Building Information Models (BIM) plug-ins. Finally section 5.6 summarizes the contributions of this database.

5.2. Database specifications

This section explains the general framework of the database and expands on the features and options that the database should include in order to be useful for the industry. The in- and output parameters of the database will be discussed. The collected information is divided in two groups (Table 5.1): general and structural information. A future integration of operational energy, maintenance and financial cost is possible.

<table>
<thead>
<tr>
<th>1. General Information</th>
<th>2. Structural Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Credits, location, program, geometry</td>
<td>Material choice, structural systems, material quantities</td>
</tr>
<tr>
<td></td>
<td>BIM, BOQ, etc.</td>
</tr>
<tr>
<td>Embodied Carbon Coefficients</td>
<td>Default or entered by user</td>
</tr>
<tr>
<td>Results</td>
<td>Comparative charts</td>
</tr>
<tr>
<td>Material Quantities or GWP ranges</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Framework for a database

5.2.1. General information

The database input asking for general information (Figure 5.2 and Figure 5.3) contains the following input parameters: project name and source information (which can be held anonymous); the date of design, construction, completion and/or publication; building stage; location specifying region, country and town; program; architect, engineer and contractor; accredited rating scheme and applied building code. These parameters are selected carefully after reviewing existing tools and assessing the need for a universal tool in the industry. The main drivers for this relatively concise interface were transparency, the ability to normalize by different functional units, the accurate estimation of ECCs, the integration of material quantities in carbon assessments, the compatibility with other existing databases, the capability to compare projects legitimately and the aim to take conclusions on low-carbon design strategies.
### General information (1)

- **Project Name:**
- **Upload photo**
- **Metric Units**
- **Imperial Units**
- **References and Sources for this information:**
- **Upload**
- **Architect:**
- **Engineer:**
- **Contractor:**
- **Client:**
- **Publication Journal:**
- **Would you like the information in this section to be publicly viewable?**
  - Anonymous
  - Publicly viewable
- **Rating scheme accredited:** None

### Date

**Construction Completion (year):**

### Location

**Location**

- **Region:**
  - North America
- **Country:**
  - USA - Eastern
- **City or detailed location:**

### Building type (choose all that apply)

- General Use
- Office
- Residential
- Commercial/Retail
- Healthcare
- Education
- Recreation
- Restaurant
- Hotel/Motel/Hostel
- Industrial
- Sport Stadium
- Sport Hall (enclosed)
- Museum or Cultural Center
- Religious Center
- Conference Center
- Civic Building
- Prison
- Bridge
- Livestock Building
- Car Parking
- Service Zone
- Train or Subway Station (aboveground)
- Train or Subway Station (belowground)
- Airport and Airport Utilities
- Fire Station
- Gas Station

---

**Figure 5.2:** Interface, “General information” section, part 1
The project name has to be entered, even if the contributor can choose to stay anonymous. The source has to be clearly noted, in order to be able to post-verify the data. In case the contributors wish to highlight their project, they are able to upload an image of their building and must specify the source of the image for later publication purposes. The program or type of building, i.e. residential, office, recreational, healthcare etc., are an important factor. Indeed, a hospital has different requirements and therefore different material quantities than an office.

Geometry analysis includes aspects such as height and number of floors. The geometry has a mandatory entry: the total useable net floor area (m² or sf). Indeed, to be able to normalize the data, a functional unit should divide the absolute values of material quantities (kg or lbs) and embodied carbon (kgCO₂e) in structures. However, another functional unit should be used if more appropriate, for example the number of seats in stadia or the number of full-time occupants for schools. The gross floor area is asked when the total useable net floor area is unknown. A percentage of this value can be used as an approximation of the net floor area.
5.2.2. **Structural information**

The second set of input parameters contains the structural information (Figure 5.4) of the building projects. The structural system is divided into vertical, horizontal and lateral systems. Then, the material choices and material quantities are requested. Furthermore, the user needs to specify which building components are included. Resilience towards earthquake and other natural hazards are taken into account. Alongside this information, factors such as the climate zone are entered. Figure 5.4 illustrates the interface asking about the structural information of a newly entered building project.

![Figure 5.4: Interface, “Structural information” section, part 1](image)

A main material is selected for vertical, horizontal and lateral loads before specifying the structural system. Table 5.2 illustrates the available structural systems the user can pick from.
Table 5.2: Main Materials and corresponding structural systems

Table 5.3 illustrates the list of building components. The user selects which components are included in the analysis. Non-structural building components are added in order to make the database expandable to non-structural material quantities in the future.

Table 5.3: Structural and non-structural building components included
Before the material quantities are entered, the source of these data is specified (dwgs, BIM, bill of quantities, etc.). For the material quantities, only the materials that have been selected in ‘material choice’ and ‘structural system’ will be displayed (Figure 5.5). They can either be entered in absolute values (in kg) or relative values (kg per appropriate functional unit, usually m²). If only the absolute value is given, this value is normalized. The absolute value is divided by the functional unit. In most cases, the functional unit will be the useable floor area, given in the general information section. The relative material quantities are consequently expressed in kilograms per square meter. Also, the applied life cycle stages entered in order to make ‘apples-to-apples’ comparisons for the GWP results.

![Figure 5.5: Interface, “Structural information” section, part 2](image)
Additional, optional information can be added such as the structural grid, typical span, the foundation and ground types (Table 5.4). If information is known on these types, it is useful to compare material quantities of structures with similar grounds/foundations. Also, the loads can be entered: dead and live load in kN/m² as well as the wind, snow and seismic loads. The database will ask whether the dead load is superimposed or total. Instead of entering a number for the live load, a use type can also be specified.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.</td>
</tr>
<tr>
<td>B</td>
<td>Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth.</td>
</tr>
<tr>
<td>C</td>
<td>Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.</td>
</tr>
<tr>
<td>D</td>
<td>Deposits of loose-to-medium cohesion less soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.</td>
</tr>
<tr>
<td>E</td>
<td>A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s &gt; 800 m/s.</td>
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<tr>
<td>S1</td>
<td>Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI 40 or more) and high water content</td>
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<td>S2</td>
<td>Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S 1</td>
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Table 5.4: Ground types

### 5.2.3. Default versus entered ECCs

The scope of the project location is worldwide. The goal is to include hundreds to thousands of structures globally and to define default ECCs for location zones, such as countries and regions. ECCs are computed considering the location of the building.

However, the user can enter his/her own ECC calculations when citing the source clearly. The GWP can then be calculated by multiplying the SMQs with the ECCs. It is important to clearly state the assumptions users make when entering their own project data. For example, if they enter the ECCs, they should state clearly which life cycle stages are included and reference the source of their calculations (GaBi, SimaPro, etc.). The quality assessment of the data will depend on these assumption specifications.

### 5.2.4. Contribution of a new database

The proposed framework for a new database results from the review of existing carbon estimating tools and conversations with experts. Table 5.5 summarizes the contribution of the parameters collected deQO and compares the parameters to those in the existing tools reviewed in Chapter 4.

The reasons for incorporating these parameters in the database, summarized in the second column of Table 5.5, are the following: data should be as transparent as possible (“transparency”) while protecting proprietary rights (“intellectual property”); data should be compatible with other tools (“compatibility”); data should allow accurate ECC estimation (“ECC”); data should be comparable (“comparison”) and therefore normalized
(“normalization”); and data should say something about design strategies (“design”). The parameters are selected carefully in order to have a limited number of questions in the interface while enabling a complete analysis of material quantities and embodied carbon in buildings.

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</table>

Table 5.5: Motivation and comparison of deQo parameters with existing tools
5.3. Relational database

A relational database has been created to collect all the entered information. This means that all the data are set in tables related to each other. Through a php script, the MySQL database and html interface are connected. Figure 5.6 illustrates how the data are stored and how they can be viewed, edited and exported.

![Figure 5.6: Relational database, accessed through phpMyAdmin](image)

All the input parameters discussed above, such as the material quantities, embodied carbon coefficients and total floor area are related to each other and can be exported to spreadsheets or used directly within the MySQL database.

The simple multiplication, illustrated by equation 2, is performed within the relational database and stored for comparison with other projects.

\[
GWP \ (\text{kg} \cdot \text{CO}_2/\text{m}^2) = \text{Relative SMQ} \ (\text{kg}_m/\text{m}^3) \cdot \text{ECC} \ (\text{kg}_\text{CO}_2/\text{kg}_m) \quad [2]
\]

5.4. Web-based interface

The web-interface is aiming at clarity and transparency. As the database becomes more useful with a higher quantity of data, the access to it should be easy and the input parameters should be well defined. The list of input parameters should therefore be short (yet complete) so that the input process is fast.
The access to the database through the web-interface is granted after an (open-source) registration (in order to insure data quality). Although the name of the participants will be published, the individual projects can either be kept anonymous or highlighted following the request of the contributor. The first page of the interface is shown in Figure 5.7.

![DeQo Interface](image)

**Figure 5.7:** Register for deQo (deQo, 2014)

In the interactive web-interface, the user can click on the ‘Search’ button to illustrate the ranges of results already entered in the database (Figure 5.8). On the y-axis of the search tool, either “Material Quantities” or “Global Warming Potential” can be shown.

![Search Tool](image)

**Figure 5.8:** Search tool
The relational database should report results separately by building type, building component, material, structural system, life cycle stage, location, loading, average floor height, span, total height and number of floors. Finally, the rating scheme a building received can also be listed as another filtering factor to give an idea how well low embodied carbon projects are rewarded.

A specific approach needs to be followed for protecting the anonymity of building projects. For example, if a data-point has a height of 800 meters and a location set in Dubai, it is publicly known to be the Burj Khalifa (Figure 5.9, right). If another project is 1776 feet tall and located in New York City, confidential data on the Freedom tower (Figure 5.9, left) will be given away. It is therefore important to give the results only in ranges (of material quantities, embodied carbon or even height).

Figure 5.9: Freedom tower (Dunlap, 2014), Burj Khalifa (photograph by the author)

In this thesis, all input parameters are expressed in metric units. However, clicking on ‘imperial’ instead of ‘metric’ allows all data entries and results to show in the appropriate unit for the user.

5.5. Collaboration with industry

5.5.1. Revit plug-in developers

In order to collect a considerable amount of data on material quantities, collaboration with plug-in developers for Building Information Models (BIM) is necessary. An example of such a tool is the recently developed Revit plug-in for estimating the environmental impact of buildings. By using Revit models of their projects, Arup and Thornton Tomasetti were able to contribute hundreds of projects to the current deQo database (Figure 5.10).

Figure 5.10: Databases and tools using Revit for collecting material quantities
5.5.2. **Industry and research database**

The growing database is an important step towards an agreement for benchmarking. Indeed, the database will define baselines for building structures in order to measure a project’s efficiency in terms of material use or carbon emissions.

To create such a database, this research relies on voluntary data input from the leading firms in the industry, such as engineering offices and contractors. Furthermore, any data to feed into the database will have to be generated according to a universal set of rules (e.g. on boundary conditions and embodied carbon coefficients) to allow for meaningful comparisons and statistical analysis.

Figure 5.11 illustrates the collaboration between MIT and WRAP as well as participation opportunities for other companies. The deQo tool collects not only embodied carbon of building structures, but also their material quantities. With an agreement on corresponding ECCs, a connection can occur with the WRAP database, that is collecting solely the embodied carbon of buildings. Industry can participate by adding to the ‘Bill of Materials Database’ as well as to the ‘Project Embodied Carbon Database’. The more industry participates to both initiatives, the more accurate conclusions will be on material efficiency in structures and benchmarking of embodied carbon.

A way to create an incentive to add more data to the database is to reward the carbon accounting in rating systems such as LEED. Also, a simple ‘release of information’ can be signed by a company to allow its employees to add data about their projects. The companies’ logos can be added to the ‘contributors’ section on the web-interface.

![Figure 5.11: Collaboration deQo & WRAP databases and participation opportunities](image-url)
5.6. Summary

In this chapter, a framework is developed for a database collecting material quantities and the environmental impact of building projects. The database developed for the purpose of this thesis focuses on embodied carbon of building structures, but is designed with possibilities to expand to operational carbon and non-structural elements.

While working with existing tools and databases such as WRAP, Tally or the SOM environmental analysis tool, the database for embodied quantity outputs (deQo) is a framework for future development. As the field of embodied carbon needs to mature in the coming decade, the various existing tools will merge in one way or another to compare and combine the available data.

The deQo tool proposes in this chapter aims to help the industry to develop new benchmarks for embodied carbon in their structural projects. In comparison with other available tools, deQo attempts to offer a succinct but complete interface to allow meaningful comparisons of the environmental impact of buildings. By also looking at the material quantities, deQo can lead to more material efficiency in design.
6. Survey of existing buildings

6.1. Introduction

This chapter summarizes the results of the data collected through deQo. A survey of the 200 existing building projects will be presented. Different normalizations, filters and presentations of the material quantities and embodied carbon will lead to conclusions.

Additionally, the developed approach is applied on case studies. The first case study compares nine stadia to assess the impact of their design strategies on the environment. The second case study compares two historic bridges with opposite sustainability strategies in order to learn lessons from history. The third case study compares skyscrapers worldwide.

6.2. Existing building structures from the industry

This section shows the results of the material quantities and embodied carbon of real existing buildings from the industry, all fully or nearly completed. Some projects are collected through literature review, but most projects are shared by leading design firms such as Arup, Thornton Tomasetti through the deQo interface.

Figure 6.1 illustrates the concrete, hotrolled and rebar steel for ten projects entered in the deQo database. A wide range appears already. An obvious trend is that healthcare buildings tend to have the highest amount of material. Only the government building has a greater number. In fact, this government project is an imposing city hall containing a high amount of concrete. The lowest material weights are in office buildings.

![Figure 6.1: Material quantities in the ten first projects entered in deQo by program](image-url)
Figure 6.1 shows that in some cases iconic design (such as the government city hall) can have a significant impact on the material efficiency.

The companies also entered ECCs, verified with the appropriate coefficient values of the corresponding location. The results for the GWP of the building projects can be obtained by multiplying these coefficients with the material quantities, as shown in Figure 6.2.

Steel having a higher ECC than concrete, the contribution of the different materials to the total number shifts compared to the material quantity analysis. Hence, these charts give a better understanding of the environmental impacts of the structures.

Figure 6.3 gives an overview of 44 individual projects, ranked again by program. Healthcare buildings are still using a considerable amount of materials, but a wider variety of office buildings appear. Indeed, the embodied carbon of office buildings can vary by height (skyscraper versus low-rise), material use (steel, timber, concrete, composite) or location (city center, distance to material extraction). A new type is the residential building, where much higher quantities are observed. This study also counts in the partitioning walls, which explains this jump. A warehouse is mainly driven by structural efficiency, as the partitioning doesn’t have to be as thorough as in residential buildings, which explains the lower impacts.
In the studies above, the projects were sorted by program. When continuing this analysis on a greater number of building structures, the projects are moreover sorted by structural system, height, number of occupants, location, etc. Figure 6.4 shows the same building projects ranked by structural systems. The results show that concrete structures vary from 100 till 450 kg\(_{CO_2e}/m^2\), masonry from 225 till 575 kg\(_{CO_2e}/m^2\), steel from 80 till 475 kg\(_{CO_2e}/m^2\) and timber from 70 till 490 kg\(_{CO_2e}/m^2\). The most common values are 275 kg\(_{CO_2e}/m^2\) for masonry and 175 kg\(_{CO_2e}/m^2\) for timber. Much higher variations exist for concrete, steel and composite structures.
The same graphical results can be obtained for other parameters, such as location, height, date, number of floors, number of occupants. However, due to intellectual property rights, the following results, including 200 projects from industry, will be shown in ranges, rather than individual projects. Moreover, the box-and-whiskers graphical representation facilitates the visualization of the ranges, outliers, minimum and maximum. For example, Figure 6.5 gives an overview of different programs and the corresponding material quantity ranges. The boxes give the standard ranges with a line indicating the median. The whiskers indicate the minimum and maximum, where the crosses indicate the outliers, excluded from the analysis.

![Figure 6.5](image)

**Figure 6.5**: Ranges of material quantities for 200 real projects per program category

Figure 6.6 illustrates another way of organizing the data, i.e. by structural system. The 200 actual projects are divided in concrete, steel and composite structures.

![Figure 6.6](image)

**Figure 6.6**: Ranges of material quantities for real projects per structural system
The same graphical representation of the GWP demonstrates the ranges of the embodied carbon of buildings by program (Figure 6.7) or structural system (Figure 6.8).

As expected, the healthcare ranges are slightly higher, as are cultural and hospitality (hotels, which are similar to residential buildings). All buildings range on average between 250 and 700 kg CO₂e/m². These ranges are a first step towards benchmarking of building projects for their environmental impact.

Figure 6.8 divides the 200 projects in concrete, steel, timber and composite structures. Next to a few outliers, the ranges are visualized with the boxes. A wider variety of results exist for the steel buildings. As expected, the timber structures have a lower GWP than other structural types. It is important to note that these numbers consider the ‘cradle to construction’ stages and not the end of life.
In the following sections, several case studies will be analyzed in more depth. The first part discusses the analysis of stadia, the second part historic bridges and the third part tall office buildings.

### 6.3. Case Study I: Analysis of stadia

The first section introduces the studied sport stadia. The second section presents the material quantities used in this case study. The third section calculates the embodied carbon of the projects. Finally, the results are discussed.

#### 6.3.1. Description

Most stadia in this study are partially covered, while some have a retractable roof. All stadia were constructed between 2000 and 2011. Table 6.1 illustrates the stadia in this case study.

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<td>2005</td>
<td>Arup</td>
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<td>Rio de Janeiro, Brazil</td>
<td>2007</td>
<td>Andrade Rezende</td>
</tr>
<tr>
<td>Aviva Stadium</td>
<td>Dublin, Ireland</td>
<td>2010</td>
<td>Buro Happold</td>
</tr>
<tr>
<td>Australia Sydney Stadium</td>
<td>Sydney, Australia</td>
<td>2000</td>
<td>Sinclair Knight Merz</td>
</tr>
<tr>
<td>Beijing Olympic Stadium</td>
<td>Beijing, China</td>
<td>2008</td>
<td>Arup</td>
</tr>
<tr>
<td>Jaber Al Ahmad Stadium</td>
<td>Kuwait, Kuwait</td>
<td>2010</td>
<td>Schlaich Bergemann &amp; Partner</td>
</tr>
</tbody>
</table>

Table 6.1: List of sport stadia with location, date of completion and structural engineer

The material quantities and embodied carbon vary with the sizes of the sport stadia. It is therefore necessary to normalize the results. Two methods are used for normalizing: per area or per seat. Also, when comparing the final results, the presence of a (partial or retractable) roof should be taken into account. Table 6.2 gives the number of seats and type of roof. The ‘area per seat ratio’ is given in order to comprehensively interpret the results. Also, the sources for material quantities are given in Table 6.2 and can be found in part 2 of the references.

<table>
<thead>
<tr>
<th>Stadium</th>
<th>Area (m²)</th>
<th># Seats</th>
<th>Area/Seat</th>
<th>Roof</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millennium Stadium</td>
<td>40,000</td>
<td>74,500</td>
<td>0.54</td>
<td>Retractable</td>
<td>[1], [2]</td>
</tr>
<tr>
<td>Allianz Arena</td>
<td>37,600</td>
<td>68,000</td>
<td>0.55</td>
<td>Partially covered</td>
<td>[3]</td>
</tr>
<tr>
<td>Joao Havelange Olympic St.</td>
<td>34,250</td>
<td>45,000</td>
<td>0.76</td>
<td>Partially covered</td>
<td>[4]</td>
</tr>
<tr>
<td>London Olympic Stadium</td>
<td>61,575</td>
<td>80,000</td>
<td>0.77</td>
<td>Partially covered</td>
<td>[5]–[8]+[14]</td>
</tr>
<tr>
<td>Wembley Stadium</td>
<td>79,578</td>
<td>90,000</td>
<td>0.88</td>
<td>Retractable</td>
<td>[9], [10]</td>
</tr>
<tr>
<td>Aviva Stadium</td>
<td>66,460</td>
<td>51,700</td>
<td>1.29</td>
<td>Partially covered</td>
<td>[11]–[13]</td>
</tr>
<tr>
<td>Australia Sydney Stadium</td>
<td>160,000</td>
<td>110,000</td>
<td>1.45</td>
<td>Partially covered</td>
<td>[14]</td>
</tr>
<tr>
<td>Emirates Stadium</td>
<td>122,000</td>
<td>60,355</td>
<td>2.02</td>
<td>Partially covered</td>
<td>[15], [16]</td>
</tr>
<tr>
<td>Beijing Olympic Stadium</td>
<td>254,600</td>
<td>91,000</td>
<td>2.80</td>
<td>Partially covered</td>
<td>[17]–[19]+[14]</td>
</tr>
<tr>
<td>Jaber Al Ahmad Stadium</td>
<td>400,000</td>
<td>65,000</td>
<td>6.15</td>
<td>Partially covered</td>
<td>[20]–[22]</td>
</tr>
</tbody>
</table>

Table 6.2: List of sport stadia with area/seat ratio, number of seats, roof type and references
6.3.2. Material quantities in stadia

A comparison of the material quantities in steel and concrete is conducted primarily through a thorough literature review (references can be found in Table 6.2). Figure 6.9.a indicates the material quantities in kg normalized per area in m². The results demonstrate that most stadia range from 800 kg/m² to 3000 kg/m². However, both the Beijing Olympic and the Allianz Stadium have relatively high concrete and steel quantities, compared to the other stadia (up to ten times higher).

Nonetheless, the ‘area/seat’ ratio reveals a significant difference: the Allianz stadium with a ratio of 0.55 m²/seat can receive the same number of spectators on a much smaller area than the Beijing stadium with a ratio of 2.80 m²/seat. This means that the comparison per square meter is inequitable: the total material quantity of the Allianz is divided by an area that is 5.68 times smaller than the Beijing stadium for the same amount of spectators. This results in a much higher normalized material quantity. Therefore, it may be more useful to consider the material quantities normalized by the number of seats, which gives a better evaluation of the fulfillment of the function. Figure 6.9.b illustrates the material quantities divided by the number of seats. The material quantities range from 500 to 4000 kg per seat, except for the Beijing Olympic Stadium or “Bird’s Nest.” The material quantity per seat in the Beijing Olympic stadium is approximately ten times higher than in the London Olympic Stadium.

Figure 6.9: Material Quantities in kg: (a) normalized per square meter; (b) normalized per seat
6.3.3. Embodied carbon of stadia

Figure 6.10 illustrates the embodied carbon or GWP of the sport stadia. For projects based in the United Kingdom and Australia, the values of the ICE database are followed. For projects in America, the values of the Carbon Working Group are used. For the Beijing, Munich and Kuwait projects, an LCA of the materials is performed using GaBi (Gabi, 2013). The numbers are illustrated in Table 6.3.

<table>
<thead>
<tr>
<th>ECC</th>
<th>United Kingdom</th>
<th>Brazil</th>
<th>Kuwait</th>
<th>China</th>
<th>Germany</th>
<th>Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.10-0.13</td>
<td>0.13</td>
<td>0.15</td>
<td>0.17</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>Hotrolled steel</td>
<td>0.88-0.89</td>
<td>0.88</td>
<td>0.71</td>
<td>0.88</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td>Rebar steel</td>
<td>1.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.71</td>
</tr>
</tbody>
</table>

Table 6.3: ECCs used for this study

Steel has a higher ECC than concrete. For the same material weights, steel will therefore have a higher impact in the total embodied carbon. Consequently, these embodied carbon charts give a better understanding of the environmental impacts of the stadia, compared to the charts of material quantities. Nevertheless, similar trends appear. The high use of steel and concrete results in a high embodied carbon in the stadia.

Figure 6.10: GWP of stadia: (a) normalized per square meter; (b) normalized per seat
6.3.4. Discussion of results

The method of normalization (by area or by seat) has an important influence on the interpretation on the results. A stadium showing both high material usage and a high embodied carbon is the Beijing Olympic Stadium. By comparing both types of normalization, a better understanding of the numbers for GWP emerges. Nevertheless, as the results by seat give a better representation of the function of stadia, this method is preferred. Both key variables result in clear trends in the different stadium design strategies.

Comparing material quantities and embodied carbon in stadia illustrates the difficulty of this field. Indeed, a simple shift in functional unit from kg CO₂e per m² to kg CO₂e per seat changes radically the comparison. Also, the lack of available data on both variables, the material quantities and the embodied carbon coefficients, can question the reliability of the results. While this research is very data-intensive, the case studies of the stadia demonstrate the simplicity and transparency of the proposed approach in equation [1].

The results show that design strategies for stadium structures have a significant impact on their embodied carbon footprint. For example, the “Bird’s Nest” had an esthetic design pattern inspired by Chinese-style ‘crazed pottery’ (National Stadium, 2014), which resulted in a high material use and embodied carbon.

6.4. Case study II: Lessons from historic bridges

This section presents two complete opposite design solutions for sustainable historic: Inca suspension bridges and Roman arch bridges (Figure 6.11). Both bridges are made from local materials, but the design approach is fundamentally different: where Roman stone arch bridges are created to be permanent and have a life time of several thousands of years, the Peruvian communities rebuild the suspension grass bridges every year. This comparative analysis will illustrate the trade-off between lightweight temporary bridges versus heavy permanent bridges in terms of embodied carbon. The key question is: “What can historic bridges teach us on sustainability?”

Moreover, the comparison between the permanent and temporary structures can raise the question on the lifetime engineers and architects should consider for their designs. Indeed, temporary and reusable structures could compensate a less durable approach.

The chosen case studies are the Roman stone arch “Pont Saint Martin” in Aosta, Italy, and the last remaining Inca suspension grassbridge “Keswha-Chaka” in Huinchiri, Peru. They both have a single span around 30 meters. It is important to note that this analysis is meant to be comparative. The historic analysis require assumptions on the materials and construction methods, so that it is not accurate to talk about absolute numbers. The absolute values are not as relevant as the comparison between the cases, so that a conclusion can follow around the differences between permanent and temporary bridge structures.
6.4.1. Description

The Roman stone arch “Pont Saint Martin” crosses the Lys river in Aosta, Northern Italy and was built between 27 B.C. and A.D. 14 (Figure 6.11, left). With a span around 35.6 meters, it is the largest known span of Roman bridges. The single span arch is mostly made of gneiss, a local stone material and filled with soil (Blake, 1947). The Inca suspension bridge “Keshwa-chaka” (which translates as grass-bridge) between the villages of Huinchiri and Quehue crosses a 30 meters wide canyon over the Apurimac River in Peru (Figure 6.11, right). The lightweight construction is composed of braided cables for the floor and handrails, connected with vertical grass ropes and fixed at both sides with stone abutments. The villages at both sides of the rivers come together in a yearly three-day festival to rebuild the grass bridge after they throwing the old grass bridge into the river (Ochsendorf, 1996).

![Pont Saint Martin and Keshwa-Chaka comparison table](image)

<table>
<thead>
<tr>
<th>Pont Saint Martin</th>
<th>Keshwa-Chaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span 35.6 m</td>
<td>Span 30 m</td>
</tr>
<tr>
<td>27 B.C. – A.D. 14</td>
<td>15th century - today</td>
</tr>
<tr>
<td>Lys</td>
<td>Apurimac</td>
</tr>
<tr>
<td>Aosta, Italy</td>
<td>Huinchiri, Peru</td>
</tr>
<tr>
<td>Segmental stone arch</td>
<td>Suspension grass bridge</td>
</tr>
</tbody>
</table>

> 2000 years  
High initial cost  
Low maintenance cost  
High quality stone  
End of Life reuse  
Local material  

1 year  
Low initial cost  
High maintenance  
Low quality plants  
Washed away yearly  
Local material  

Images after [8]  
Information after [6], [7]  
Images after [12]  
Information after [10]

Figure 6.11: Pont Saint Martin (left) and Keshwa-Chaka (right)

The two bridges have a single span with similar length. However, the Roman arch Pont Saint Martin is working in compression and designed for a permanent lifetime, where the Inca Bridge Keshwa-Chaka is working in tension and designed for a lifespan of one year. The Roman arch uses high quality stone that could be reused at the end of life of the structure as opposed to the low quality grass used in the Inca Bridge, which is washed away every time the old bridge is thrown in the river. Nevertheless, both bridge designs have a sustainable approach that current bridge engineers and architects can learn from: they use local material and offer efficient solutions to the design problem (Ochsendorf, 2004).
6.4.2. Material quantities in historic bridges

First, the material quantities are estimated, based on geometry descriptions in publications, drawing and construction video’s. The sources for the two bridges can be found in part 3 of the references. The ECCs are estimated based on the material descriptions and the ICE database (Hammond and Jones, 2010). The calculations are summarized in (Figure 6.12).

![Figure 6.12](image)

**PONT SAINT MARTIN**

- **Vault, spandrel walls, pavimentum & parapets**
  - Local gneiss – ECC 0.017
  - Filling
  - Soil – ECC 0.023

**KESHWA-CHAKA**

- **Abutments** – 9070 kg
  - Stone – ECC 0.056
- **Vertical ropes, floor & handrails** – 3630 kg
  - Twisted cords, diameter 5 cm for ropes
  - Braided cables, 6 x 45 m for floor and rails
  - Puna grass – ECC 0.01
- **Deck** – 225 kg
  - Sticks & matted reeds

**Figure 6.12:** Weight/ECC Pont Saint Martin & Keshwa-Chaka, images after [4], [5], [9], [10], [11]

The results of the calculation of the material quantities in the Pont Saint Martin are illustrated in Table 6.4. An extended calculation can be found in appendix B.4.a.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Volume m³</th>
<th>Material</th>
<th>Density kg/m³</th>
<th>ECC</th>
<th>Weight kg</th>
<th>Weight per meter kg/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault</td>
<td>270</td>
<td>Gneiss</td>
<td>2610</td>
<td>0.017</td>
<td>704700</td>
<td>22443</td>
</tr>
<tr>
<td>Spandrel walls</td>
<td>390</td>
<td>Gneiss</td>
<td>2610</td>
<td>0.017</td>
<td>1017900</td>
<td>32417</td>
</tr>
<tr>
<td>Pavimentum</td>
<td>42</td>
<td>Limestone</td>
<td>2500</td>
<td>0.017</td>
<td>105000</td>
<td>3344</td>
</tr>
<tr>
<td>Parapets</td>
<td>26</td>
<td>Gneiss</td>
<td>2610</td>
<td>0.017</td>
<td>67860</td>
<td>2161</td>
</tr>
<tr>
<td>Filling</td>
<td>780</td>
<td>Soil</td>
<td>1600</td>
<td>0.023</td>
<td>1248000</td>
<td>39745</td>
</tr>
</tbody>
</table>

**Table 6.4:** Calculation weights and ECC for Pont Saint Martin

The results of the calculation of the material quantities in the Keshwa-Chaka bridge are illustrated in Table 6.5. An extended calculation can be found in appendix B.4.b.
### 6.4.3. Embodied carbon of historic bridges

Now that the weights and ECCs are determined, the Global Warming Potential (GWP) is given by multiplication. The total weight of the different parts have been divided by the span, in order to obtain a “linear” GWP, i.e. the GWP per meter of length of the bridge for the sake of comparison. Considering the Roman arch has a lifespan of more than 2000 years, where the Inca suspension bridge is less permanent, the lifetime of the bridges should be taken into account while looking at the Global Warming Potential. The “linear” GWP is divided by the number of years for which it has been standing to obtain an “annual” GWP. The results are shown in Table 6.6 for Pont Saint Martin and in Table 6.7 for the Keshwa-Chaka bridge.

#### Table 6.6: GWP of Pont Saint Martin

<table>
<thead>
<tr>
<th>Parts</th>
<th>Material</th>
<th>Weight / meter (kg/m)</th>
<th>GWP / meter (kgCO₂/m)</th>
<th>GWP / meter / year (kgCO₂/m/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault</td>
<td>Gneiss</td>
<td>22442.68</td>
<td>381.53</td>
<td>0.19</td>
</tr>
<tr>
<td>Spandrel walls</td>
<td>Gneiss</td>
<td>32417.20</td>
<td>551.09</td>
<td>0.28</td>
</tr>
<tr>
<td>Pavimentum</td>
<td>Limestone</td>
<td>3343.95</td>
<td>56.85</td>
<td>0.03</td>
</tr>
<tr>
<td>Parapets</td>
<td>Gneiss</td>
<td>2161.15</td>
<td>36.74</td>
<td>0.02</td>
</tr>
<tr>
<td>Filling</td>
<td>Soil</td>
<td>39745.22</td>
<td>914.14</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1940.34</strong></td>
<td><strong>0.97</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 6.7: GWP of Keshwa-Chaka

For the Keshwa-Chaka, the bridge is divided in a permanent and a temporary part. Indeed, the abutments are not rebuilt every year. This is the permanent part, which is divided by the number of years that the bridge has been in use (600 years). The suspended part, the grass bridge itself, is divided by one, as it requires the whole construction and material supply again every year. The “linear” and “annual” GWP are given in Table 6.7.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Material</th>
<th>Weight / meter (kg/m)</th>
<th>GWP / meter (kgCO₂/m)</th>
<th>GWP / meter / year (kgCO₂/m/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abutments</td>
<td>Stone</td>
<td>302.33</td>
<td>16.93</td>
<td>0.03</td>
</tr>
<tr>
<td>Cables</td>
<td>Puna grass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Ropes</td>
<td>Puna grass</td>
<td>121.00</td>
<td>1.21</td>
<td>1.21</td>
</tr>
<tr>
<td>Deck</td>
<td>Sticks, matted reeds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>18.14</strong></td>
<td><strong>1.24</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 6.5: Calculations sheet weights and ECC for Keshwa-Chaka
If comparing the “linear” GWP without taking into account the lifespan, the Roman arch has an embodied carbon (1940 kg$_{CO2}$/m) more than 100 times higher than the Inca suspension bridge (18 kg$_{CO2}$/m). However, if dividing the permanent parts by the years that the bridge has been in use, the Inca Bridge has a higher embodied carbon (1.24 kg$_{CO2}$/m/y) than the Roman arch (0.97 kg$_{CO2}$/m/y).

### 6.4.4. Comparison Roman arch and Inca suspension bridge

In Table 6.8, the comparison of both bridges is illustrated, with both the “linear” and the “annual” GWP compared.

<table>
<thead>
<tr>
<th></th>
<th>Pont Saint Martin</th>
<th>Keshwa-Chaka</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of Life reuse</td>
<td>High quality stone</td>
<td>Low quality plants</td>
</tr>
<tr>
<td>Local material</td>
<td>Gneiss &amp; Soil</td>
<td>Stone &amp; Puna grass</td>
</tr>
<tr>
<td>Embodied Carbon</td>
<td>1940.34 kg$_{CO2}$/m</td>
<td>18.14 kg$_{CO2}$/m</td>
</tr>
<tr>
<td></td>
<td>0.97 kg$_{CO2}$/m/y</td>
<td>1.24 kg$_{CO2}$/m/y</td>
</tr>
</tbody>
</table>

**Table 6.8**: Comparison Pont Saint Martin and Keshwa-Chaka, images from (Foer, 2013; O’Connor, 1993; The Last Handwoven bridge, 2013)

The first number shows that the Roman arch Pont Saint Martin has an embodied carbon of 1940 kg$_{CO2}$/m or a factor hundred more than the Inca suspension bridge Keshwa-Chaka with an embodied carbon of 18 kg$_{CO2}$/m. When taking the lifespans into account, the Roman arch has a slightly lower embodied carbon than the Inca Bridge.

When comparing both bridges, other aspects than embodied carbon, span and lifespans would need to be taken into account. The load capacity of the Roman arch is much higher (car traffic instead of pedestrian loads). Moreover, the Inca suspension bridges are also subject to a lot of lateral movements, especially during consequent wind loads. The Inca suspension bridge is part of a cultural heritage and community energy and vitality. Additionally, the bridge would probably last longer, at least up to two years, than the one-year lifespan it is given due to the annual festivities.

In both cases, the (linear or annual) GWP value is very low in general. The use of local materials, traditional manufacturing and efficient design has a significant impact on the embodied carbon. These low environmental impacts can teach current engineers and architects about efficient design.
6.4.5. **Comparison with recent bridge designs**

A comparison with recent bridges puts previous results in perspective. Figure 6.13 illustrates the material quantities of recent bridges with various spans (Clune, 2013). However, recent bridges are road bridges with multiple lanes carrying much heavier live loads than the historic counterparts discussed in this case study, so that the comparison is only theoretical.

![Graph showing material quantities of recent bridges](image)

**Figure 6.13:** Recent Bridges, material quantities (Clune, 2013)

The bridge with the most similar span (around 45 m) has a mass of 500 kg/m². This bridge has the lowest embodied carbon (best case!) among the recent bridges. With a width similar to Pont Saint Martin (which allows traffic), i.e. 6 m, the mass becomes 83 kg/m. An ECC for steel of 1.77 gives an embodied carbon of 147.5 kg CO₂/m. If we consider a lifetime of 50 years, the “annual” GWP becomes 2.95 kg CO₂/m/y, which is three times more than the two historic bridges. The upper bound of the range, a cable-stayed bridge, has a “linear” GWP of 590 kg CO₂/m and an “annual” GWP of 11.8 kg CO₂/m/y. These numbers do not include non-structural materials or maintenance. Indeed, recent bridges often require a new layer of asphalt every twenty years or a new layer of protective paint.

Though paving materials and maintenance are not included in results for recent bridges, the GWP is still ten times higher than for the two historic bridges (Table 6.9). The Oakland Bay Bridge, San Francisco, (Figure 6.14) has a mass of 2100 kg/m² and a width of 17.5m. The “linear” mass is of 120 kg/m. Multiplying with the ECC gives an embodied carbon of 212.4 kg CO₂/m, and dividing with the lifetime of the bridge of 76 years, gives 2.8 kg CO₂/m/y.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Mass/Area (kg/m²)</th>
<th>Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pont Saint Martin</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>Keshwa-Chaka</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>Oakland Baybridge</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Recent bridge range</td>
<td>2.8–11.8</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6.9:** Comparison of “annual” Global Warming Potential

![Oakland Bay Bridge, San Francisco, United States](image)

**Figure 6.14:** Oakland Bay Bridge, San Francisco, United States (photograph by the author)
6.5. Case study III: Comparing tall buildings

This section discusses the material quantities and embodied carbon in tall buildings. A comparison of tall landmark buildings worldwide is illustrated by ten case studies.

6.5.1. Description

The ten skyscrapers considered in this study are listed in Table 6.10, with their location, date of completion, structural engineer, structural system, height and sources (see part 4 in references).

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Date</th>
<th>Structural Engineer</th>
<th>Structure</th>
<th>Height (m)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Willis Tower</td>
<td>Chicago</td>
<td>1974</td>
<td>SOM</td>
<td>Steel</td>
<td>443</td>
<td>[21]</td>
</tr>
<tr>
<td>One World Trade Center</td>
<td>New York</td>
<td>2014</td>
<td>WSP Cantor Seinuk</td>
<td>Hybrid</td>
<td>546</td>
<td>[27]</td>
</tr>
<tr>
<td>Shanghai Tower</td>
<td>Shanghai</td>
<td>2014</td>
<td>Thornton Tomasetti</td>
<td>Concrete</td>
<td>632</td>
<td>[28] – [33]</td>
</tr>
<tr>
<td>Burj Khalifa</td>
<td>Dubai</td>
<td>2010</td>
<td>SOM</td>
<td>Buttressed Core</td>
<td>828</td>
<td>[34] – [41]</td>
</tr>
</tbody>
</table>

Table 6.10: Case studies for tall buildings

The height of the skyscrapers varies from 180 m for 30 St Mary Axe or “Gherkin” in London till 828 m for the Burj Khalifa in Dubai. As demonstrated by Khan (see section 2.1), the height of tall buildings influences the material quantities. Therefore, the results are always shown in graphics with increasing building height from left to right (or from top to bottom in case of Table 6.10). All buildings have been completed between 2004 and 2014, except for the Willis Tower in Chicago, in order to see how recent buildings relate to older skyscrapers.

6.5.2. Material quantities in tall buildings

Figure 6.15 gives the material quantities normalized by floor area. As opposed to the previous calculations in this thesis, the gross floor area has been used, as the internal floor area was not always available for the ten towers. The sources (Bibliography and references, part 4) are mostly publications, bill of quantities or design office documents.

Although the sources used to collect the data were fairly reliable, the accuracy could be improved. For example, The United Tower and The Shanghai Tower were both constructed with reinforced concrete, which has a certain percentage of steel. Therefore to obtain more accurate results the exact percentage of reinforcement bars in the concrete should be known. When this percentage was not known for the different cases, a general average of steel percentage in the reinforced concrete was taken.
To have a better understanding of the environmental impact of the tall buildings, the used ECCs were adapted to each region: the United Kingdom, the United States, the Middle East and China. Based on the ICE coefficients, LCA calculations adapted the ECCs to include transportation for the different countries. The modification consisted in the multiplication of the original transportation input by a ratio taking into account the surface area of the country. Then, a review of the concrete mix proportions used in every country was performed. The collection of data represented many challenges during this step. For example, no reliable source on the exact concrete mix of the World Financial Center, Shanghai, was found. Therefore, published information on high strength concrete was used, since this is the type of concrete used in the tower. The common water/cement ratio used for concrete lies between 0.45 and 0.6. However in the case of the high strength concrete, the water/cement ratio lies between 0.3 and 0.4. Consequently, the average value of 0.35 was used with a gravel-content of 950 kg/m³. Moreover, the typical cement content for this type of concrete varies between 350 to 500 kg/m³ of cement. Hence, a value of 450 kg/m³ of cement was selected and by applying the water cement ratio chosen the amount of water was calculated to be 157 kg. The water content is slightly lower than the usual water portion found in regular concrete due to the addition of plasticizers.

Figure 6.15: Material quantities normalized per gross floor area

6.5.3. Embodied carbon of tall buildings

To have a better understanding of the environmental impact of the tall buildings, the used ECCs were adapted to each region: the United Kingdom, the United States, the Middle East and China. Based on the ICE coefficients, LCA calculations adapted the ECCs to include transportation for the different countries. The modification consisted in the multiplication of the original transportation input by a ratio taking into account the surface area of the country. Then, a review of the concrete mix proportions used in every country was performed. The collection of data represented many challenges during this step. For example, no reliable source on the exact concrete mix of the World Financial Center, Shanghai, was found. Therefore, published information on high strength concrete was used, since this is the type of concrete used in the tower. The common water/cement ratio used for concrete lies between 0.45 and 0.6. However in the case of the high strength concrete, the water/cement ratio lies between 0.3 and 0.4. Consequently, the average value of 0.35 was used with a gravel-content of 950 kg/m³. Moreover, the typical cement content for this type of concrete varies between 350 to 500 kg/m³ of cement. Hence, a value of 450 kg/m³ of cement was selected and by applying the water cement ratio chosen the amount of water was calculated to be 157 kg. The water content is slightly lower than the usual water portion found in regular concrete due to the addition of plasticizers.
In the case of the United Tower in Kuwait, the main inputs used in the Life Cycle Assessment were extracted from the Bill of Quantities (BOQ) obtained from the client, United Real Estates. All information on the construction and the structure of the tower in Kuwait is confidential, and therefore it is difficult to obtain accurate information. From the BOQ, the main reinforced concrete quantities were extracted. However, the additional information regarding the structural system was obtained from construction magazines published in the Gulf. The only information on the exact concrete mix in the BOQ available was the Specification 03300. Therefore, technical papers published in Kuwait were used to adjust the cement content and water/cement ratio in the LCA sheet. Moreover, The BOQ does not specify the proportion of reinforcement in the concrete. Therefore it was assumed that steel reinforcement represents 0.5 percent of the reinforced concrete.

One of the challenges of this research is to be very transparent about the data used and the assumptions made. Therefore, the case studies are analyzed with different ECCs, given in Table 6.11. The values of the various sources are comparable in order of magnitude. The recycling and the reuse phases of the materials were not taken into account. Consequently, to assure the accuracy of the numbers found, a comparison is performed with the values from the ICE database and the Carbon Working Group. The results for the embodied carbon of tall buildings are shown in Figure 6.12.

<table>
<thead>
<tr>
<th>ECC</th>
<th>United Kingdom</th>
<th>Middle East</th>
<th>China</th>
<th>United States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.16</td>
<td>0.15</td>
<td>0.17</td>
<td>0.13</td>
</tr>
<tr>
<td>Hotrolled steel</td>
<td>0.89</td>
<td>0.71</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>Rebar steel</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Table 6.11:** ECCs used for this study

![Figure 6.16: Embodied carbon per area of tall buildings](image-url)
The results show the highest impact from concrete and reinforcement for the Al Hamra Firdous Tower and the United Tower, both in Kuwait. The Taipei 101 tower also represents a higher impact due to concrete quantities used for the construction. The 30 St Mary Axe or “Gherkin” in London has the lowest embodied carbon impact. It used a steel diagrid to enhance the structural efficiency of the tower. It should be noted that, though it was constructed in 1974, the Willis tower has the second lowest impact.

6.5.4. Discussion of the results

The high emissions for the Kuwait towers can be linked to the structural system of the skyscrapers. The architectural shape of the Al Hamra Tower (Figure 6.17.a.) requires more concrete than the other tall buildings. Also, the reinforced concrete structure with the concrete core in the United Tower (Figure 6.17.b.) was designed to accommodate the architectural wave feature of the building. The architectural design did not take into account material reduction.

![Figure 6.17: (a) Al Hamra (photograph by the author), (b) United Tower (KPF, 2012), (c) Gherkin (Munro, 2006)](image)

The design of the steel diagrid in the 30 St Mary Axe Tower or “Gherkin” (Figure 6.17.c.) demonstrates that integrating sustainable design and structural engineering starting from the concept stage influences the embodied carbon emissions of the tall buildings and that iconic design is not incompatible with embodied carbon reductions.

6.6. Summary

This chapter surveys over 200 existing buildings as well as historic and recent case studies. The survey of material quantities in buildings designed by leading engineering firms was conducted and the results of the ECCs in Chapter 4 lead to a range of embodied carbon values for various building types and different structural systems. Then, three case studies illustrated the process in sport stadia, historic bridges and tall buildings.
The survey of existing buildings demonstrated that the highest weight of material come from concrete, where the highest impacts are mainly due to concrete and hotrolled steel. The survey reveals that healthcare buildings have the highest amount of material (range between 1000 and 2300 kg/m²), followed by residential buildings (range between 1500 and 1800 kg/m²), whereas office or government buildings have the lowest amount of material (range between 500 and 1500 kg/m²). The GWP shows similar trends with typical values between 100 and 1000 kg CO₂e/m². The various structural systems, such as concrete, steel, timber and composite, were compared. Timber had the lowest cradle-to-site impact.

The case studies of the stadia illustrated an important aspect of estimating the GWP of buildings: the choice of functional unit. Dividing the total amount of materials by area or by seat resulted in different conclusions. When normalizing by seat, the Beijing Olympic Stadium was shown to have an impact ten times higher than the London Olympic Stadium.

The case studies of the historic bridges showed that recent bridge design can take lessons from history. The Keshwa Chaka Inca bridge illustrates temporary low-carbon design as opposed to the Roman arch Pont Saint Martin using a permanent low-carbon design.

Finally, the case studies of the tall buildings illustrate the impact of structural design on the material quantities and embodied carbon in structures. The results range from 250 to 2500 kg/m² for the material quantities and 50 to 450 kg CO₂e/m² for the GWP.

“How much does your building weigh Mr. Foster?” – An Art Commissioners film
This chapter is the first attempt in research in answering this question asked by an Art Commissioners film and by many structural engineers and architects.
7. Conclusions

“There’s only one creature capable of leaving a footprint that size…”
From King Kong movie

7.1. Discussion of results

This thesis has three types of results: (1) a critical review, (2) a new database and (3) a survey analysis. First, this research synthesizes the challenges and opportunities for collecting material quantities and embodied carbon. Second, to collect this information, it develops a framework for a database. Third, a survey of 200 real building projects formulates an understanding of the material efficiency and life cycle impact of actual buildings.

(1) The first part of this thesis discusses the challenges and opportunities in estimating the embodied carbon in structures. In order to obtain the Global Warming Potential (GWP), Structural Material Quantities (SMQ) are multiplied by Embodied Carbon Coefficients (ECC). For each of these three parameters, one main challenge and one main opportunity are defined.

For the material quantities, the industry needs incentives to share enough data on their building projects. Confidence in the results on material efficiency relies on voluntary data input from the leading firms in the industry, such as design offices, engineering firms and contractors. Motivations are necessary for stakeholders to spend additional time entering the material amounts in the database. However, BIM models such as Revit offer the opportunity to collect thousands of projects in an automated way. Linking Revit models to the database will generate thousands of data on material quantities in buildings.

Another challenge is to identify accurate ECC values. The available numbers vary widely, due in part to different life cycle stages included. Most currently available ECCs are cradle-to-gate. Therefore, parts of the life cycle such as transportation, construction or demolition are omitted. However, there is an opportunity to define default ECCs, based on the existing literature. For unreinforced concrete, ECCs range between 0.1 and 0.2 kg\(\text{CO}_2\)/kg depending on the strength. For reinforced concrete, the values lie between 0.13 and 0.23 kg\(\text{CO}_2\)/kg for 2% rebar and between 0.18 and 0.28 kg\(\text{CO}_2\)/kg for 5% rebar. Average values for steel are 1.7 kg\(\text{CO}_2\)/kg for rebar and 0.8 kg\(\text{CO}_2\)/kg for hotrolled steel. Values shift according to varying location, manufacturing, transportation, fly ash replacement, recycled content, etc.

After obtaining these two key variables, calculating the GWP itself presents challenges. Indeed, many firms request that their data be kept confidential. However, protecting the intellectual ownership of companies critically compromises comprehensive transparency. Nonetheless, a unified methodology will facilitate benchmarking of embodied carbon in structures. The opportunity lies in defining a universal assessment of the GWP, by obtaining the two key variables, SMQ and ECC, in a transparent way. Using the database developed in part (2) and the survey in part (3), a greater confidence in the numbers on embodied carbon in building structures will identify reference buildings for comparison.
(2) The second part of this thesis synthesizes the opportunities developed in part (1) into a new database, called “deQo” or “database for embodied Quantity outputs”. This thesis establishes a framework for this database collecting material quantities and embodied carbon of building projects.

A relational database is developed in MySQL connected to an html web-interface through php scripts. The deQo tool collects not only the embodied carbon, in addition to the work from the WRAP embodied carbon database (WRAP, 2014), but also the amounts of steel, concrete, timber and other materials in building structures. The interface targets structural materials, but the database was designed to expand to all building materials.

Many leading engineers are developing methods for estimating the embodied carbon of their projects, such as the SOM environmental analysis tool (SOM, 2013) or the Tally environmental impact tool (Tally, 2014). The review of these existing tools and conversations with leading experts have defined the parameters in deQo.

The field of life cycle impacts of buildings is maturing and the existing efforts will likely soon merge into a comprehensive approach. This database is a first step towards an agreement on ranges for material weights and embodied carbon in typical buildings. In the long term, deQo will offer the industry a basis for benchmarks on material efficiency as well as low-carbon buildings.

(3) The third part of this thesis analyzes a survey of over 200 buildings collected through deQo developed in part (2). A unified methodology (GWP = SMQ • ECC) is applied to the data from the survey and to three case studies in more detail.

A survey of 200 existing buildings reveals the material efficiency and the carbon impact of structures. As can be expected, healthcare buildings have the highest material amounts between 1000 and 2300 kg/m² and the highest embodied carbon between 300 and 800 kgCO₂e/m². Residential buildings also have high impacts, with material quantities ranging from 1100 to 1900 kg/m² and GWP values ranging from 250 to 750 kgCO₂e/m². The lowest impacts can be found in office and government buildings with material quantities between 500 and 1500 kg/m² and GWP between 200 and 1000 kgCO₂e/m². In general, the typical embodied carbon in structures ranges from 100 to 1000 kgCO₂e/m². Additionally, the different structural systems are compared, with timber having the lowest impact when taking into account cradle-to-site life cycle stages.

Furthermore, detailed case studies illustrate three important aspects on comparing embodied carbon and material efficiency in buildings. The first case study analyzes stadia. The study illustrates the importance of an appropriate functional unit. Indeed, when the material quantities are normalized by floor area, stadia have a lower impact compared to other building types in the survey. However, for a more comprehensive view on the GWP of stadia, the material quantities can be divided by number of seats as a functional unit. The Beijing Olympic Stadium or “Bird’s Nest” shows the highest amount of materials and impact, up to ten times higher than the London Olympic Stadium. Results therefore debate whether the floor area is the best choice as a functional unit. Another option for comparing the embodied carbon across building types is the number of total occupants, focusing on the service of the building rather than the geometry.
The second case study is the comparison of two historic bridges: the Inca grass bridge “Keshwa Chaka” and the Roman stone arch “Pont Saint Martin”. The trade-offs between temporary and permanent structures raise the question of what the total lifespan of buildings should be. Lessons learned from these historic structures are the following: using local materials and manufacturing and using force paths to shape structures. These strategies are followed in both the temporary and permanent options.

The last case study consists of tall buildings. The material quantities range widely from 250 to 2500 kg/m² as does the embodied carbon from 130 to 450 kg CO₂e/m². The structural system revealed itself crucial to lower the impact on the environment.

Taken as a whole, the three contributions (1), (2) and (3) offer a new understanding of material efficiency and the life cycle impact of building structures.

The critical review of the current challenges in part (1) has helped to develop a transparent, interactive, growing database in part (2). This database is crucial in the comparison of existing buildings in part (3). The combination of all results provides confidence in the numbers for material quantities and GWP of building structures.

7.2. Summary of contributions

This thesis answers the following key question: “What is the embodied carbon for different structures?” The answer to this question is important for multiple reasons. First, unlike operational carbon, embodied carbon is permanent. Lowering the latter therefore leads to immediate savings in carbon emissions. Moreover, the percentage of embodied carbon in the whole building life cycle is becoming significant with increasing operational energy efficiency and shortening building lifespans. Finally, structural engineers and architects need a transparent way of comparing the life cycle impact of their projects against reference buildings, especially since rating schemes started incorporating embodied carbon in their credits.

The major contribution of this thesis is to pave the way to a more unified method for collecting material quantities, defining accurate ECC ranges and calculating the GWP of building structures. The results discussed in Section 7.1 are a first attempt to estimate the material efficiency and environmental impact of buildings in a transparent way. An understanding of the emissions of buildings will become as intuitive as the CO₂ emissions of cars. For comparison, driving from Philadelphia to Boston (480km) would generate 104 kg of carbon, whereas the construction of the One World Trade Center or “Freedom Tower” generated 100,000,000 kg of carbon.

First, the challenges and opportunities encountered in existing literature and tools are analyzed. Three aspects are studied: the two key variables, SMQ and ECC, and an equation calculating the GWP. Separating the current practice in three topics develops a transparent approach. With a critical review of current literature and tools, this thesis creates a basis for a more unified and transparent methodology.
Second, the synthesis of the opportunities rising from the challenges led to a framework for a new database. Indeed, a new interactive, growing database was created to collect thousands of building projects from leading structural design firms. The database of embodied Quantity outputs or “deQo” incorporates the simple method multiplying two key variables to obtain the GWP.

Third, deQo already collected over 200 existing projects from worldwide architecture or structure companies. The survey of these projects contributed to a new understanding of material efficiency and environmental impact of structures. The results for building structures are normalized material weights ranging on average between 500 and 2500 kg/m² and normalized embodied carbon ranging on average between 250 and 750 kg CO₂e/m².

This thesis lays the groundwork that industry and research needs for benchmarking embodied carbon in buildings. All of this work is motivated by the prospect that ultimately, designers will incorporate Global Warming Potential as one of the factors to take into account in their design process.

### 7.3. Future research

Based on the approach developed in this thesis, the following paths are open for exploration:

- **Integrate Building Information Modeling (BIM) in carbon estimating tools**

While this thesis used BIM such as Revit through the data collection from practitioners, ultimately, there is a need for integrating BIM models directly into the database in order to compute thousands of projects at the time. Plugging in Revit software will allow benchmarking through comparison of thousands of projects across companies.

- **Dynamic alternative to the GWP**

The measure of the GWP, i.e. “carbon dioxide equivalent”, is a static way of measuring the environmental impact of buildings. However, Kendall (2014) demonstrates this static measurement could skew the results, because methane tends to disappear with the years as opposed to carbon dioxide emissions. Converting gases such as methane to the equivalent in carbon dioxide is consequently a static simplification of a dynamic phenomenon. Though this thesis used GWP as the most feasible, currently available assessment method, future research can explore how to integrate complex dynamic parameters such as the instantaneous climate impact (ICI) or the cumulative climate impact (CCI). These factors would better reflect the dynamic aspect of greenhouse gases.

- **Expanding to non-structural materials and to operational carbon**

The thesis is limited to structural materials only and the embodied life cycle stages. The method can be extrapolated to non-structural materials such as cladding and services. Also, combining the embodied and operational carbon will give a complete view of the whole life cycle impact of buildings.
• Extrapolating on the urban scale

This thesis looks at the embodied carbon on the material and building scale. However, current research efforts exist to implement embodied carbon at the urban scale. The “Urban Modeling Interface” or “umi” (umi, 2014), developed in the building technology program at MIT, simulates the life cycle impact of neighborhoods. A building’s massing model is associated with selected materials from a database. The result is a visualization of the LCA impacts per year (Figure 7.1).

![Figure 7.1: Massing model and yearly impact visualization in “umi” after (umi, 2014; Cerezo, 2013)](image)

• Incorporate embodied carbon in design, starting at the initial conceptual scheme stage

Architecture answers a combination of many different boundary conditions. Embodied carbon cannot be analyzed in isolation from other design factors. This thesis offers an objective analysis of the GWP of buildings, the baselines for benchmarking and the survey of case studies. Further research can develop a multi-scale synthesis (Figure 7.2) to integrate embodied carbon in architecture, starting at the initial concept scheme.

First, a study is necessary on the followed strategies in low impact buildings in the database. By exploring the successful case studies, themes will appear in the design process. Second, an analysis should determine how embodied carbon correlates with financial cost. Balancing material and construction cost with financial advantages due to accreditation will pave the way to a cost efficient strategy for low impact buildings. Third, it is crucial to take into account how strategies for decreasing embodied carbon in buildings interact with other variables in the design process. Indeed, a method that lowers the embodied carbon of a building could in some cases undermine the operational energy, the structural efficiency, the functionality or the spatial experience of the architecture. Further research can explore how life cycle impacts relate to these other parameters. The relationship of embodied carbon to other criteria will identify its importance in the design process.
The objective analysis in this thesis combined with a future multi-scale synthesis will lead to a new design approach in architecture. The qualitative and quantitative assessment of embodied life cycle impacts of buildings will develop new design criteria. While leaving all design options open to architects and engineers, the expanded knowledge will inform designers and their clients on the impact of their choices. These new guidelines will create opportunities for reducing the embodied carbon in the built environment.

- Making the business case

Finally, research on embodied carbon alone is not enough to incorporate change in design. Not only structural engineers and architects should be informed of low-carbon design strategies, but also the government and the public. It is important to make the business case for lowering the embodied carbon of structure, either by informing, rewarding through rating schemes such as LEED and BREEAM or by legislation.

"Informing both government and the media of the need for the right legislation, and the long-term cost benefits of this, is probably as important in the delivery of significant change as developing the actual solutions to deliver energy and carbon savings in buildings." – David Clark (CLARK, 2013)
Bibliography and references

The references and bibliography of this thesis can be found hereunder. Part 1 gives the general bibliography and references in alphabetical order. Part 2, 3 and 4 give the references specific to the case studies. A detailed list of references for the material quantities in the stadia, historic bridges and tall buildings enhances the transparency of the applied method.

Part 1: General bibliography and references


deQo (2014) “database for embodied Quantity outputs.” available at embodiedco2.scripts.mit.edu


SEAONC Sustainable Design Committee and SEI Sustainability Committee (2013) “For practicing structural engineers to provide comments to improve MIT Database Inputs Template.” Report by Frances Yang, San Francisco.


The Concrete Centre (2013) “Embodied carbon dioxide (CO2e) of concretes used in buildings.” mpa The Concrete Centre on behalf of the Sustainable Concrete Forum, London.


Yang, Frances, Arup, personal conversation with Catherine De Wolf, San Francisco, July 11, 2013.


Part 2: Stadia references

This section gives the references for the stadia. The material quantities were cross-referenced with the following sources. They are classified per stadium.

Millenium Stadium, Cardiff


Allianz Arena, Munich


Joao Havelange Olympic Stadium


London Olympic Stadium


Wembley Stadium


Aviva Stadium

Australia Sydney Stadium


Emirates Stadium


Beijing National Stadium


Jaber Al-Ahmad Stadium


Part 3: Historic bridges references

This section gives the references for the historic bridges. The material quantities were cross-referenced with the following sources. They are classified per bridge.


Pont Saint Martin


Keshwa-Chaka bridge


**Part 4: Tall building references**


**30 St Mary Axe**


**The United Tower**


The Shard


Al Hamra Firdous Tower


Willis Tower


World Financial Center


Taipei 101

One World Trade Center

Shanghai Tower

Burj Khalifa
[38] Abdelrazaq, A. “Validating the Structural Behavior and Response of Burj Khalifa: Synopsis of the Full Scale Structural Health Monitoring Programs.”
Appendices

Appendix A: Nomenclature

A.1. List of acronyms

BIM  Building Information Models
BOM  Bill of Materials
BOQ  Bill of Quantities
CCI  Cumulative Climate Impact
CIF  Carbon Intensity Factor, synonym of ECC
CO₂e Carbon dioxide equivalent
delo database of embodied Quantity outputs, available at: embodiedco2.scripts.mit.edu
ECC  Embodied Carbon Coefficient
EEC  Embodied Energy Coefficient
GHG  Greenhouse Gases
GWP  Global Warming Potential
html HyperText Markup Language
ICE  Inventory of Carbon & Energy (Hammond and Jones, 2010)
ICI  Instantaneous Climate Impact
IPCC Intergovernmental Panel on Climate Change
LCA  Life Cycle Assessment
LCI  Life Cycle Inventory
MIT Massachusetts Institute of Technology
MySQL Open-source relational database management system, named after co-founder Michael Widenius’s daughter, My and SQL stands for Structured Query Language
PECD Project Embodied Carbon Database, developed by Arup and Climate Earth (Yang, 2014)
php Hypertext PreProcessor (backronym), a server-side scripting language
RICS Royal Institution of Chartered Surveyors, available at: www.rics.org
SOM Skidmore, Owings & Merrill LLP, available at: www.som.com
SQM Structural Material Quantities
umi urban modeling interface
WRAP Waste Reduction Action Program, developed the wrap embodied carbon database, available at: ecdb.wrap.org.uk
A.2. Lexicon

**Carbon Dioxide Equivalent (CO₂e)**  
The “equivalent” in carbon dioxide of all emitted greenhouse gases (GHGs).  
*Carbon Dioxide* (Only the CO₂) ≠ *Carbon Dioxide Equivalent (CO₂e)*, which converts all GHGs to the “equivalent” in CO₂.  
For example, 1 lbs of methane (CH₄) is equivalent to 21 lbs of carbon dioxide (CO₂).

**Cradle to Gate**  
The life cycle stages from the material extraction till the finished product.

**Cradle to Site**  
The life cycle stages from the material extraction till the product arrives on site.

**Cradle to Grave**  
All the life cycle stages: material extraction, processing, product manufacturing, transport to site, construction, use, demolition and either reuse/recycling/landfill.

All the life cycle stages of a building are illustrated in Figure A.1.

---

**Operational energy**  
Energy used for the heating, cooling, hot water, ventilation and lighting of a building.

**Embodied energy**  
Energy used for the material extraction, material processing and product manufacturing, the transport of products to the construction site, the construction of a building and the demolition at the end of life. It is all the life cycle energy excluding the operational energy.
Whole life cycle energy

Whole life cycle energy = operational energy + embodied energy (definition a)

Sometimes, the transport of the building occupants (≠ transport of product), for example commuting of employees for an office building, and their consumption are also considered. The definition of whole life cycle energy then also contains these aspects.

Whole life cycle energy = operational energy + embodied energy + transportation energy + consumption energy (definition b)

In this thesis, when talking about the whole life cycle energy, definition (a) is implied.

Embodied carbon

Embodied carbon corresponds to the emitted greenhouse gases (GHGs) to produce the embodied energy. ‘Carbon’ is not the same as ‘energy’, as the GHG emissions depend on the fuel used and the carbon emitted or absorbed by the materials processed too. For example, processing cement can emit CO$_2$, where timber sequestrates CO$_2$.

Functional unit

A specified metric used to normalize the carbon footprint of buildings in order to compare ‘apples to apples’. For example, the useable floor area can be the functional unit, so that the total embodied carbon is divided by the total useable floor area. The GWP is consequently measured in kg$_{CO2e}$/m$^2$. The number of occupants is another example of a functional unit. The GWP is then measured in kg$_{CO2e}$/occupant.

Global Warming Potential

Measure of embodied carbon of a building project, expressed in kg of carbon dioxide equivalent (kg$_{CO2e}$) per functional unit (usually m$^2$).
## Appendix B: Tables

### B.1. Ten first projects in deQo

<table>
<thead>
<tr>
<th>Program</th>
<th>Location</th>
<th>Structural System</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office, high rise</td>
<td>London, UK</td>
<td>Steel, diagrid</td>
<td>47,850</td>
</tr>
<tr>
<td>Government</td>
<td>New Port Beach, USA</td>
<td>Composite</td>
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<tr>
<td>Healthcare</td>
<td>San Francisco, USA</td>
<td>Concrete</td>
<td>46,755</td>
</tr>
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<td>Healthcare</td>
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<td>Healthcare + Office</td>
<td>LA, USA</td>
<td>Concrete</td>
<td>6,821</td>
</tr>
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<td>Office</td>
<td>CA &amp; Mexico</td>
<td>Concrete</td>
<td>7,870</td>
</tr>
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<td>USA</td>
<td>Composite</td>
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<td>Seattle, USA</td>
<td>Concrete</td>
<td>89,354</td>
</tr>
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<td>LA, USA</td>
<td>Composite</td>
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</tr>
<tr>
<td>Car Parking</td>
<td>USA</td>
<td>Concrete</td>
<td>181,951</td>
</tr>
</tbody>
</table>

Table B.1: Ten projects entered through deQo, name made anonymous

Table B.2 gives the material quantities divided into sub- and superstructure and divided by material: concrete (C), hotrolled steel (S) and reinforcement bar (R).

<table>
<thead>
<tr>
<th>Program</th>
<th>C kg/m²</th>
<th>S kg/m²</th>
<th>R kg/m²</th>
<th>C kg/m²</th>
<th>S kg/m²</th>
<th>R kg/m²</th>
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<td>195</td>
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<td>70</td>
<td>404</td>
<td>153</td>
<td>13</td>
</tr>
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<td>Healthcare + Office</td>
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<td>0</td>
<td>24</td>
<td>305</td>
<td>75</td>
<td>9</td>
</tr>
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<td>Office</td>
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<td>38</td>
<td>112</td>
<td>71</td>
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<tr>
<td>Office, high rise</td>
<td>287</td>
<td>0</td>
<td>10</td>
<td>111</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>Office, mid rise</td>
<td>776</td>
<td>0</td>
<td>14</td>
<td>215</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td>Central Utility Plant</td>
<td>979</td>
<td>0</td>
<td>26</td>
<td>645</td>
<td>179</td>
<td>21</td>
</tr>
<tr>
<td>Car Parking</td>
<td>210</td>
<td>0</td>
<td>7</td>
<td>518</td>
<td>16</td>
<td>24</td>
</tr>
</tbody>
</table>

Table B.2: Material quantities of the 10 projects in Table B.1.1.

<table>
<thead>
<tr>
<th>Program</th>
<th>Source</th>
<th>ECC kgCO₂/kg</th>
<th>GWP per material kgCO₂/m²</th>
<th>GWP total kgCO₂/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office, high rise</td>
<td>LCA</td>
<td>0.16</td>
<td>0.89 0.89</td>
<td>31 156 4</td>
</tr>
<tr>
<td>Government</td>
<td>Arup</td>
<td>0.14</td>
<td>1.41 0.57</td>
<td>83 157 11</td>
</tr>
<tr>
<td>Healthcare</td>
<td>Arup</td>
<td>0.10</td>
<td>0.56 0.57</td>
<td>101 37 12</td>
</tr>
<tr>
<td>Healthcare</td>
<td>Arup</td>
<td>0.15</td>
<td>1.40 0.57</td>
<td>185 215 47</td>
</tr>
<tr>
<td>Healthcare + Office</td>
<td>Arup</td>
<td>0.15</td>
<td>1.42 0.57</td>
<td>139 106 19</td>
</tr>
<tr>
<td>Office</td>
<td>Arup</td>
<td>0.15</td>
<td>1.38 0.56</td>
<td>52 98 29</td>
</tr>
<tr>
<td>Office, high rise</td>
<td>Arup</td>
<td>0.11</td>
<td>1.49 0.57</td>
<td>42 37 8</td>
</tr>
<tr>
<td>Office, mid rise</td>
<td>Arup</td>
<td>0.12</td>
<td>1.48 0.57</td>
<td>124 66 11</td>
</tr>
<tr>
<td>Central Utility Plant</td>
<td>Arup</td>
<td>0.08</td>
<td>1.04 0.43</td>
<td>130 187 20</td>
</tr>
<tr>
<td>Car Parking</td>
<td>Arup</td>
<td>0.15</td>
<td>1.88 0.57</td>
<td>107 30 17</td>
</tr>
</tbody>
</table>

Table B.3: ECCs used for the materials and GWP of the 10 projects in Table B.1.1.
### B.2. Analysis of stadia

#### Table B.4: Data on stadia, five first stadia

<table>
<thead>
<tr>
<th>location</th>
<th>unit</th>
<th>Aviva</th>
<th>Australia</th>
<th>Emirates</th>
<th>Beijing</th>
<th>Jaber Al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor area</td>
<td>m²</td>
<td>40,000</td>
<td>37,600</td>
<td>34,250</td>
<td>61,575</td>
<td>79,578</td>
</tr>
<tr>
<td>number of seats</td>
<td></td>
<td>74,500</td>
<td>68,000</td>
<td>45,000</td>
<td>80,000</td>
<td>90,000</td>
</tr>
<tr>
<td>area/seat</td>
<td>m²/seat</td>
<td>0.54</td>
<td>0.55</td>
<td>0.76</td>
<td>0.77</td>
<td>0.88</td>
</tr>
<tr>
<td>total steel</td>
<td>kg</td>
<td>12,000,000</td>
<td>20,000,000</td>
<td>2,700,000</td>
<td>10,700,000</td>
<td>23,000,000</td>
</tr>
<tr>
<td>total rebar</td>
<td>kg</td>
<td>4,000,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total concrete</td>
<td>kg</td>
<td>40,000,000</td>
<td>256,800,000</td>
<td>96,000,000</td>
<td>102,000,000</td>
<td>216,000,000</td>
</tr>
<tr>
<td>steel per area</td>
<td>kg/m²</td>
<td>300</td>
<td>532</td>
<td>79</td>
<td>174</td>
<td>289</td>
</tr>
<tr>
<td>rebar per area</td>
<td>kg/m³</td>
<td>100</td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>concrete per area</td>
<td>kg/m²</td>
<td>1,000</td>
<td>6,830</td>
<td>2,803</td>
<td>1,657</td>
<td>2,714</td>
</tr>
<tr>
<td>steel per seat</td>
<td>kg/seat</td>
<td>161</td>
<td>294</td>
<td>60</td>
<td>134</td>
<td>256</td>
</tr>
<tr>
<td>rebar per seat</td>
<td>kg/seat</td>
<td>54</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>concrete per seat</td>
<td>kg/seat</td>
<td>537</td>
<td>3,776</td>
<td>2,133</td>
<td>1,275</td>
<td>2,400</td>
</tr>
<tr>
<td>ECC steel</td>
<td>kgCO₂/kg</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.89</td>
<td>0.88</td>
</tr>
<tr>
<td>ECC rebar</td>
<td>kgCO₂/kg</td>
<td>1.71</td>
<td>1.71</td>
<td>1.71</td>
<td>1.71</td>
<td>1.71</td>
</tr>
<tr>
<td>ECC concrete</td>
<td>kgCO₂/kg</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>EC steel per area</td>
<td>kgCO₂/m²</td>
<td>264</td>
<td>468</td>
<td>69</td>
<td>155</td>
<td>254</td>
</tr>
<tr>
<td>EC rebar per area</td>
<td>kgCO₂/m²</td>
<td>171</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EC concrete per area</td>
<td>kgCO₂/m²</td>
<td>130</td>
<td>888</td>
<td>364</td>
<td>159</td>
<td>353</td>
</tr>
<tr>
<td>EC steel per seat</td>
<td>kgCO₂/seat</td>
<td>142</td>
<td>259</td>
<td>53</td>
<td>119</td>
<td>225</td>
</tr>
<tr>
<td>EC rebar per seat</td>
<td>kgCO₂/seat</td>
<td>92</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EC concrete per seat</td>
<td>kgCO₂/seat</td>
<td>70</td>
<td>491</td>
<td>277</td>
<td>122</td>
<td>312</td>
</tr>
</tbody>
</table>

#### Table B.5: Data on stadia, five last stadia
B.3. Analysis of historic bridges

B.3.a. Calculations Pont Saint Martin

The **Pont Saint Martin** has a span of approximately 35.6 m with a rise of one-third of the span. The width of the bridge is 5.8 m (4.6 m between parapets) and the height is 12 m (13.6 m when counting the parapet). The main material used in the bridge is blocks of local gneiss (O’Connor, 1993).

Based on the drawings and descriptions in (Frunzio and Monaco, 1998; Sinopoli, 1998), the volumes of different parts of the Roman arch could be determined. The detailed calculations are shown in attachment. The volume of the vault, spandrel walls, pavimentum and parapets, which are made of stone, is 686 m³. The densities of the stones (Alden) are set at 2610 and 2500 kg/m³. This part weighs 1790 tonnes. The interior part of the bridge, which is filled by 780 m³ of soil, with a density of 1600 kg/m³ (Soil, 2008), weighs 1248 tonnes.

The ECC factors given by (Hammond and Jones, 2010) for gneiss and limestone are 0.017 kg CO₂/kg and 0.023 kg CO₂/kg for soil.

### Table B.6: Calculations Pont Saint Martin

<table>
<thead>
<tr>
<th>Parts</th>
<th>Volume m³</th>
<th>Material</th>
<th>Density kg/m³</th>
<th>ECC kg CO₂/kg</th>
<th>Weight kg</th>
<th>Weight kg/m</th>
<th>GWP kg CO₂/m</th>
<th>GWP kg CO₂/m/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault</td>
<td>270</td>
<td>Gneiss</td>
<td>2610</td>
<td>0.017</td>
<td>704700</td>
<td>22443</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Spandrel</td>
<td>390</td>
<td>Gneiss</td>
<td>2610</td>
<td>0.017</td>
<td>1017900</td>
<td>32417</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Pav.</td>
<td>42</td>
<td>Limestone</td>
<td>2500</td>
<td>0.017</td>
<td>105000</td>
<td>3344</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Parapets</td>
<td>26</td>
<td>Gneiss</td>
<td>2610</td>
<td>0.017</td>
<td>67860</td>
<td>2161</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Filling</td>
<td>780</td>
<td>Soil</td>
<td>1600</td>
<td>0.023</td>
<td>1248000</td>
<td>39745</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1940</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Legend**

- **drawing**
- **other**
- **literature**

**Span**

31.4 m

**Life time**

2000 years
B.3.b. Calculations Keshwa-Chaka

To calculate the embodied carbon of the 30 meter long Keshwa-chaka, a description of the construction components is necessary.

The strands of grass used to braid are 45 centimeters (18 inch) long. Over 15240 meters (50000 feet) of grass cord are produced every year. The grass comes from the local mountainside and is manufactured by twisting it by hand. The twenty-four cords are one centimeter (3/8 inch) thick and almost 60 meters (200 feet) long. These cords are twisted into ropes with a diameter of five centimeters (two inches). Next, these ropes are themselves braided in six 45 meters long cables. These are the main structural elements of the grass bridge itself. This first part takes one day and the help of all villagers to accomplish (Ochsendorf, 1996).

The second day of the festival, only adult male villagers work on the cutting of the old bridge and the installation of the cables by minimizing the sag in the middle and wrapping and tying them around the stone abutments. The stone abutments are masonry of 9070 kilogram (20000 pounds).

The last day, the Chaka-Camayoc or bridge-keeper ties the floor cables together and adds the vertical cords between the floor and the handrails. He adds sticks and matted reeds to create a deck on the floor (Ochsendorf, 1996).

The weight of one cable and decking is 907 kg (4100 pounds – 14*150 pounds = 2000 pounds). The total weight of the bridge is 8000 pounds, which is 3630 kg. The stone abutments are 9070 kg (Ochsendorf, 1996). The grass used for the Keshwa-chaka is cut of the local mountainsides and is typically the Puna grass found in the Andes. The ECC is similar to that of straw, 0.01 kgCO2/kg (Hammond and Jones, 2010).
### B.4. Analysis of tall buildings

#### Table B.8: Data on stadia, five last stadia

<table>
<thead>
<tr>
<th>Location</th>
<th>Mary Axe</th>
<th>United T.</th>
<th>The Shard</th>
<th>Al Hamra</th>
<th>Willis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>London</td>
<td>Kuwait</td>
<td>London</td>
<td>Kuwait</td>
<td>Chicago</td>
</tr>
<tr>
<td>Date</td>
<td>2004</td>
<td>2011</td>
<td>2012</td>
<td>2011</td>
<td>1974</td>
</tr>
<tr>
<td>Structural Engineer</td>
<td>Amp</td>
<td>WSP</td>
<td>WSP</td>
<td>SOM</td>
<td>SOM</td>
</tr>
<tr>
<td>Structural System</td>
<td>Steel Diagrid</td>
<td>Reinforced Concrete</td>
<td>Hybrid Reinforced Concrete</td>
<td>Reinforced Concrete</td>
<td>Steel</td>
</tr>
<tr>
<td>Floor area m²</td>
<td>74,300</td>
<td>98,000</td>
<td>126,712</td>
<td>195,000</td>
<td>416,000</td>
</tr>
<tr>
<td>Height m</td>
<td>180</td>
<td>240</td>
<td>306</td>
<td>413</td>
<td>443</td>
</tr>
<tr>
<td>Number of floors</td>
<td>41</td>
<td>59</td>
<td>87</td>
<td>80</td>
<td>111</td>
</tr>
<tr>
<td>Total steel kg</td>
<td>8,358,000</td>
<td>752,781</td>
<td>12,671,200</td>
<td>50,000</td>
<td>76,000</td>
</tr>
<tr>
<td>Total rebar kg</td>
<td>187,035</td>
<td>2,936,146</td>
<td>9,800,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total concrete kg</td>
<td>9,351,736</td>
<td>146,807,304</td>
<td>77,040,896</td>
<td>490,000,000</td>
<td>132,115,200</td>
</tr>
<tr>
<td>Steel per area kg/m²</td>
<td>112</td>
<td>8</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rebar per area kg/m²</td>
<td>3</td>
<td>30</td>
<td>50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Concrete per area kg/m²</td>
<td>126</td>
<td>1,498</td>
<td>608</td>
<td>2,513</td>
<td>318</td>
</tr>
<tr>
<td>ECC steel kgCO₂/kg</td>
<td>0.89</td>
<td>0.71</td>
<td>0.89</td>
<td>0.71</td>
<td>0.89</td>
</tr>
<tr>
<td>ECC rebar kgCO₂/kg</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>ECC concrete kgCO₂/kg</td>
<td>0.16</td>
<td>0.15</td>
<td>0.16</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>EC steel/area kg/m²</td>
<td>100</td>
<td>5</td>
<td>89</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EC rebar/area kg/m²</td>
<td>4</td>
<td>51</td>
<td>0</td>
<td>85</td>
<td>0</td>
</tr>
<tr>
<td>EC concrete/area kg/m²</td>
<td>20</td>
<td>225</td>
<td>97</td>
<td>377</td>
<td>51</td>
</tr>
</tbody>
</table>

### Table B.9: Data on stadia, five last stadia

<table>
<thead>
<tr>
<th>Location</th>
<th>WFC</th>
<th>Taipei 101</th>
<th>1WTC</th>
<th>Shanghai</th>
<th>Burj Khalifa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Shanghai</td>
<td>TaiPei City</td>
<td>New York</td>
<td>Dubai</td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>2008</td>
<td>2004</td>
<td>2014</td>
<td>2014</td>
<td>2010</td>
</tr>
<tr>
<td>Structural Engineer</td>
<td>Leslie E. Robertson Associates</td>
<td>Thronton T.; Evergreen Engineering</td>
<td>WSP</td>
<td>Thornton T.</td>
<td>SOM</td>
</tr>
<tr>
<td>Structural System</td>
<td>Trusses &amp; columns</td>
<td>Composite</td>
<td>Hybrid</td>
<td>Concrete</td>
<td>Butressed Core</td>
</tr>
<tr>
<td>Floor area m²</td>
<td>381,600</td>
<td>193,400</td>
<td>325,279</td>
<td>521,000</td>
<td>334,000</td>
</tr>
<tr>
<td>Height m</td>
<td>492</td>
<td>508</td>
<td>546</td>
<td>632</td>
<td>828</td>
</tr>
<tr>
<td>Number of floors</td>
<td>101</td>
<td>106</td>
<td>82</td>
<td>128</td>
<td>162</td>
</tr>
<tr>
<td>Total steel kg</td>
<td>13,861,826</td>
<td>48,000,000</td>
<td>28,390,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total rebar kg</td>
<td>4,748,813</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total concrete kg</td>
<td>237,440,637</td>
<td>489,600,000</td>
<td>381,600,000</td>
<td>739,820,000</td>
<td>574,480,000</td>
</tr>
<tr>
<td>Steel per area kg/m²</td>
<td>36</td>
<td>148</td>
<td></td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Rebar per area kg/m²</td>
<td>12</td>
<td></td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Concrete per area kg/m²</td>
<td>622</td>
<td>2,532</td>
<td>1,173</td>
<td>1,420</td>
<td>1,720</td>
</tr>
<tr>
<td>ECC steel kgCO₂/kg</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.71</td>
</tr>
<tr>
<td>ECC rebar kgCO₂/kg</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>ECC concrete kgCO₂/kg</td>
<td>0.17</td>
<td>0.17</td>
<td>0.13</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>EC steel/area kgCO₂/m²</td>
<td>32</td>
<td>0</td>
<td>130</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>EC rebar/area kgCO₂/m²</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EC concrete/area kgCO₂/m²</td>
<td>106</td>
<td>430</td>
<td>153</td>
<td>241</td>
<td>258</td>
</tr>
</tbody>
</table>