Low Carbon Pathways for Structural Design:
Embodied Life Cycle Impacts of Building Structures

by

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ABSTRACT

Whole life cycle emissions of buildings include not only *operational* carbon due to their use phase, but also *embodied* carbon due to the rest of their life cycle: material extraction, transport to the site, construction, and demolition. With ongoing population growth and increasing urbanization, decreasing immediate and irreversible embodied carbon emissions is imperative. With feedback from a wide range of stakeholders – architects, structural engineers, policy makers, rating-scheme developers, this research presents an integrated assessment approach to compare embodied life cycle impacts of building structures.

Existing literature indicates that there is an urgent need for benchmarking the embodied carbon of building structures. To remediate this, a rigorous and transparent methodology is presented on multiple scales. On the material scale, a comparative analysis defines reliable Embodied Carbon Coefficients (ECC, expressed in $\mathrm{kg_{CO2e}/kg}$) for the structural materials concrete, steel, and timber. On the structural scale, data analysis evaluates the Structural Material Quantities (SMQ, expressed in $\mathrm{kg/m^2}$) and the embodied carbon for existing building structures (expressed in $\mathrm{kg_{CO2e}/m^2}$). An interactive database of building projects is created in close collaboration with leading structural design firms worldwide. Results show that typical buildings range between 200 and 550 $\mathrm{kg_{CO2e}/m^2}$ on average, but these results can vary widely dependent on structural systems, height, size, etc. On the urban scale, an urban modeling method to simulate the embodied carbon of neighborhoods is proposed and applied to a Middle Eastern case study.

A series of extreme low carbon case studies are analyzed. Results demonstrate that a novel design approach can lead to buildings with an embodied carbon as low as 30 $\mathrm{kg_{CO2e}/m^2}$, which is an order of magnitude lower than conventional building structures today. Two pathways are implemented to lower the embodied carbon of structures: choosing low carbon materials (low ECC) and optimizing the structural efficiency of buildings (low SMQ). This research recommends new pathways for low carbon structural design, crucial for lowering carbon emissions in the built environment.

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NOMENCLATURE

AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
BEM	Building Energy Models
BNB	Assessment System for Sustainable Building (Bewertungssystem Nachhaltiges Bauen)
BREEAM	Building Research Establishment Environmental Assessment Method
BoQ	Bill of Quantities
CALGreen	California Green Building Standards Code
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CBECS	Commercial Buildings Energy Consumption Survey
CLF	Carbon Leadership Forum
CO_2e	Carbon dioxide equivalent
DEA	Data Envelopment Analysis
deQo	database of embodied Quantity outputs
DGBC	Dutch Green Building Council
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen / German Sustainable Build. Council
ECC	Embodied Carbon Coefficient
EEC	Embodied Energy Coefficient
EIA	Energy Information Administration
EPD	Environmental Product Declaration
EoLEC	End-of-life Embodied Carbon
EUI	Energy use intensity
GHG	Greenhouse gases
GIA	Gross Internal Area
GWP	Global Warming Potential
GWW	Assessment Method Environm. Performance Construction & Civil Eng. Works
GIS	Geographic Information Systems
GSAS	Global Sustainability Assessment System
HFA	Heated Floor Area
HQE	Haute Qualité Environnementale
HVAC	heating, ventilation and air conditioning
ICE	Inventory of Carbon and Energy
IE4B	Impact Estimator for Buildings (Athena)
IEA-EBC	International Energy Agency's Energy in Buildings and Communities Program
IEC	Initial Embodied Carbon
IgCC	International Green Construction Code
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost Analysis
LCEC	Life Cycle Embodied Carbon
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
MMG	Milieugerlateerde materiaalprestatie van gebouwelementen
MQ	Material Quantities
MR	Materials and Reources (LEED group)
MRPI-MPG	Milieurelevante Productinformatie MilieuPrestatie Gebouwen
NIA	Net Internal Area
NIST	National Institute of Standards and Technology

NMD	Nationale Milieudatabase
PCR	Product Category Rule
PEF	Product Environmental Footprint
PFA	Pulverized Fuel Ash
PV	photovoltaic
R&D	Research and development
REC	Recurrent Embodied Carbon
REPA	Resource and Environmental Profile Analysis
SBK	Stichting Bouwkwaliteit
SEI	Structural Engineering Institute
SETAC	Society of Environmental Toxicology and Chemistry
SI	International System of Units
SMQ	Structural Material Quantities
UBEM	Urban Building Energy Model
UMI	Urban Modeling Interface
UNEP	United Nations Environmental Programme
USGBC	United States Green Building Council
WBCSD	World Business Council for Sustainable Development
WBLCA	Whole Building LCA
WLC	Whole Life Carbon = Embodied + Operational Carbon

PART I • INTRODUCTION

This dissertation proposes an innovative way to measure embodied carbon using a standardized, uniform, and agreed-upon methodology that, until now, has not been available. Architects and structural engineers have needed a consensus on the benchmarks for the carbon emissions of structures and a quantifiable understanding of the pathways that will actually lower the embodied life cycle impacts of building structures. This work presents a consistent benchmarking method as well as two quantifiable pathways for low carbon structural design. The embodied life cycle impacts of building structures are standardized and normalized to encourage the structural designer to be engaged in the discussion about sustainability in the built environment.

Part I is comprised of the introduction and literature review. The motivation and problem statement of this doctoral research is followed by the role played by structural engineers, who both cause and solve environmental challenges. Next, the scope is discussed in terms of life cycle stages and the methodology of assessing embodied carbon is presented. Further, the literature is reviewed on three scales: material, structural, and urban. Published data, industry databases, and software tools available globally are reviewed. This includes a framework developed for an interactive database of structural material quantities and embodied carbon emissions of building structures.

1. Introduction

1.1. Motivation

The latest Intergovernmental Panel on Climate Change (IPCC, 2014) reports that substantial carbon reductions need to occur now to avoid severe climate catastrophes. In light of the urgent need to *reduce material quantities and embodied carbon* in the construction sector to avoid these extreme climate disruptions, innovative structural design needs to play a critical role in improving material efficiency and life cycle design in the built environment.

By 2040, three quarters of the world population will be living in cities, compared to one half today. By 2030, three billion people will need new homes (UN Habitat, 2016). The future challenge for structural engineers, architects, and urbanists is to design buildings that can respond to these global housing needs while reducing greenhouse gas (GHG) emissions. Yet this is no easy task. Recent innovations are beginning to help lower the operational carbon due to the use phase of buildings: heating, cooling, ventilation, lighting, and equipment. However, a lack of knowledge hinders the reduction of embodied carbon due to the rest of their lifecycle: material extraction, transport to sites, construction, maintenance, and demolition. Carbon reduction is needed now. To do so, it is critical to reduce the embodied carbon of buildings. Indeed, while the magnitude of operational carbon can be reduced with energy efficiency measures over time, that of embodied carbon cannot be reduced in the same manner – embodied carbon emissions occur in the immediate present and the effects are irreversible (Jones, 2015).

In fact, embodied carbon has often been underestimated (Weight, 2011). This dissertation will demonstrate that buildings often use carbon-intensive materials in a wasteful way, even for projects only used at full capacity for a single event, such as World Cups and Olympic Games. Right now, designers have no means of reliably knowing the carbon footprint of buildings. Although rating schemes such as Leadership in Energy and Environmental Design (LEED; USGBC, 2013) and the Building Research Establishment Environmental Assessment Method (BREEAM, 2015) have begun including embodied carbon in their credit system, baselines for benchmarking are still lacking and urgently needed (Yang, 2014). While they exist for the operational carbon, there are no reliable and consistent benchmarks yet for embodied carbon (Dixit et al., 2012). Leading firms are attempting to establish in-house benchmarks, but there is no standardization from one company to another due to inconsistencies in methodology, boundary conditions, life cycle stages, and other variables. This dissertation fills this gap by establishing uniform benchmarks, giving engineers and architects the quantitative guidelines they need to be able to design buildings differently.

This research focuses on the structural component of buildings in particular, which comprises the majority of their material weight (Webster et al., 2012; Kaethner and Burridge, 2012). Considering the complexity of Whole Building Life Cycle Assessment (WBLCA), this approach presents a clear quantitative method that structural engineers can use to estimate the embodied carbon of building structures. With this newly developed method, structural engineers can join architects in playing a crucial role in sustainability.

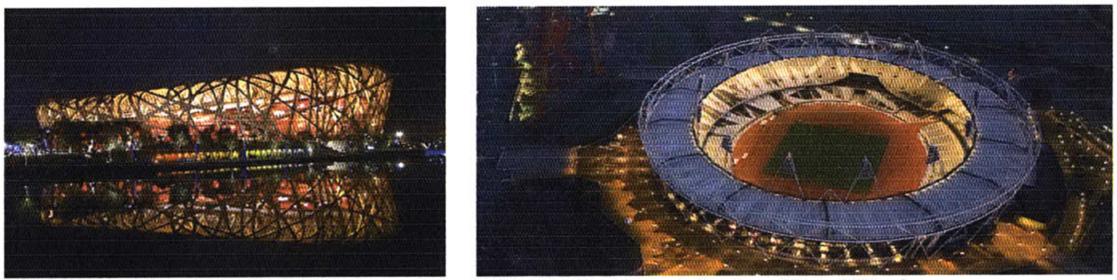
Next to responding to the need for a uniform method and data, this dissertation also introduces pathways for extreme material efficiency and low carbon material choices. At the boundary of architecture and structure, this doctoral research looks at environmental design from materials to cities. Integrating architecture, structural and environmental engineering remains a vast challenge for building designers. To take on this challenge, this research is at the intersection of three main areas: LCA, structural design, and urban building modeling. To move forward, this dissertation presents *innovative low carbon pathways for structural design.*

1.2. A new role for structural engineers in the design process

1.2.1. Early stage low carbon design

To meet the targets set by the Paris Climate Agreement (UNFCCC, 2015) to keep global temperatures from rising above 2°C causing irreversible climate change, the building sector is aiming to be carbon free by 2050 (IPCC, 2014). Initiatives such as the Architecture 2030 Challenge and the American Institute of Architects' 2030 Commitment pledge to make all new buildings, developments, and major renovations carbon-neutral by 2030 (Architecture 2030, 2017; AIA 2030, 2017), looking mainly at how architects can lower operational energy in buildings. Too often, structural engineers are only involved at later stages of the design of a building, when their decisions and calculations can no longer significantly lower the embodied carbon of structures (Ochsendorf, 2012). The choices of material, structural system, shape, window-to-wall ratio, etc. are already made at that point, and strategies for low carbon structural design are limited to minimizing the impacts of a potentially poor design.

Because carbon reduction is needed now, a global, uniform embodied carbon assessment method is needed for both architects and structural engineers. The results of the database described in this dissertation showed that the 2008 Beijing Olympic stadium, also known as the Bird's Nest, used a huge amount of steel, resulting in incredibly high emissions (Figure 1.1). Four years later, the London Olympic Stadium was designed intentionally integrating sustainable thinking, starting at the concept scheme stage. For example, they used low carbon concrete and built part of the stadium to be demountable after the Olympic Games. This strategy resulted in embodied carbon emissions ten times lower than those of the Bird's Nest (De Wolf et al., 2014b). In other words, roughly ten London stadiums could have been built for the same carbon emitted by one Beijing stadium.



(a) Beijing Olympic Stadium, China. Image from Arup (2016)

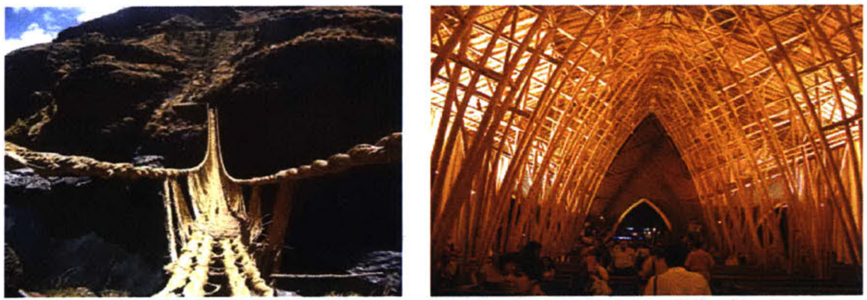
(b) London Olympic Stadium, United Kingdom. Image from Seele (2017)

Figure 1.1: Olympic stadiums illustrating the environmental impact of two design strategies

This dissertation encourages designers to incorporate these life cycle impacts right at the beginning of the design process. The structural inefficiency of contemporary architecture wastes material and consequently money, leading to GHG emissions that could have been avoided.

1.2.2. *Material choice and life span*

A few kilometers from Machu Picchu in Peru, a construction tradition for a grass bridge has persisted since Inca times 600 years ago (Figure 1.2.a; Wilford, 2007). Every year, the four villages on both sides of the water come together for a three-day festival to cut and braid the grass from the local hills and replace the old bridge. The new bridge's materials are naturally and locally grown and the construction is by hand, leading to almost no pollution. Another example of renewable materials used in structures is Simon Velez's bamboo cathedral in Colombia (Figure 1.2.b): bamboo grows one foot a day in some regions, which makes it a renewable construction material (Simon Velez Foundation, 2017). These design examples illustrate that renewable materials can be a solution for flexible needs.



(a) Inca bridge in Huinchiri, Peru. Image from Atlas Obscura (2017)

(b) Bamboo cathedral in Colombia. Image from the Simon Velez Foundation (2017)

Figure 1.2: Design examples illustrating renewable versus durable materials

Some buildings have a short life span, which results in a high percentage of embodied carbon in the total environmental impact of a building. The Pantheon in Rome (Figure 1.3.a) and the Kingdome in Seattle (Figure 1.3.b) were both the largest domes in the world at the moment of their construction. The carbon emitted for both of these buildings is only justified if they last. Evidently, the Pantheon has met this criterion by lasting 2000 years, but the Kingdome, which was built in the seventies, was demolished after only 26 years of use. The environmental impact of buildings is often solely defined by their "operational carbon," but in the case of the Kingdome in Seattle, the embodied carbon is a big part of the whole impact of the building.

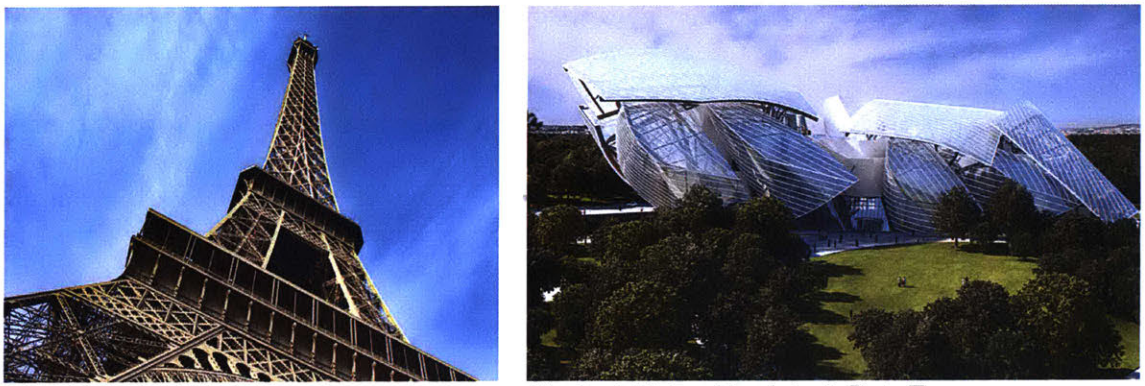
(a) Pantheon in Rome, Italy. Image from Ancient (2017)

(b) Kingdome in Seattle, United States. Image from US Navy (2017)

Figure 1.3: Design examples illustrating long versus short lifespans

1.2.3. *Structural elegance of reducing the environmental impact*

The Eiffel tower in Paris shows it is possible to combine both efficient structural design and iconic architecture. The Louis Vuitton Foundation compares its building to the Eiffel Tower, boasting about using twice as much steel (Figure 1.4; Fondation Louis Vuitton, 2017), even though material minimization should be prioritized to reduce environmental impact.



(a) Eiffel Tower in Paris, France. Image from Live Science (2017)

(b) Louis Vuitton Foundation in Paris, France. Image from FLV (2017)

Figure 1.4: Material efficiency as a strategy to lower the environmental impact of structures

Structural designers can learn from nature, history, and other cultures to design with limited resources. This dissertation helps designers by presenting low carbon pathways and examples of low carbon yet elegant structures. While leaving all design options open to architects and engineers to create architecture that can lift the human spirit, this dissertation aims to contribute to a brand new, innovative assessment approach as to how we design and build our structures.

1.3. Key Questions Addressed

As structural engineers and designers do not know what the embodied carbon is of their structures, this dissertation determines the benchmarks of embodied carbon emissions in building structures. Therefore, it answers the following first fundamental question:

"How are benchmarks established to determine the embodied carbon of structures?"

To answer this question, this research analyzes the embodied carbon of structures on multiple scales: the *material* scale, the *structural* scale, and the *urban* scale. The GHG emissions are expressed in "carbon dioxide equivalent" or CO_2e.

LCA has been around since the 70s (Guinée, 2002) but it did not reach its intended goals in the building sector as it is time consuming, costly, and requires an LCA expert. This dissertation offers a simple and transparent contribution for which only two key variables are required: the Embodied Carbon Coefficients (ECC, expressed in kg_{CO2e}/kg) of the structural materials and the Structural Material Quantities (SMQ, expressed in kg/m^2). If we exclude operational emissions, the Global Warming Potential of a structure (GWP, expressed in

kg_{CO2e}/m^2 when normalized by floor area) can be calculated by multiplying these two key variables, as illustrated in Equation 1.1.

$$GWP = \sum_{i=1}^{N} [SMQ_i \times ECC_i] \qquad \text{Equation 1.1}$$

where:

i a particular component or material in the building structure i = 1, 2, 3, etc., N
GWP Global Warming Potential (kg_{CO2e}/m^2)
SMQ_i Structural Material Quantities (kg_m/m^2)
ECC_i Embodied Carbon Coefficients (kg_{CO2e}/kg)

This approach differs from previous benchmarking efforts (WRAP, 2017; Simonen et al., 2017a), that only collected end results on embodied carbon in buildings. There is a high degree of uncertainty around the ECCs, which change over time and location, which is why this research presents a database that collects SMQs to create benchmarks that the industry can get behind. The approach is straightforward and reproducible with an emphasis on transparency, by reporting the material quantities in a standardized and normalized way. Once the field will have matured towards more accurate ECCs, the GWP results can easily be updated thanks to the collection of SMQ. Collecting these quantities from industry gives a greater degree of confidence in the embodied carbon results.

The proposed metric, GWP, expressed in kg_{CO2e}/m^2, is to the field of embodied carbon what the Energy Use Intensity (EUI, expressed in kWh/m^2 per year) is to the field of operational energy.

To establish benchmarks for the embodied carbon of structures, three questions are asked on each of the three scales addressed in this research:

- *Material scale*: How can we define reliable ECCs?
  Available ECCs lack transparency and are not always using the most recent data on material production emissions. There is a need for uniform coefficients showing comparable emissions to help designers in their material choices. In order to calculate the environmental impact of building structures and infrastructure, it is necessary to know how much carbon emissions are related to the production of the structural materials themselves. Currently, no transparent and consistent ECCs exist across different structural materials produced in different regions. This dissertation fills this gap on the material scale.

- *Structural scale*: What are the SMQs and embodied carbon of building structures and infrastructures?
  After estimating the ECCs on the material scale, the embodied carbon of structures can be estimated based on the SMQs of projects. Structural designers do not intuitively know what the order of magnitude is for the embodied carbon of their structures. Industry lacks the appropriate benchmarks to know how much materials are needed for various structures. This is why this dissertation develops ranges for the embodied carbon of building structures as a baseline for comparison. Rating schemes such as LEED can use these newly developed benchmarks. This dissertation contains data collection on the structural scale for hundreds of buildings worldwide to answer this question.

- *Urban scale*: Can we simulate the GWP embodied in cities?
  Finally, this is scaled to the urban level, by testing how we can simulate the embodied carbon of entire neighborhoods and make recommendations for lowering their emissions. Current urban studies use urban modeling mainly for evaluating operational energy consumption of cities. However, city governments have a considerable potential to influence the design of new neighborhoods towards more low carbon design. This research also helps assess tradeoffs between embodied and operational carbon in the built environment.

After finding the benchmarks for embodied carbon of structures, this dissertation uses the results to the questions posed on the three scales to examine the following second fundamental question:

"How low can we go?"

The aim of this dissertation is to make recommendations for low carbon pathways to structural designers, by developing, establishing, and validating a transparent, quantifiable, and consistent assessment approach to estimate the embodied life cycle impacts of building structures. The objectives are to identify literature gaps, validate a low carbon assessment method, and develop a low carbon design strategy. This will lead to recommendations on new policies and design guidelines.

The target audience is two-fold: benchmarks will be provided for rating scheme developers and policy makers, and the design guidelines will influence early design decisions of architects and engineers. To conclude, this research makes two major contributions: (1) it recommends new benchmarks and regulations and (2) it develops low carbon structural design strategies. This dissertation aims at lowering the environmental impact of architectural and structural practice in the building sector.

1.4. Definitions of scope

1.4.1. Carbon and Global Warming Potential (GWP)

"Carbon" in this dissertation is used as short-hand for "carbon dioxide (CO_2) equivalent". All GHGs are converted to their equivalent in carbon dioxide, noted as "CO_2e" (OECD, 2017). Other GHGs include CH_4, N_2O, SF_6, PFC and HFC and are converted to CO_2 with factors given by the IPCC (2014). This allows LCA practitioners to have a simple metric that conveys all the GHG emissions in one number.

The GWP metric is measured in kg of CO_2e. Commonly, the ECC (expressed in kg_{CO2e}/kg) is called its GWP. However, the term ECC will be used for materials in this dissertation to avoid confusion with the GWP of a building or building structure. In this dissertation, the term GWP refers to the Embodied Carbon (EC, expressed in kg_{CO2e}/m^2) of buildings or building structures to normalize the values per square meter of gross floor area. The GWP does not include the GHG emissions due to operational energy on top of embodied impacts as can be found in some studies. The Whole Life Carbon (WLC, also expressed in

kg_{CO2e}/m^2) includes both embodied and operational CO_2e. These definitions are detailed in Section 1.4.5. As shown in Table 1.1, the term "GWP" is used for defining different metrics across literature, but will only be used for designating the embodied carbon of a building or building structure, excluding operational carbon, in this dissertation.

Dissertation's terminology	Measures	Units	Other terminology
ECC	The CO_2e of a material	kg_{CO2e}/kg	GWP of material
GWP	The embodied CO_2e of a building or building structure	kg_{CO2e}/m^2	GWP, EC
WLC	The embodied and operational CO_2e of a building over its whole life cycle	kg_{CO2e}/m^2	GWP, WLC

Table 1.1: Terminology

1.4.2. Impact factors of Life Cycle Assessment (LCA)

An important tool for calculating the embodied carbon of building structures is LCA. It looks at the complete life cycle of buildings and products, from the material extraction to end-of-life. LCA is used to evaluate different environmental impacts, such as the resource use, the global warming, acidification, eutrophication, the depletion of the ozone layer, smog, etc. (Table 1.2). This research focuses on the global warming measured in kg_{CO2e} as discussed in Section 1.4.1. This is one of the impact factors included in the LCA methodology, which aims to evaluate and mitigate the building sector's role in climate change.

Impact factors LCA
Abiotic depletion
Acidification
Eutrophication
Global Warming Potential (GWP)
Ozone Layer Depletion (OLD)
Human toxicity
Fresh water aquatic ecotoxicity
Marine aquatic ecotoxicity
Terrestrial ecotoxitcity
Photochemical oxidation

Table 1.2: Impact factors of LCA as defined in ISO (2017)

1.4.3. Embodied energy and carbon

This dissertation focuses on embodied carbon, rather than embodied energy. For producing the same structure in two different contexts or materials, the same embodied energy does not translate to the same embodied carbon. First, the embodied energy can be converted to embodied carbon depending on the energy mix (kg_{CO2e}/kWh) of the region or the fuel used. Second, carbon can be emitted due to chemical processing, such as that involved in cement production. Third, carbon can also be sequestered, as is the case with wood during its growth phase. The reason that this research focuses on carbon rather than energy is to measure the contribution of building structures to climate change. It can also be helpful to compare with other metrics that are already expressed in terms of carbon emissions (Kaethner and Burridge, 2012).

1.4.4. Declared unit

The declared unit is used to normalize the CO_2e of building structures, in order to compare like with like. The declared unit expresses the reference to which in- and outputs are associated. In this dissertation, the results are normalized by floor area (m^2) of the building unless noted otherwise. The embodied carbon of building structures is then measured in kg_{CO2e}/m^2. Different structural systems have different performances, so that the same weight or volume of structural materials can have different environmental impacts. To compare two different systems, the same floor area is used as a measure of the studied buildings. Examples of functional units measuring the function of a building can be the number of seats for stadiums or the number of occupants for residential buildings. Using the floor area as a declared unit allows for comparison with other metrics, such as energy use intensity (EUI, commonly measured in kWh/m^2-yr).

1.4.5. Life cycle stages

While there is little consistency in the data and methodologies used in practice, considerable work has been done over the last few years to develop norms, standards and guides. The International Organization for Standardization (ISO, 2017) includes life cycle thinking in ISO 14001, describes LCA and the life cycle stages of buildings in ISO 14040 and ISO 14044, defines calculation methods for the carbon footprint of products in ISO 14067, discusses the sustainability in buildings and civil engineering works in ISO 21929, and explains Environmental Product Declarations (EPD) for building construction in ISO 21930. The four parts of LCA are the following: define goal and scope, Life Cycle Inventory (LCI), impact assessment, and interpretation. An EPD document is verified and registered to offer transparent and comparable LCA information about products. Meanwhile the European Standards Technical Committee CEN TC350 (Sustainability of Construction Works) has defined the assessment of buildings in EN 15643, the calculation method for the assessment of the environmental performance of buildings in EN 15978, and the Product Category Rules (PCR) for EPDs of construction products in EN 15804 (EN, 2017). The TC350 standards use LCA to define the "cradle to grave" impact of buildings (Moncaster and Symons, 2013) and civil engineering works (Vuorinen, 2012), as illustrated in Figure 1.5.

The product stage includes raw material supply (A1), transport of materials from extraction to manufacturing site (A2), and manufacturing itself (A3). The construction process stage is divided in the transport from gate to site (A4) and the construction-installation process (A5). The use stage includes the impacts arising from anticipated conditions of use of components (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5). The operational energy use (B6) and operational water use (B7) are excluded from the embodied carbon assessment, but are part of the whole life carbon calculations. The end-of-life stage comprises deconstruction and demolition (C1), transport to landfill, incineration or recycling facilities (C2), waste processing (C3) and disposal (C4). Beyond these life cycle stages, potential benefits and loads of reuse, recovery, or recycling (D) can be taken into account.

The stages A1-A3 are often called "cradle-to-gate," stages A1-A4 "cradle-to-site," stages A1-C4 "cradle-to-grave," and stages A1-D "cradle-to-cradle". The Structural Engineering Institute (SEI) Sustainability Committee and the American Society of Civil Engineers (ASCE) have prepared a standard practice for comparing whole building LCA (WBLCA) for use with building codes and rating systems (SEI/ASCE, 2016).

PRODUCT stage			CONSTRUCTION PROCESS stage		USE stage					END OF LIFE stage				BEYOND
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction Demolition	Transport	Waste Processing	Disposal	Ruse, Recovery, Recycling Potential
					B6									
					Operational Energy Use									
					B7									
					Operational Water Use									

Figure 1.5: Life cycles defined by EN 15978, adapted from (Moncaster and Symons, 2013)

According to EN 15978, the data should be as recent as possible and should be checked with the rules of EN 15804. The data should also be geographically coherent with the location of the production, which is rarely the case. Data also need to correspond to the system boundaries set for the assessment.

Depending on the life cycle stages included, different definitions of embodied carbon are possible: the Initial Embodied Carbon (IEC) only includes stages A1-A3, the Transportation Embodied Carbon (TEC) only includes stage A4, the Construction Embodied Carbon (CEC) only includes stage A5, the Recurrent Embodied Carbon (REC) only includes stages B1-B5, and the End-of-life Embodied Carbon (EoLEC) only includes stages C1-C4. The construction process stage (A4-A5) is often absent in calculations, as it is assumed they are negligible compared to the other life cycle stages. The operational stage (B6-B7) is excluded from the embodied carbon of structures. The total Life Cycle Embodied Carbon (LCEC) is the summation of the embodied carbon due to the production (IEC), the transportation (TEC) and construction (CEC), the carbon emitted during use phase (REC) and the end-of-life carbon (EoLEC).

Finally, Whole Life Carbon (WLC) includes both life cycle embodied carbon and the operational carbon. With the exception of aspects such as thermal mass, the structure is mainly playing a role in the embodied carbon emissions rather than the operational carbon emissions. As this research aims to include structural engineers in the conversation about sustainability, the focus will be on the embodied carbon of building structures. Operational carbon emissions are only calculated in order to assess tradeoffs and full life cycle evaluations of buildings and building structures.

As discussed in Section 1.1, this work on the structural part of buildings allows us to focus on a well-defined quantity and to include structure in the discussion about sustainability. Also, the aim is to reduce carbon emissions in the next decades rather than focusing on the end-of-life of a building. As the structural layer of a building usually requires little maintenance or replacement during the building's lifetime and the highest weight of materials and production emissions lies in the structure, the IEC is often used to simplify the embodied calculations for the structure. The TEC and CEC can be addressed on a case by case basis.

1.5. Methodology

This dissertation is divided in three parts: Part I includes the problem statement and literature review, Part II establishes benchmarks for embodied carbon, and Part III defines low carbon pathways. To define the key questions and complement the literature review in Part I, interviews with industry practitioners were conducted (1.5.1). To answer the key questions in Part I, the embodied carbon of building structures was assessed on three different scales: LCA studies and EPDs were used for the assessment of embodied carbon on the material scale (1.5.2), a database was developed to collect data on the material quantities in building structures on the structural scale (1.5.3), and urban modeling was used to evaluate the embodied carbon of a neighborhood on the urban scale (1.5.4). Finally, a comparative analysis was conducted to define design guidelines for low carbon buildings in Part III (1.5.5). More specific methodologies will be further explained throughout the chapters of this dissertation. The calculations for the embodied carbon of buildings can be detailed for each life cycle stage depending on the boundaries of the LCA. The detailed equations are given in more detail in Appendix C.

1.5.1. Interviews with industry practitioners

A pilot study of industry experts within the Implementing Whole Life Carbon in Buildings (IWLCiB, 2016) project at the University of Cambridge was used to define areas of concern and variation within practice. This was followed by six focus groups as part of an Embodied Carbon and Energy Symposium at the University of Cambridge in April 2016.

Table 1.3 illustrates the participants in the pilot study (a) and the focus groups (b), selected based on their expertise in embodied carbon of buildings. The focus group discussions were audio-recorded and summarized in writing. The themes of the focus groups were: embodied carbon calculation; the role of practice; risk and uncertainty; mitigation strategies; embodied carbon during use phase; demolition versus refurbishment. The initial pilot study and focus groups with industry experts were used to develop a preliminary understanding of the issues and to create interview questions.

Profession	*Company Sector*
a) Pilot Study	
Head of Research	Architecture & the Environment
Senior Consultant	Carbon Consultant
Senior Project Consultant	Engineering
Environmental Manager	Developer
b) Focus Groups	
Senior Consultant	Construction
Researcher in Engineering	Engineering
Student in Environmental Design	Environmental Building Design
Architect	Architecture
Engineer	Engineering
Student in Engineering	Engineering
Sustainable design / LCA strategist	Engineering
Structural Engineer & Senior Consultant	Structural Engineering
Researcher in Engineering	Engineering
Monitoring officer and Assessor	NGO
Director	Architecture
Energy Consultant	Energy
Partner	Construction
Sustainability Officer	Construction
Researcher in Engineering	Engineering
Sustainability Consultant	Construction
Researcher in Engineering	Engineering
Partner	Management Consulting
Sustainability Analyst	Commercial Real Estate
Professor	Engineering
Professor	Engineering
Social Entrepreneur	Architecture
Principal Sustainability Consultant	Built Environment Consulting
Researcher in Engineering	Engineering
Researcher in Engineering	Engineering
Director	LCA, Carbon Footprint
Student in Engineering	Engineering
Development Manager	Insurance
Structural Engineer	Structural Engineering
Researcher in Engineering	Engineering
Chartered Structural Engineer	Construction
Engineer	Structural Engineering
Researcher in Engineering	Engineering
Senior Consultant	Carbon Consulting
Lecturer in Engineering	Engineering
Student in Structures	Engineering
Lecturer	Environmental Sciences
Researcher in Engineering	Engineering
Engineer	Engineering
Architect	Architecture
Researcher in Engineering	Engineering
Sustainability Officer	Environmental Building Design
Senior Consultant	Architecture and Engineering
Senior Consultant	Carbon Consulting
Senior Engineer	Engineering
Senior Consultant	Environmental Building Design

Table 1.3: Participants to Pilot Study (a) and Focus Groups at the Embodied Carbon and Energy Symposium (b)

The issues discussed within the focus groups were addressed in greater detail, through a series of semi-structured expert interviews in order to develop a wider understanding of perceptions and barriers towards the implementation of measurement in industry practice.

The interviews were conducted with individuals who had expertise in this area, either industry practitioners in this field, or researchers collaborating closely with industry. Participants were identified through the snowballing technique (Morgan, 2008) using established contacts of the authors, the 2016 Embodied Carbon and Energy Symposium, and the IWLCiB project. Both a general interview guide approach and a standardized semi-structured interview were combined to ensure the same areas of information were collected, analyzed and compared (Knight and Ruddock, 2008).

The 15 core questions gathered data on drivers, barriers, calculation methods, and available tools, and were supplemented with additional questions depending on the interviewee's response. The interviews lasted between 30 and 90 minutes. A list of the interviewees' roles, company's sectors, and countries are given in Table 1.4.

Role	Company Sector	Country	
Head of Research	Architecture & the Environment	Czech Rep. (CZ)	[a]
Senior Consultant	Carbon Consultant	United Kingdom (UK)	[b]
Senior Project Consultant	Engineering	UK & United States (US)	[c]
Environmental Manager	Developer	UK	[d]
Coordinator in climate & materials	Contractor	Norway (NO)	[e]
Sustainable Business Developer	Project Developer & Contractor	Sweden (SE)	[f]
CEO Environmental Consultant	Environmental Consultancy	Australia (AU)	[g]
Associate Professor	Carbon Leadership Forum	US & Canada (CA)	[h]
Engineer Architect Researcher	Institute Technological Research	Belgium (BE)	[i]
Engineering Sustainability Leader	Engineering & Contractor	UK & AU	[j]
Senior Structural Engineer, P.E.	Structures & Enclosure Design	US	[k]
Director of Sustainable Design	Structural, civil & traffic engineering	US, Panama (PA) & India (IN)	[l]

Table 1.4: List of interviewees *(references [a] to [l] are used in the results of the Section 6.1)*

Figure 1.6 shows the roles of the participants in the pilot study, focus groups and interviews within the construction industry. All participants were offered anonymity. The focus groups and interviews were audio-recorded and transcribed.

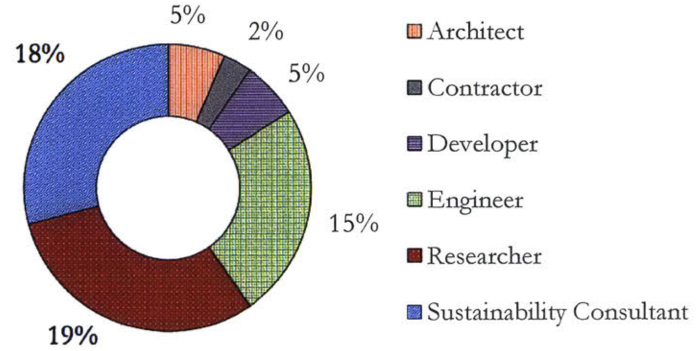


Figure 1.6: The role of the participants of the pilot study, focus groups and interviews in the construction industry

1.5.2. LCA studies on the material scale

The assessment of embodied carbon is studied on multiple scales. On the material scale, LCA of common structural building materials is an essential tool. A detailed global literature review is conducted to identify methods and approaches to calculate ECCs in design practice including common boundaries and datasets. Literature is analyzed to identify inconsistencies in approach. The purpose of this review is to pre-empt inconsistencies and issues with the ECCs currently used by industry. Environmental Product Declarations (EPDs) are evaluated to offer regional verified and registered data about common structural materials.

1.5.3. Database on the structural scale

On the structural scale, a robust, interactive, growing database has been developed to collect data on the SMQ in building projects worldwide (De Wolf and Ochsendorf, 2014). The development of this database includes three primary techniques:

1. Collect data from the published LCA literature in recent decades;
2. Collaborate with a network of worldwide leading engineering and design firms to build a useful database of their projects; and
3. Create an interactive interface where participants can input projects in a growing database including the GWP of thousands of structures worldwide.

As an example, the user can input the SMQ of an office building in London. Then, the participants can opt for the default ECC value offered by the database or enter their own customized value. The result will give the GWP of the project correlated to other similar structures for comparison (Figure 1.7).

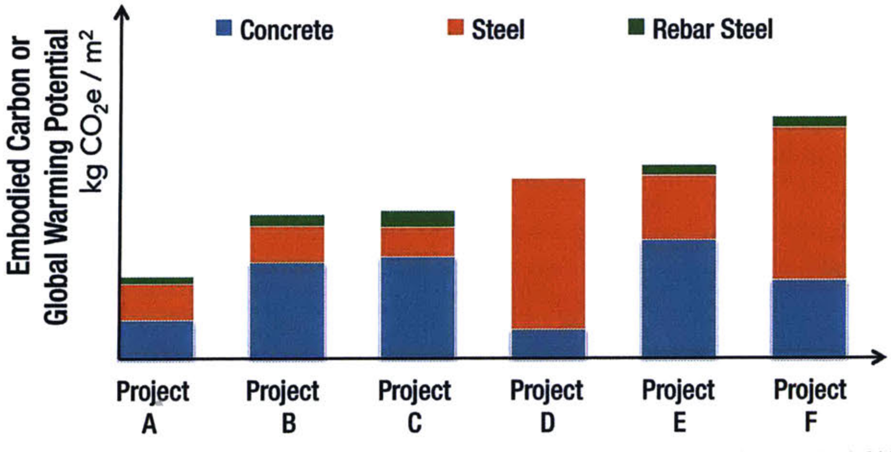


Figure 1.7: Comparing embodied carbon of entered projects (De Wolf and Ochsendorf, 2014)

This database is developed in close collaboration with industry. Interviews have been conducted to identify the in- and output fields needed in the database and interactive web-interface to maximize the collection of useful results from industry practitioners. A committee of structural engineers and experts in embodied carbon of structures has been consulted for regular feedback during the development, coding, and pilot phase of the database.

1.5.4. Urban Modeling Interface (UMI) on the urban scale

On the urban scale, the embodied carbon results on the material and structural scale were applied to a case study of a neighborhood. A survey has been conducted to measure the material quantities and specifications in a residential neighborhood in Kuwait. An Urban Building Energy Model (UBEM) was used to perform simulations of embodied and operational carbon on the urban scale. To combine data on building information including parcel and building footprints, building height, age and use from multiple sources into a single data model, Geographic Information Systems (GIS) is used.

The case study in Kuwait has been simulated more specifically with the UBEM tool called Urban Modeling Interface (UMI). The urban simulation tool was developed at MIT (UMI, 2016; Reinhart et al., 2013; Reinhart and Cerezo, 2016).

1.5.5. Comparative analysis of low carbon designs

Based on the embodied carbon results on the material, structural, and urban scale, strategies are established. To recommend low carbon design guidelines, different low carbon case studies have been compared. These case studies were selected from the lower bound of the results in the database developed for this dissertation. The low carbon case studies have been studied to formulate strategies to lower the embodied carbon of building structures.

The materials and structural efficiency of low carbon buildings is highlighted. The material quantities and material choices of three vaulted masonry structures are studied in more detail through conversations with the architects and structural designers, a literature review, the analysis of bill of quantities, material extractions from Building Information Modeling (BIM) drawings. Then the three exemplary projects are compared to the average of 600 existing buildings. The studied tile vaulting system is used to illustrate the principles of better design for efficiency and low-carbon material choices.

Finally, the United States Green Building Council (USGBC) database for LEED certified buildings is used to identify broader industry strategies. An extensive literature review, the collection of data on LEED buildings, and follow-up interviews with industry experts shape a list of the potential strategies for lowering carbon emissions in structural design. Rating schemes, industry challenges and commitments, national initiatives and policies, educational approaches, engineer-architect collaboration, research directions, direct feedback design tools, and client involvement are examples of the proposed strategies.

1.6. Organization of dissertation

This research presents benchmarks for the embodied carbon of structures and low carbon pathways for structural design on multiple scales. On the material scale, how can we define reliable ECCs? On the structural scale, how can we collect SMQs in existing buildings? On the urban scale, how can we simulate the embodied carbon of cities? To answer these questions, this dissertation is divided in three parts: *Introduction*, *Benchmarking embodied carbon*, and *Low carbon pathways*.

Part I, *Introduction*, includes the motivation and problem statement (Chapter 1) and a critical literature review on the topic of low carbon structural design (Chapter 2).

- Chapter 2 presents the existing literature and work on the three scales. On the material scale, the database and software that can be used to define ECCs are critically studied. On the structural scale, the building codes, academic research and available industry tools are reviewed to identify inconsistencies in existing embodied carbon benchmarks of structures. Moreover, the framework of the database developed in the Master thesis (De Wolf, 2014) and the further implementation of the database during this doctoral research are clarified. On the urban scale, both urban building energy modeling and material flow analysis (MFA) as a tool for urban metabolism are linked to defining the embodied carbon of the built environment in a neighborhood or city.

Part II, *Benchmarking embodied carbon*, presents assessments on the three scales. Each of the core chapters in Part II answers one of the key questions mentioned above (Chapters 3, 4, 5).

- Chapter 3 analyzes the existing ECCs, in particular for the main structural materials concrete, steel, and timber. For the same materials, the chapter then proposes ranges for ECCs in different regions of the world based on industrial data.
- Chapter 4 illustrates the embodied carbon assessment of structures. First, a database of existing building structures, collected from leading structural engineering firms worldwide, is established. The cradle-to-gate embodied carbon of these structures is calculated with the database and analyzed. A data quality assessment and a statistical analysis will be conducted.
- Chapter 5 applies the findings from the two previous chapters to a case study from a neighborhood in Kuwait. This study shows how embodied carbon can be assessed on a larger scale through an urban simulation platform. Policy recommendations are made for Middle Eastern cities as an example of how the results of this dissertation can be used in practice.

Part III, *Low carbon pathways*, formulates recommendations based on the findings of this dissertation. It offers low carbon pathways for building structures based on the answers to the key questions. Exemplary case studies are discussed (Chapter 6) leading to conclusions and future work (Chapter 7).

- Chapter 6 discusses the findings and recommends low carbon pathways. First, the contribution of structures to the embodied carbon of whole buildings is discussed. Then, the low carbon case studies from the database are used to establish guidelines to lower the embodied carbon of building structures. Finally, big picture strategies to lower the GHG emissions of the construction sector as a whole are discussed.
- Chapter 7 discusses the contributions and conclusions of the work. The chapter makes recommendations for low carbon pathways that structural designers can follow on the three different scales. Finally, the future work includes industry participation, the development of LCA expertise, and holistic design taking operational and financial costs into account through multi-objective optimization.

2. Literature[1]

This chapter reviews the existing literature on embodied carbon on the three scales studied in this dissertation: the material, structural, and urban scale. On the material scale, available ECCs in existing industry data reports, materials databases, LCA software, and academic research publications are reviewed. On the structural scale, available results from building structures databases, whole building LCA software, and published benchmarks are discussed. On the urban scale, MFA and urban modeling are shown as tools for assessing the carbon footprint of the built environment in cities.

The importance of material quantities and embodied carbon in building structures has been recognized a century ago. In the 1920s, Buckminster Fuller askes how much your house weighs (Braham and Hale, 1929) and Freidrich et al. (1922) compared the amount of coal required for heating a building to that for the production of building products. A renewed interest peaked during the oil price crisis in the 1970s (Haseltine, 1975; Bousted and Hancock, 1079). This chapter discusses the recent efforts in benchmarking embodied carbon in literature, in standards, and in industry.

2.1. Embodied Carbon Coefficients (ECC)

Reliable and consistent literature on embodied energy and embodied carbon is often lacking for specific materials (Simonen, 2011; Webster, 2012). Alcorn (1996) has defined the term "Embodied Energy Coefficients" (EEC) of building materials, while Dias and Pooliyadda (2004) have defined "Embodied Carbon Coefficients" (ECC). One of the key data requirements to assess embodied carbon of buildings is this coefficient for all materials and components in the building. As this dissertation focuses on structures, this section discusses the available sources for ECCs of structural materials.

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[1] The literature review presented in this chapter has been published in several papers, including: De Wolf, C. (2014) "Material quantities in building structures and their environmental impact" *Massachusetts Institute of Technology (MIT) Master of Science in Building Tech ology thesis*, supervised by John Ochsendorf, June 2014; De Wolf, C., Iuorio, O., and Ochsendorf, J. (2014a) "Structural Material Quantities and Embodied Carbon Coefficients: Challenges and Opportunities." *Proceedings of the Sustainable Structures Symposium*, Corey Griffin (ed.), Portland State University, Oregon, USA, April 17-18, 309-324; De Wolf, C., Hogroian, J., and Ochsendorf, J. (2014b) "Comparing material quantities and embodied carbon in stadia." *International Association for Shell and Spatial Structures - SLTE 2014*, Brasilia, Brazil, September 15-19; De Wolf, C. and Ochsendorf, J. (2014) "Participating in an Embodied Carbon Database. Connecting structural material quantities with environmental impact." *The Structural Engineer*, February Issue 2, 30-31; De Wolf, C., Bianquis, R., Verbeeck, K., and Ochsendorf, J. (2015) "The environmental impact of bridges, special structures and artworks." *Proceedings of the International Association for Bridge and Structural Engineering (IABSE)*, Geneva, Switzerland, September 23-25; De Wolf, C., Yang, F., Cox, D., Charlson, A., Hattan, A., and Ochsendorf, J. (2016a) "Material quantities and embodied carbon dioxide in structures," *ICE Journal of Engineering Sustainability*, 169(ES4), 150-161, DOI: 10.1680/ensu.15.00033; De Wolf, C., Ramage, M., and Ochsendorf, J. (2016b) "Low Carbon Vaulted Masonry Structures." *Journal of the IASS*, 57(4), December n. 190, 275-284; De Wolf, C., Pomponi, F., and Moncaster, A. (2017a) "Measuring embodied carbon of buildings; a review and critique of current industry practice." *Energy and Buildings*, 140(1) April 2017, 68-80, DOI: 10.1016/j.enbuild.2017.01.075; De Wolf, C., Rodriguez, B.X., and Simonen, K. (2017b) "Counting Carbon – What we know and how we know it about embodied carbon" in: King, B. (ed.) "New Carbon Architecture." *New Society Publishers*, Canada; De Wolf, C., Cerezo, C., Murthadhawi, Z., Hajiah, A., Al Mumin, A., Ochsendorf, J., and Reinhart C. (2017c) "Life cycle impact of a Middle Eastern residential neighbourhood." *Energy* (under review).

2.1.1. *Industry data reports*

Industry is developing better LCA data for construction materials by assessing the environmental impact of all life cycle stages, in particular the GHG emissions related with the production of the materials, or ECCs. The National Ready Mixed Concrete Association (NRMCA, 2015) publishes data for concrete, the World Steel Association (World Steel, 2016) for steel, and the Consortium for Research on Renewable Industrial Materials (CORRIM, 2016) for timber. However, there is a substantial variability in the data. Reports and journal papers have highlighted the urgent need for a standardized database for the environmental impact of building materials in industry (Business, Innovation and Skills, 2010).

In the United Kingdom, the open-source Inventory of Carbon and Energy (ICE) database from the University of Bath summarizes EECs and ECCs for common construction materials as published over time (Hammond and Jones, 2010). The ICE is currently the most frequently used ECC database in industry, due to its comprehensive summary of the best available embodied carbon data. The limitations are shown by the variability of steel data in Figure 2.1.

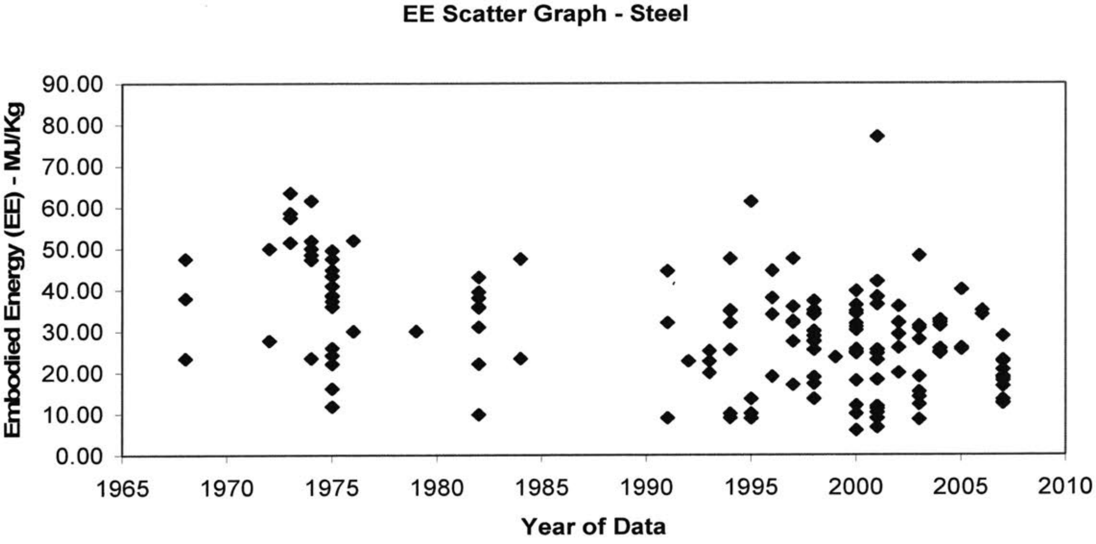

Figure 2.1: Variability of the publicly available data of embodied energy of steel (Hammond and Jones, 2010)

The Hutchins UK Building Blackbook (2011) also reports ECCs of materials. However, there is still a need for updated values per country or region, as both databases are specific for the United Kingdom and have not been updated since 2011. 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 due to different emissions related to transport and manufacturing (Ochsendorf et al., 2011).

In the United States, the Carbon Working Group (Webster et al., 2012) discusses the embodied carbon of main structural materials and the uncertainty of carbon footprints, data quality, and variability. As different sources might not use the same assumptions, the Carbon

Working Group identifies a need for a more reliable and comparable definition of ECC values.

2.1.2. Databases of building materials

The National Renewable Energy Laboratory (NREL) and its partners have also developed a general energy and material flows database for the United States, based on an input-output economic model (US LCI, 2016). Moreover, a database of common products, Quartz, has been created in order to collect and provide data on the environmental impact of common products and materials used in construction (Quartz, 2016). The Canadian Raw Materials Database (CRMD, 2017) is an initiative collecting environmental in- and outputs of Canadian commodity materials based on LCI data.

The Joint Research Centre (JRC) from the European Commission offers the European reference Life Cycle Database (ELCD, 2016) with LCI data from business associations in the European Union. The Netherlands (milieudatabase.nl, 2016), Belgium (BBRI, 2016), France (INIES, 2016) and Germany (oekobaudat.de, 2016) offer open-access national databases of their construction materials. The Netherlands also has a licensed database (IVAM, 2016). In Sweden, ECCs are provided by IVL Swedish Environmental Research Institute (IVL, 2016). EcoInvent (2016) provides thousands of LCI datasets in Switzerland and globally.

In Australia, all the major trade associations of concrete, timber, windows, pipes, etc. also included their data in the open-access Building Product Life Cycle Inventory database (BPLCI, 2016) between 2007 and 2011. In New Zealand, Alcorn (2003) at the Victoria University of Wellington has developed a building materials embodied energy database.

The Japan Environmental Management Association for Industry (JEMAI, 2017) has developed an LCI database. Also, the Embodied Energy and Emissions Intensity Data (3EID, 2017) for Japan uses Input-Output tables with environmental burdens. The Chinese Life Cycle Database (CLCD, 2017) uses process LCA in 600 LCI datasets for various materials. Australia also has its National Life Cycle Inventory Database (AusLCI, 2017).

Many other countries are developing national EPD databases that will help improve the accuracy of embodied carbon calculations on the material and structural scale as long as industry participates. Indeed, EPDs offer registered and verified LCA data for products, including their embodied carbon. Mandatory EPD uploads would help speed up the process of populating these regional databases.

2.1.3. LCA software

Several LCI and LCA tools exist to calculate impacts of single projects or materials. The National Institute of Standards and Technology (NIST) in the United States developed the Building for Environmental and Economic Sustainability (BEES, 2016) software. Tally (2016) and the Athena tools (2009) are used for LCA on the building scale and are discussed in Section 2.2.3.

The Environment Agency in the United Kingdom also developed a carbon calculator for materials, transportation, site energy and waste management (Jensen, 2016). PE International developed the commercial LCA software Ganzheitliche Bilanzierung Integrated Assessment (GaBi, 2016), and the Centre of Environmental Science of Leiden University (CML) developed SimaPro (2016). OpenLCA (2016) and the Carbon Calculations over the Life Cycle of Industrial Activities tool (CCaLC Tool) are examples of LCA tools using EcoInvent data. Other LCA tools include but are not limited to novaEQUER, Eco-Bat 2.1, Global Emissions Model for integrated Systems (GEMIS), LEGEP, LTE OGIP, Qantis suite, SankeyEditor, Bousted Model, and Umberto (Kotaji et al., 2003). Table 2.1 is a non-exhaustive list of industry reports, software, tools and databases for ECCs of materials.

	EEC	**ECC**	**LCA**	**Region**	**Free**
Industry data reports					
ICE database	✓	✓		UK	✓
Carbon working group		✓		US	✓
Hutchins UK Building Blackbook		✓		UK	
WBCSD on cement		✓		World	✓
NRMCA on concrete		✓	✓	US	
World Steel Association on Steel		✓	✓	World	
CORRIM on timber		✓	✓	US	
Databases					
US LCI		✓	✓	US	✓
Quartz		✓	✓	US	✓
CRMD		✓	✓	Canada	✓
European Life Cycle Database (ELCD)		✓	✓	Europe	✓
Milieudatabase.nl (Dutch Database)		✓	✓	Netherlands	✓
BBRI (Belgian Database)		✓	✓	Belgium	
INIES (French Database)		✓	✓	France	✓
Oekobaudat.de (German Database)		✓	✓	Germany	✓
IVAM		✓		Netherlands	
IVL Swedish Environmental Research I.		✓	✓	Sweden	✓
EcoInvent		✓	✓	Switzerland	
Building Products LCI (BPLCI)		✓	✓	Australia	✓
New Zealand building materials EE	✓			NZ	✓
JEMAI, 3EID		✓	✓	Japan	✓
CLCD		✓	✓	China	✓
AusLCI		✓	✓	Australia	✓
Software and tools					
BEES	✓	✓	✓	US	✓
Carbon Calc. Environmental Agency		✓		UK	✓
GaBi		✓	✓	Germany	
SimaPro		✓	✓	Netherlands	
OpenLCA		✓	✓	Netherlands	✓
CCaLC Tool		✓	✓	UK	✓
Tally		✓	✓	US/World	✓
Athena tools		✓	✓	US/Canada	✓
GEMIS		✓	✓	Germany	
LEGEP Software GmbH		✓	✓	Germany	
LTE OGIP		✓	✓	Germany	
Sankey Editor	✓		✓	Germany	
Umberto		✓	✓	Germany	
EQUER and novaEQUER		✓	✓	France	
Qantis suite		✓	✓	France	
Eco-Bat 2.1		✓	✓	Switzerland	
Bousted Model	✓		✓	UK	
Umberto	✓		✓	UK	

Table 2.1: Non-exhaustive summary of the available industry reports, databases, and tools to find ECCs globally

The main challenge with the available LCA software is the "black box" effect created by the intellectual property protection of the data, resulting in a lack of transparency and consistency across tools and countries. In order to compare across different tools, a uniform and transparent methodology is needed.

2.1.4. Overview of published ECCs

When using ECCs of materials in structural design, the structural engineer can use several forms of representation. First, the embodied carbon can be shown by material. Various papers have analyzed the environmental impact of concrete (Vares and Häkkinen, 1998; Lagerblad, 2005; Collins, 2010; Struble and Godfrey, 1999), cement (Young et al., 2002), steel (Stubbles, 2007), and timber (Pullen, 2000), with different assumptions on life cycle stages and boundary conditions. The advantage is the detailed description of the environmental impact of a single material, the disadvantage is that scope and methodology varies from one paper to another, making the numbers difficult to compare.

Second, it can be useful to represent the embodied impacts of materials in relation to their other characteristics essential to structural design, such as strength, stiffness, and financial cost. In *Materials and the Environment*, Ashby (2012) explores the environmental consequences on materials that humans depend on. Data, methods, and design parameters of materials are given in "Ashby diagrams," illustrated in Figure 2.2.

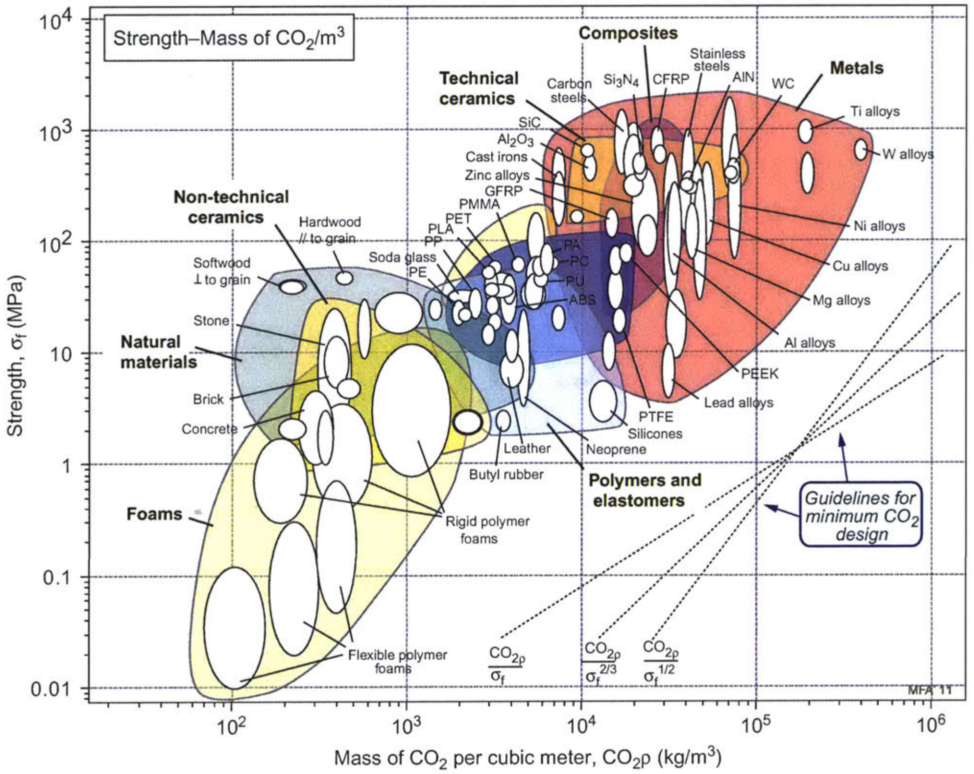

Figure 2.2: Ashby diagrams Embodied carbon (kgCO2e/m3) versus strength (MPa) (Ashby, 2012)

The University of Cambridge (2017) also offers Ashby diagrams with several material properties, measuring embodied energy and carbon against strength and financial cost, illustrated in Figure 2.3.

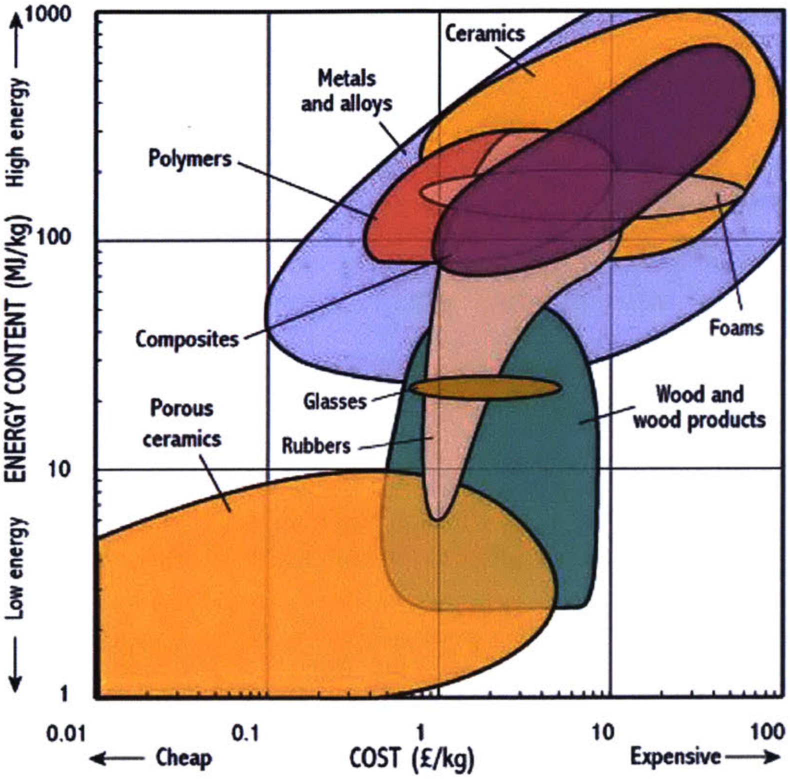

Figure 2.3: Ashby diagrams Embodied energy (MJ/kg) versus cost (£/kg) (University of Cambridge, 2017)

Third, an overview of various construction materials with their density and thermal conductivity can give a bigger picture of energy savings possible in terms of both embodied and operational carbon. Bribian et al. (2011) published LCA results for bricks and tiles, insulation materials, cement, concrete, and wood products. Tables showing the materials with their density (kg/m^3), thermal conductivity (W/mK), primary energy demand (MJe/kg), embodied carbon (kg$_{CO2e}$/kg), and water demand (l/kg) can help designers make a choice for the materials in order to significantly lower the environmental impact of their projects.

Fourth, the coefficients normalized by load capacity can be plotted on graphics illustrating different beam depths or column sizes, to help the structural designer evaluate the advantages of the various structural materials in specific load bearing cases. Purnell (2013) gives the embodied carbon of concrete by kNm^2 of a beam versus the beam depth in mm, as shown in Figure 2.4. The steel and timber beams are taken from standard sections. The dimensions of the reinforced concrete beams are taken from the Eurocodes and the ECCs from the ICE database.

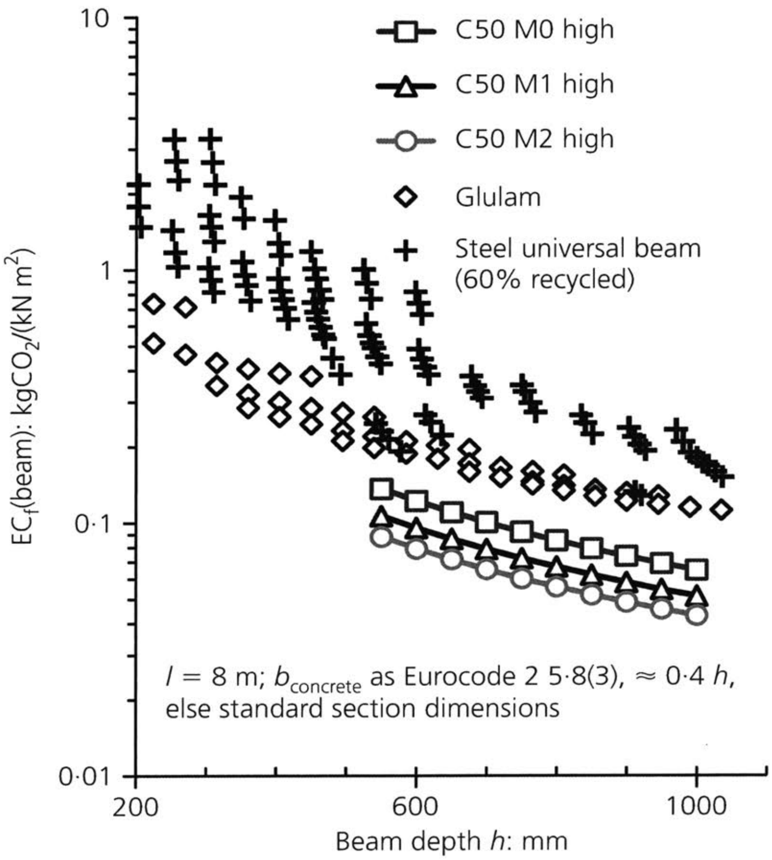

Figure 2.4: Embodied carbon plotted against beam section depth for various structural materials (Purnell, 2013)

Fifth, papers can also give the embodied impact of an entire assembly instead of a single material (Crawford et al., 2010). Roof, external walls, and floor assemblies composed of timber frames, steel sheets, concrete, and brick veneer can be evaluated using the ECCs of the composing materials.

The different representations in literature can be useful for structural designers to base their choices on, but the main challenge is still the lack of a uniform and transparent calculation methodology. Whether Asbhy (2012) diagrams, tables with other energy indicators, graphics with load bearing capacity indicators, or impacts of entire assemblies are given, confidence in the ECC of structural materials is always needed to develop and to believe these representations. A more detailed literature review of the ECCs of the structural materials concrete, steel and timber is given in Chapter 3 on the embodied carbon on the material scale.

2.2. Embodied carbon of building structures

2.2.1. Databases of buildings and building structures

Many leading structural engineering firms have started an in-house database of structural material quantities or embodied carbon of their own projects. One thoroughly developed example is the Arup Project Embodied Carbon and Energy (PECD) mainly consisting of Arup buildings or projects from literature (Kaethner and Burridge, 2012; Yang, 2013). Although PECD contains a few hundreds of projects, it does not allow the definition of a baseline yet due to the data scarcity and their wide ranges. Other companies such as Thornton Tomasetti have also developed a database of material quantities, extracted via a Revit plug-in, and embodied carbon in their projects (Thornton Tomasetti, 2016).

In collaboration with the United Kingdom Green Building Council, the Waste & Resources Action Programme (WRAP, 2017) started an initiative collecting whole building LCA results from industry in order to have data available on the building scale across companies. The contributors need to define the life cycle stages and used LCA software before entering end results of their own embodied carbon calculations of building projects. This still leads to a lack of transparency of ECCs used in calculations. To remedy this, this dissertation will introduce a database that collects not only the embodied carbon of buildings, but also the material quantities (deQo, 2017). This will be discussed in Section 2.2.2. While this database focuses on the structural part of buildings, the University of Washington and the Carbon Leadership Forum (CLF) have developed an Embodied Energy Data Visualization (CLF, 2017) through the Embodied Carbon Benchmark (ECB) Study (Simonen et al., 2017a) for whole buildings, including data from the database developed for this dissertation. This study only published the embodied carbon end results and identified that the next step needed in this field is the collection of material quantities to improve transparency and accuracy.

2.2.2. Database of embodied Quantity outputs (deQo)

Collecting data on material quantities in buildings and their environmental impact is needed to define a baseline, a starting point for comparing embodied carbon. All programs to assess the environmental performance of buildings require the comparison of the proposed design with a *reference building* as a base case. To obtain a green building certification, the proposed design must achieve the performance targets set by a reference building (for example the proposed design must reduce its embodied carbon by a certain percentage compared to the reference building). Defining these reference buildings will pave the way to lower embodied carbon in structures. Recognizing this need, this dissertation has created an interactive, growing database of building projects, called database of embodied Quantity outputs (deQo, 2017 – accessible online at deqo.mit.edu).

The online interface allows architects, engineers and researchers to input data on the material quantities and embodied impact of their projects. The designers may then compare their project results to the growing database of projects. The aim is to provide designers a level of confidence in the Global Warming Potential (GWP) of structures, expressed in kg_{CO2e}/m^2. The framework for this database was initially developed in the author's Master's thesis (De Wolf, 2014). The database was implemented during this doctoral research and results are discussed in Chapter 4 and throughout this dissertation.

While companies are developing in-house tools and databases, it is important to identify the challenges and opportunities for collecting these variables. The *first goal* is to facilitate and reward the participation of Architecture, Engineering and Construction firms in order to increase the number of projects added to the database to hundreds of projects, needed to create a representative sample pool.

BIM tools such as Revit (Autodesk, 2017) are an opportunity to quickly and automatically generate project data. Furthermore, the participating firms will gain access to other data variables to compare their projects with. While protecting the anonymity of the project data, branding for the participants as "carbon conscious firms" can also be an incentive.

The *second goal* is to implement the database. Unlike other available databases, deQo collects and presents the material quantities on top of the embodied carbon of building structures. In general, two questions arise: (1) how to ensure transparency of the data, and (2) how to protect intellectual ownership? The database management validates the accuracy of the data impartially while keeping the anonymity of the companies for each project. Only resulting ranges are published and sensitive project information may be removed (Figure 2.5). These ranges are analyzed by program type, structural system, size, number of floors, rating scheme certification, etc.

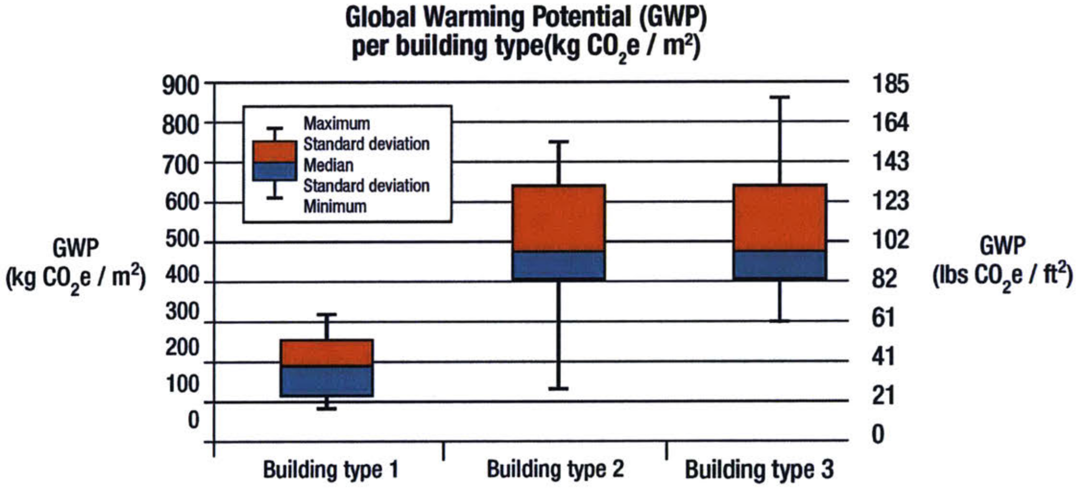

Figure 2.5: Sample ranges of embodied carbon per building type

2.2.3. *Whole Building LCA (WBLCA) software*

Commercial and open-source software are available to perform WBLCA. Kieran Timberlake and PE International released the Tally tool (2016), which extracts data from Revit models to calculate embodied impacts. A license is needed to use Tally. In Canada and the United States, the Athena Institute has integrated LCI data into two open-source building industry specific tools (Athena, 2009): the Athena Eco Calculator and the Athena Impact Estimator for Buildings (IE4B). The SOM Environmental Analysis tool estimates the embodied carbon of design projects and is available for free (SOM, 2016). The Atkins Carbon Critical Masterplanning tool calculates the embodied carbon of existing buildings (RICS, 2012).

There is no agreed upon software available yet that combines embodied carbon and operational carbon simulations. EnergyPlus (2016) is an energy simulation engine validated by the US Department of Energy generating annual, monthly or hourly energy demands for a building based on weather files. This dissertation will show how to combine EnergyPlus results with the proposed embodied carbon estimation method to study trade-offs between embodied and operational carbon in the built environment in Chapter 5.

Table 2.2 summarizes the available databases and tools to find the embodied carbon of building structures.

	SMQ	Embodied carbon	Structure	Building
Building & building structures databases				
Arup PECD		✓	✓	
Thornton Tomasetti	✓	✓	✓	
WRAP		✓		✓
CLF ECB		✓	✓	✓
deQo (current study)	✓	✓	✓	
Whole Building LCA software				
Tally		✓	✓	✓
Athena IE4B		✓	✓	✓
Atkins Carbon Critical Masterplanning tool		✓		✓

Table 2.2: Summary of the available databases and tools to find the embodied carbon of building structures

2.2.4. Overview of published benchmarks

There is a large body of academic literature available to practitioners for developing methodologies for calculating embodied carbon, and providing benchmarks for different buildings types. Dixit et al. (2010) showed a significant variation between authors in their embodied energy results illustrating inconsistencies in the data used, coming from disparate sources and countries. This is one of several factors that lead to a wide range in values. The definitions of embodied life cycle stages also demonstrate the lack of agreement on which stages to include in assessments. However, an overview of general results on embodied energy (Figure 2.6) and carbon (Figure 2.7) shows the inconsistencies in data, methods and protocols used.

Clark (2013) looked at both academic and industry calculations for embodied carbon and obtained a wide range of results between 300 and 1650 kg_{CO2e}/m^2 from case studies provided by various companies using different methodologies. Ding (2004) reviewed previous literature on embodied energy in residential and commercial buildings with a wide variation between 3.6 and 19 GJ/m^2.

Cole and Kernan (1996) were one of the first to compare the life-cycle energy use in office buildings for alternative wood, steel and concrete structural systems and found an initial embodied energy between 0.7 – 1.5 GJ/m^2. Eaton and Amato (1998) included a pioneering study of the embodied carbon of steel, composite, reinforced and precast concrete office buildings, with results varying between 200 and 350 kg_{CO2e}/m^2 for the structure only and between 600 and 850 kg_{CO2e}/m^2 for the whole building. Vukotic et al. (2010) publish results for the life cycle embodied energy and carbon emissions of two design alternatives for a single-story structure: timber panels (130 kg_{CO2e}/m^2) and steel frame with infill concrete blockwork (220 kg_{CO2e}/m^2). The study demonstrated that material choice and sourcing were the most significant life cycle stages in terms of potential for carbon reduction, as well as the waste handling. Many other studies have designed concrete, steel, and timber structural systems for a case study to compare the environmental impacts of building structures (Xiong and Zhao, 2011). Moussavi Nadoushani and Akbarnezhad (2015) reviewed existing publications to find a range between 128 and 731 kg_{CO2e}/m^2 for concrete structures and between 87 and 190 kg_{CO2e}/m^2 for steel structures.

Allwood and Cullen (2011) give an average embodied carbon for steel structures around 500 kg_{CO2e}/m^2 in typical office buildings and show that this increases considerably (up to eight times) with recent skyscrapers while it decreases when building with more efficient structural systems. Moynihan (2014) showed that substantial structural efficiency measures could be made in current construction practice for SMQ savings.

Authors such as Sartori and Hestnes (2007) have shown a slight increase in embodied energy for low-energy or zero (operational) energy buildings. Ramesh et al. (2010) confirmed this increase in embodied energy with passive and active technologies, showing that low energy building cases performed better than zero (operational) energy buildings over their whole life.

Inconsistencies are also found in different LCA software; Sinha et al. (2016) compared the Swedish Environmental Load Profile tool and the commercial LCA tools GaBi and SimaPro. The results obtained from the three tools showed significant differences. They discussed in particular the lack of reliable and transparent data for the impacts related to materials and transport, and the need for data associated to the location of the project.

Many of these published results show a high variability. Data quality should be evaluated in terms of reliability, completeness, and temporal, geographical, and technological correlation (Khasreen et al., 2009). Results for embodied energy of buildings and building structures are shown in Figure 2.6 and results for embodied carbon are shown in Figure 2.7.

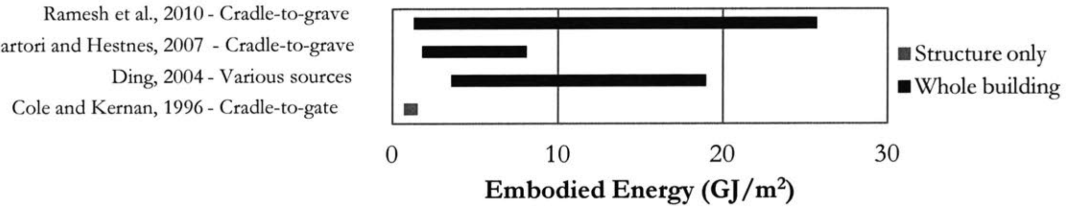

Figure 2.6: Variation in published embodied energy results

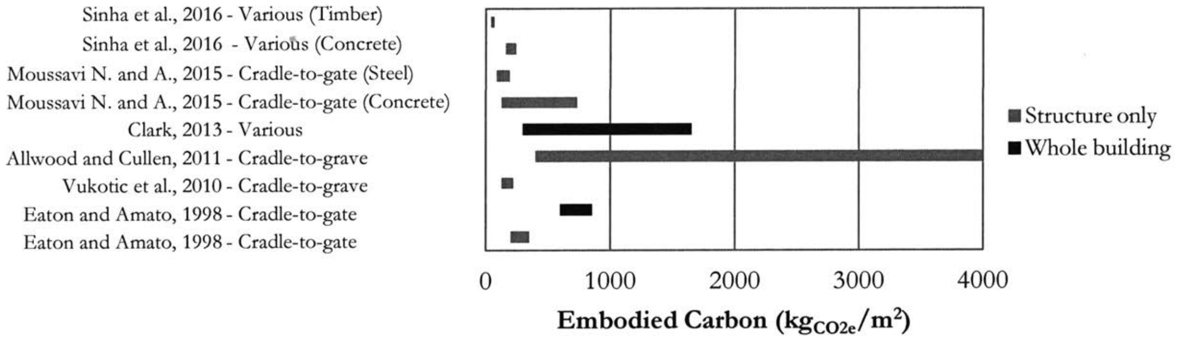

Figure 2.7: Variation in published embodied carbon results

The proportion of embodied versus operational energy and carbon is also variable from one study to another. Figure 2.8 illustrates the variation of different authors in terms of the life span considered and the minimum and maximum of the contribution of embodied impacts to the whole life cycle of buildings.

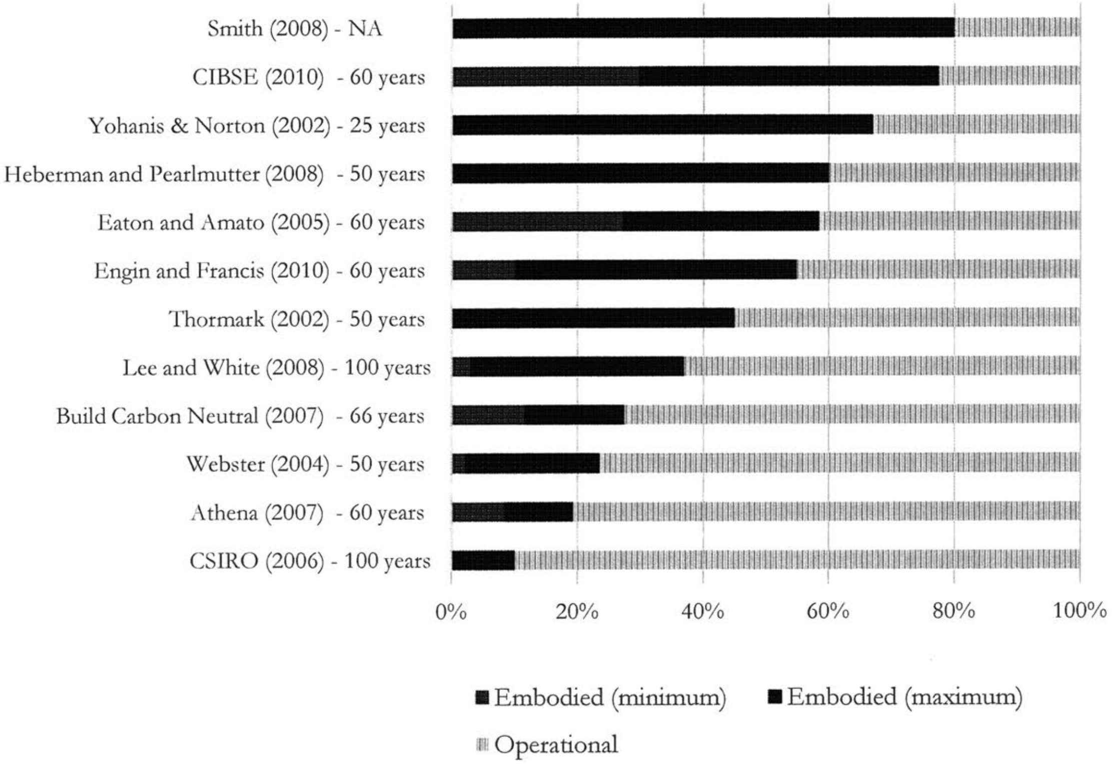

Figure 2.8: Variation of embodied emissions versus operational emissions in different buildings and infrastructure, adapted from (Ibn-Mohammed et al., 2013)

Lützkendorf et al. (2015) have recommended designers incorporate embodied impacts in net-zero energy buildings. Brown and Mueller (2016) look at the tradeoffs between embodied and operational impacts among other design criteria for structural and energy performance of long span buildings. Basbagill and Lepech (2013) express the need to look at environmental impact implications of building design decisions, especially in extreme climates in the Middle East, as improving operational performance can result in unwanted higher embodied impacts. Therefore, they present an automated optimization method with a multi-objective genetic algorithm for minimizing the environmental impact on the building scale. Most studies of the tradeoffs between embodied and operational impacts are on the structural and building scale.

2.2.5. *Incentives and barriers in current industry practice*

No national policies provide formal incentives yet for calculating embodied carbon, other than the Netherlands, within Building Regulations. However, many companies do engage in embodied carbon assessment, and decide to do so in prospect of future regulations and rating advantages. These industry leaders commit to various carbon targets including the

Science Based Targets (2016), the Dow Jones Sustainability World Index (2016), GRESB (2016), CDP (2016), RE100 (2016), and Structural Engineers 2050 (SE 2050, 2017). In current practice, incentives mostly rely on corporate liability and the willingness of the client.

> "The business drivers behind why we calculate embodied carbon are that we as a business have recently signed up to a carbon target. The reason why we are measuring embodied carbon is because over the coming years we will inevitably need to report it and we want to be ahead of the game." *Environmental Manager, Real Estate Investment Trust in the United Kingdom [I].*

Rating schemes including BREEAM (2015) and LEED (2013) also incentivize practitioners to assess the embodied carbon of their projects. The new development of user-friendly tools in recent years gives an incentive to architects and engineers to look at the embodied carbon of their designs. A list of incentives and enablers varying by country is given in Table 2.3. Rating schemes are recurrent incentives, whereas the national databases are enablers for embodied carbon assessments.

Country	Drivers	Enablers
Australia	Green Star	BPLCI
Belgium	BREEAM; MMG tool	Law on EPDs for manufacturers
China / India	RE100	
Europe	RE100; EN 15978 and EN 15804	
France	HQE	INIES database
Germany	DGNB German Sustainable Building Council	oekobaudat.de
Japan	CASBEE	
Norway	BREEAM; CEEQUAL	Fremtidens byer
Sweden	Business opportunity, design criterion, costs savings	IVL
Switzerland	Minergie	EcoInvent
The Czech Republic	LEED; BREEAM; Green Light for Savings	SBToolZ
The Netherlands		milieudatabase.nl; IVAM
United Kingdom	BREEAM; sciencebasedtargets.org	ICE database
United States	LEED v4 WBLCA credit; RE100; Self-promotion	US LCI, Quartz
World	Dow Jones Sustainability World Index; GRESB; CDP	

Table 2.3: Incentives in different countries

2.3. Urban studies on carbon emissions

Carbon emissions on the urban scale can be analyzed through Material Flow Analysis (MFA) or urban modeling. MFA is a tool used in the field of urban metabolism (Kennedy et al., 2009; Ferrão and Fernández, 2013). Converting the construction material flows to CO_2 emissions can give information on the embodied carbon of the built environment in cities. Ferrão and Fernández (2013) offer a metabolic perspective on promoting urban sustainability in terms of exchanges of matter and energy. Using the concept of urban metabolism applied to structural materials used in the built environment can offer a view on the embodied carbon of structures on the urban scale in a top-down approach.

Studies of embodied carbon on a neighborhood or city scale are usually based on economic data. Consequently, the influence of technical design changes on the building scale is difficult to assess on the urban scale. Therefore, a bottom-up approach starting from the building scale to the urban scale can also be followed. Urban Building Energy Modeling (UBEM) is often used to evaluate the EUI of neighborhoods (Sokol et al., 2017). The tradeoffs between both embodied and operational carbon are rarely avaluated in current design practices on the building scale, let alone on the urban scale, as tools tend to look at one or the other separately. This dissertation will address this gap in Chapter 5. This section gives an overview of the published references for both MFA and UBEM for embodied carbon on the urban scale.

Almost all building construction needs city government approval, making urban embodied carbon assessment a crucial tool for speeding up carbon reduction in the built environment (Lütken and Wretlind, 2016).

2.3.1. *Material Flow Analysis (MFA)*

Kennedy et al. (2009) quantify what we know on CO_2 emissions of cities by studying ten global cities in terms of the relationship between their GHG emissions and geophysical (climate, resources) or technical factors (power generation, urban design, waste processing). The GHG emissions *per capita* of 10 cities are illustrated in Figure 2.9 in terms of electricity, heating and industrial fuels, industrial processes, ground transportation, aviation, marine and waste. Their seminal work on energy consumptions confirms what is already known on the reasons of carbon emissions: heating degree hours, fuels used to provide energy, bad public transport, etc. The GHG emissions of cities depend on location, urban form, technology, and economic factors. One main challenge in urban metabolism is also gathering consistent data. To establish the embodied carbon on the city scale, the building material flows and construction emissions should be studied separately.

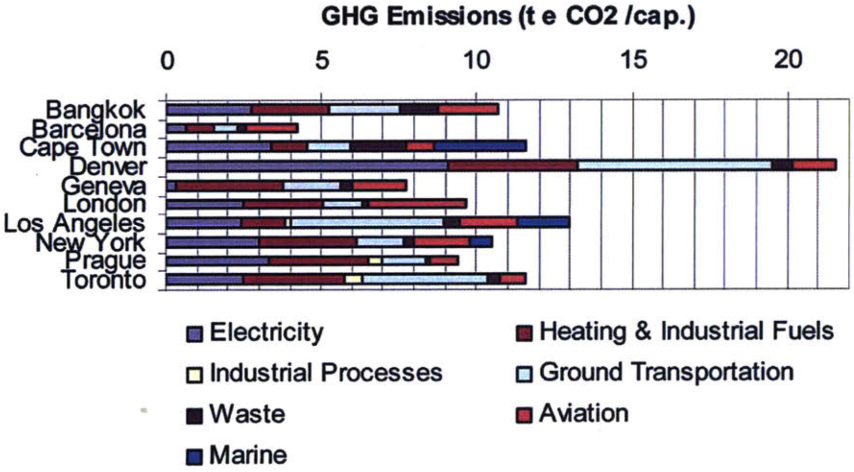

Figure 2.9: GHG emissions of 10 cities (Kennedy et al., 2009)

The study of GHG emissions can have policy implications thanks to the inventorying procedure, encouraging cities to recognize their impacts. Cities can learn from other cities, within a cohort of similar geophysical environments. For example, Geneva would not gain much by reducing electricity demand as it is produced with clean hydropower, but Cape Town would as it is produced with coal.

2.3.2. Urban Building Energy Modeling (UBEM)

Energy modelling of buildings on the urban scale falls into two categories. The "top-down" approach uses macroeconomic variables including population trends and economic activity to model energy in building stocks (Kavgic et al., 2010; Howard et al., 2012). The "bottom-up" approach uses statistical or engineering analytical models to represent buildings in order to evaluate new technologies or interventions (Fabbri et al., 2014; Kolter and Ferreira, 2011; Wilke et al., 2013). To support complex scenario development, UBEM (Reinhart and Cerezo, 2016) was recently introduced as a new type of bottom-up model representing individual buildings as dynamic thermal models, based on individual Building Energy Models (BEM) (Hensen and Lamberts, 2011). As with single building simulation models, the generation of UBEM models requires the definition of multiple data inputs, including the local climate conditions, the 3D geometry of all buildings and their context, and all non-geometric building parameters, including constructions, internal loads and systems. Automation of the workflows for defining all these parameters for potentially thousands of individual building energy models is needed on the urban scale.

GIS shapefiles enable the input of all data in a single UBEM model (Cerezo et al., 2015). Other more advanced 3D urban building information models such as CityGML (Open Geospatial Consortium, 2012) have been proposed for UBEM but are currently only available in select cities in Europe. While there are already multiple tools developed for the generation of UBEM models to calculate operational building impacts, no urban modelling tool exists to estimate the trade-off operational and embodied energy and carbon on a neighborhood scale. This dissertation therefore developed and combined both simulations for the case study in Chapter 5.

2.3.3. Overview of published carbon emissions of neighborhoods

LCA has been applied to building products for the past four decades. More recently, it is also applied to mesoscale systems such as neighborhoods for policy recommendations or environmental urban development purposes (Lotteau et al., 2015). Different definitions of functional units used for normalization lead to results that are difficult to compare to each other: km^2 of neighborhood, inhabitant, m^2 of living space, m^2 floor area, or household are commonly used. Boundaries vary also from one study to another: some only include buildings, while others add roads, power lines, water distribution, gas distribution, sewage, passenger cars, trains, etc. The life cycle stages can include construction, operation, and/or deconstruction.

Figure 2.10 illustrates different published results for carbon emissions per year normalized by floor area (m^2). Cherqui (2005) obtained 19.9 $kg_{CO2e}/(m^2.year)$ for a 0.02 km^2 residential neighborhood in La Rochelle, France, including construction, operation, and deconstruction over a life span of 80 years. Norman et al. (2006) obtained 77.7 and 107.3 $kg_{CO2e}/(m^2.year)$ for two residential neighborhood in Toronto, Canada, including construction and operation over a life span of 50 years. Peuportier et al. (2006) obtained 10.8 $kg_{CO2e}/(m^2year)$ for a mixed-use neighborhood in Lyon, France, including construction, operation, and deconstruction over a life span of 80 years. Colombert et al. (2011) obtained 25.8 $kg_{CO2e}/(m^2year)$ for a 0.15 km^2 mixed-use neighborhood in Paris, France, including construction, operation, and deconstruction over a life span of 80 years. Riera-Perez and Rey (2013) obtained 70.2 $kg_{CO2e}/(m^2year)$ for a 0.07 km^2 residential neighborhood in Lausanne, Switzerland, including construction, operation, and deconstruction over a life span of 60 years. Stephan et al. (2013) obtained 123.8 $kg_{CO2e}/(m^2year)$ for a 1.5 km^2 residential neighborhood in Melbourne, Australia, including construction and operation over 100 years. These results show that the variability of the existing results on the urban scale varies highly due to the different types of cities (density, size, type, region) but also the different scopes of the studies (life cycle stages, life span).

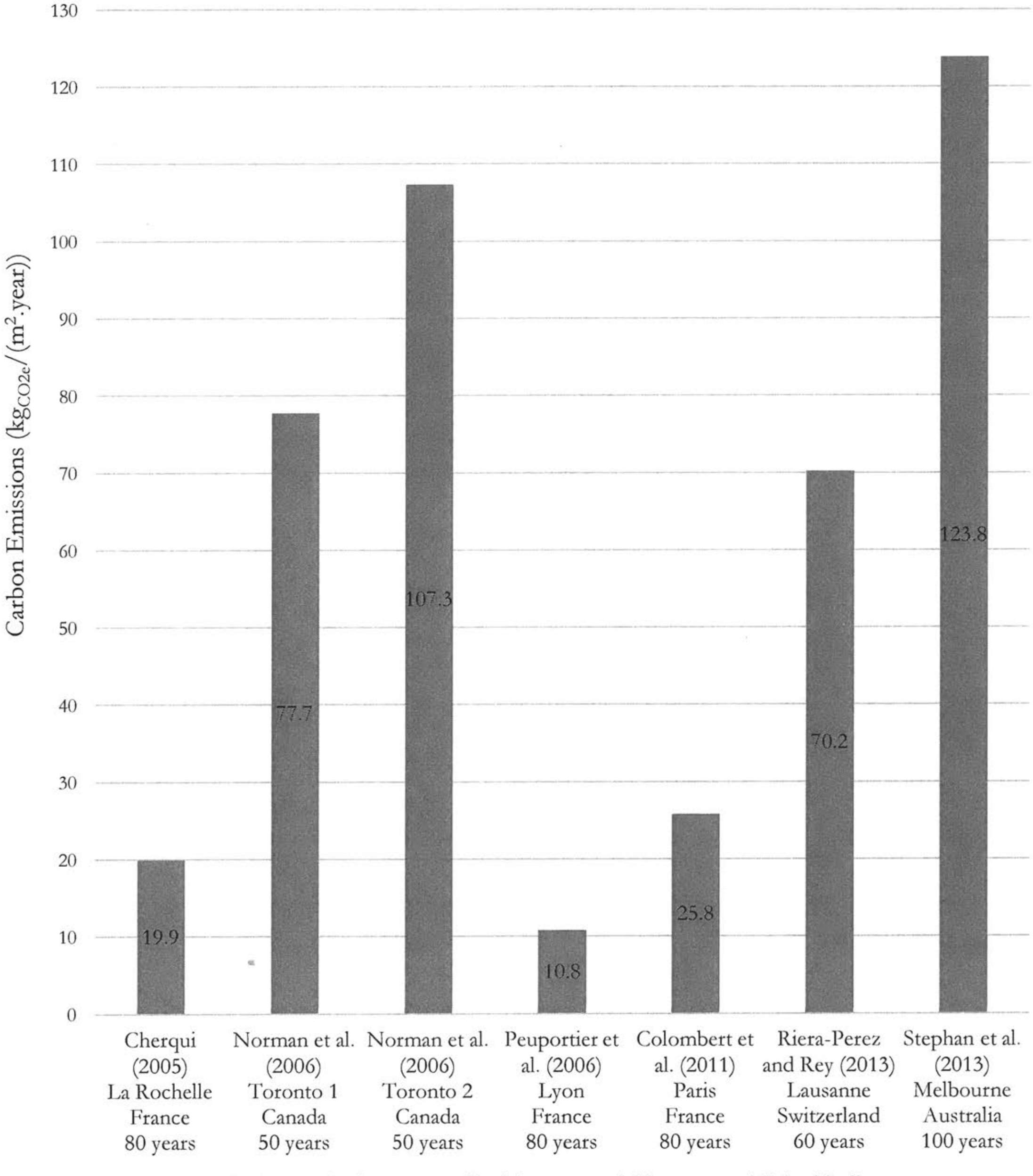

Figure 2.10: Carbon emissions normalized by area and life span, published in literature

2.4. Summary

This chapter presented a literature review of existing reports, databases, software, tools, and academic publications on the embodied carbon of building structures on three scales: the material, structural, and urban scale.

The embodied carbon of materials is expressed in ECCs. Various representations of these ECC results can help structural designers make informed material choices. However, there is a lack of comparable coefficients, as different industries advocate assumptions such as including the life cycle stages that are most advantageous to their products. National EPD databases will help define comparable results that are taking into account geographical and temporal variations.

The embodied carbon of building structures is still relatively unknown. Various in-house databases have been developed in leading structural engineering firms. A framework for deQo has been created to collect data on SMQs and embodied carbon in building structures worldwide and has been implemented during this doctoral research. The benchmarks for building structures published in academic literature illustrate the lack of a uniform methodology. One of the main challenges with assessing the environmental impact of building structures is the quality of the data. A lack of reliable, accessible, complete, recent, comparable, and regional data causes strong variability in the benchmarks for buildings and buidling structures. Key numbers published in literature are varying from 40-240 kg_{CO2e}/m^2 (Sinha et al., 2016) to 400-4000 kg_{CO2e}/m^2 (Allwood and Cullen, 2011), or 200-350 kg_{CO2e}/m^2 (Eaton and Amato, 1998), 130-220 kg_{CO2e}/m^2 (Vukotic et al., 2010) for example. This wide variation illustrates the need for transparent and reliable benchmarks for the embodied carbon of building structures.

Evaluating the embodied carbon of structures and buildings on the urban scale has the crucial potential to reduce the embodied carbon of the built envrionment at a faster pace than that achieved with rating schemes evaluating individual buildings. Indeed, all buildings need city government approval, so that a change in requirements and building codes could make reduction of embodied carbon in structural design mandatory. Therefore, tools are needed to assess the embodied carbon of structures at the neighborhood level. While material flow analysis is an excellent top-down approach for an inventory of the building materials imported, used, and exported by cities, the bottom-up approach of urban modeling will be used in this dissertation to evaluate how structural design alternatives can offer low carbon pathways for structural design of new cities.

PART II • BENCHMARKING EMBODIED CARBON

The second part of this dissertation examines the assessment of embodied carbon in materials, building structures, and neighborhoods. First, a transparent methodology to calculate the embodied carbon emissions of the main structural materials is illustrated. Then the database developed for this research evaluates the embodied carbon of structures. In collaboration with leading structural engineers, the quantities of structural materials and the embodied emissions of hundreds of structures are collected and thoroughly analyzed. Finally, the results on the structural and building scale are applied to the urban scale in the case study of a Kuwaiti neighborhood.

3. Embodied carbon on the material scale[2]

This chapter discusses the embodied carbon of the main structural materials: concrete, steel, and timber, as quantified by available Embodied Carbon Coefficients (ECCs) measured in kg_{CO2e}/kg of material. First, the existing ECCs from available datasets are critiqued in Section 3.1. Then, ranges for regional ECCs are proposed for the three structural materials in different regions of the world in Section 3.2. The purpose of this chapter is to give confidence in the ECCs of materials used in structures.

3.1. Analysis of existing Embodied Carbon Coefficients (ECCs)

3.1.1. Challenges with available ECC datasets

The definition of ECCs is an important and complex matter. Typically, this data is obtained from Life Cycle Inventory (LCI) databases. Most available databases are protected by intellectual property rights within commercial LCA software. To answer the need for an open-source database of embodied energy and carbon in common building materials, the ICE database was developed by the University of Bath (Hammond and Jones, 2010). The "cradle-to-gate" data has not been updated since 2011 and is mainly focused on materials in the United Kingdom.

Other databases or LCA software exist without transparency about their LCI data. For an LCA of a specific material or building product, GaBi (2016) can be used after buying a license. The Impact Estimator for Buildings (IE4B) from Athena Sustainable Materials Institute (Athena, 2009) is available for free, but the LCI data is protected by intellectual property rights. The "cradle-to-gate" and "cradle-to-grave" coefficients used in IE4B have been compared to other data sources, though they are specific to the United States and Canada. Average transportation distances, construction, maintenance and demolition impacts are used. The tool is oriented towards users performing a whole building LCA. ETH Zurich developed EcoInvent (2016), which presents industrial data and is compatible with a number of LCA and eco-design software tools, but it requires a license.

While ICE and IE4B are available for free, they are specific to a certain region, respectively the United Kingdom and the United States. EcoInvent and GaBi are respectively Swiss and German based, but offer global coefficients. However, the assumptions and methodologies are not transparent due to intellectual property right protection. Also, some regions are not covered. The reliability of the data is difficult to evaluate when transparency is lacking. The ICE database uses an average of existing literature from the last few decades. The sensitivity to usage of different datasets can vary due to interpolation errors, indirect access to ECC values, misinterpretation of the units, or different boundary definitions. Finally, the geographical variation of the available datasets, makes it difficult to compare projects in

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[2] The conclusions of this chapter are published in a book chapter in: De Wolf, C., Rodriguez, B.X., and Simonen, K. (2017b) "Counting Carbon – What we know and how we know it about embodied carbon" in: King, B. (ed.) "New Carbon Architecture." *New Society Publishers*, Canada. The analysis of existing ECCs in Section 3.1 was developed in collaboration with Dr. Ornella Iuorio. The values of concrete in Section 3.2.1 were established in collaboration with Wesley K. Lau.

different parts of the world to one another. Therefore, this chapter will define "regional" coefficients for the three main structural materials: concrete, steel, and timber.

The challenges of the main available datasets for ECCs are the reliability of data, uncertainty issues, the access to data, the sensitivity to the assessor's choices, geographical variation, and more. The lack of transparency of available ECC datasets impedes the reliability and uncertainty of the data. The accessibility of data depends on the database: some are available for free while others require a license. The sensitivity to the choices made by embodied carbon assessors depend on the clarity of the definition of materials and on the number of available materials in existing datasets. The geographical variation depends on the source of the information.

Leveraging uncertainty is important to conduct a robust comparative LCA of building materials. Gregory et al. (2016) developed a methodology for robust comparative LCA incorporating uncertainty that evaluates a series of scenarios probability while performing an uncertainty analysis in input data. To make design decisions and material choices, a clear environmental preference amidst the alternative options needs to occur.

As illustrated in Figure 3.1, preferences can only be defined when one alternative has a clearly lower environmental impact than the other. The difference needs to be significant given the uncertainty in the parameters and assumptions. These parameters can be determined with a sensitivity analysis, so that decision-tree partitioning algorithms can isolate meaningful scenario groups. The information needed for a complete LCA of building materials requires significant time and resources, which led to streamlined LCAs reducing quantitative and qualitative efforts, consequently introducing additional variability and uncertainty into the results (Olivetti et al., 2013). Care should be taken when comparing ECCs of different materials to each other.

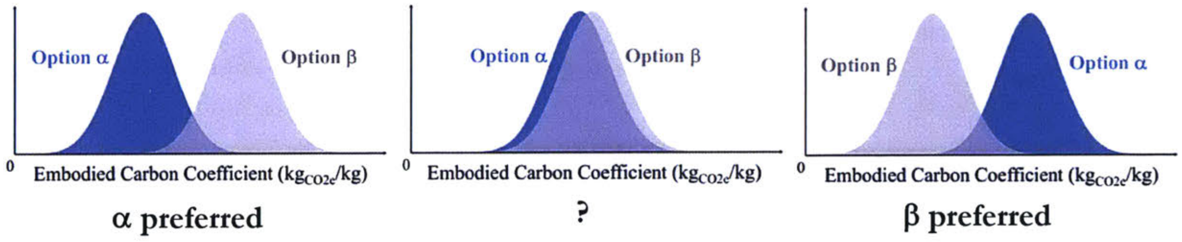


Figure 3.1: Comparative LCA incorporating uncertainty, adapted from (Gregory et al, 2016)

Whilst a recent PhD has reviewed the state-of-the art of uncertainty analysis in embodied carbon assessments (Hoxha, 2015), it is crucial to highlight that uncertainty plays a role in at least two stages in embodied carbon assessments (De Wolf et al., 2017a). First, different sources are used with boundaries and assumptions that are not often declared, thus preventing a transparent comparison of the results which in turn further increase the uncertainty around numbers. Second, such sources are used to produce assessments which result in unique, definite numbers with no information on their uncertainty and probability distribution, as explained by Pomponi and Moncaster (2016).

Furthermore, in each stage, the uncertainty can be caused by or related to three main elements. This was initially framed by Lloyd and Ries (2007) and represents seminal work in uncertainty analysis in LCAs. These are:

- Parameter uncertainty, i.e. the uncertainty refers to the values of a parameter such as the embodied carbon of processes and/or assemblies;
- Scenario uncertainty, i.e. the uncertainty refers to the likelihood of different scenarios, such as the energy mix of the United States in 30 years' time;
- Model uncertainty, i.e. the uncertainty refers to the specific model being used, such as the model developed by the Intergovernmental Panel on Climate Change (IPCC, 2014) to calculate the Global Warming Potential related to GHGs over 20, 50, and 100 years' horizons (Trancik and Cross-Call, 2013).

The uncertainty of the ECCs of structural materials is explained by data quality and variability issues, discussed in Table 3.1 (Webster et al., 2012). Data quality is rarely discussed in the LCI databases. The date at which ECCs were published can influence the results as manufacturing processes or energy sources can change over time. This also is the case for the location; energy mixes are different from one country to another for example. Building materials can be produced in many ways, leading to the question of technical relevance of an ECC. The data may not always be complete, for example when neglecting the impact of admixtures in concrete. When doing a comparative analysis, the data must be consistent and must use the same scope, life cycle stages and environmental impacts (CO_2 versus CO_2e). Moreover, the data also varies based on regional differences in materials, different ingredients in the concrete mixes, differences in steel production processes, and material specification such as sawn softwood versus engineered timber.

Data quality	Data variability
Date	Geographical variation
Technical relevance	Ingredients
Completeness	Production
Consistency	Material specification
Geography	

Table 3.1: Sources for uncertainty in ECCs, after (Webster et al., 2012)

3.1.2. Concrete

A wide variability in the ECC of concrete is related to the different ingredients in concrete mixes. The ECC can vary significantly depending on the strength, the cement content, the percentage of cement replaced by fly ash or ground-granulated blast furnace slag, and the percentage of reinforcing steel (rebar) when looking at reinforced concrete (Table 3.2). Figure 3.2 illustrates the variability between different data sources with different strengths of concrete. The variation can range from 0.08 to 0.22 kg_{CO2e}/kg with the same assumptions on rebar percentage and cement replacements due to different strengths and databases.

Concrete variations
Strength
Cement content
Fly ash percentage as cement replacement
Ground-granulated blast furnace slag percentage as cement replacement
Reinforcing bar (rebar) percentage

Table 3.2: Reasons for variations in the ECC of concrete

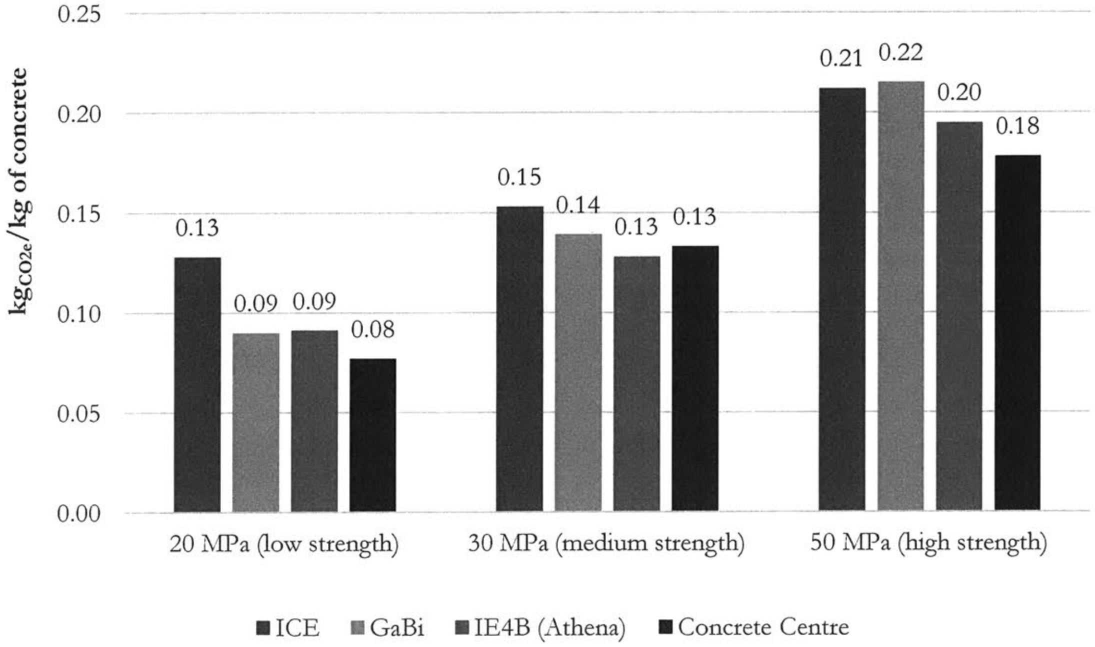
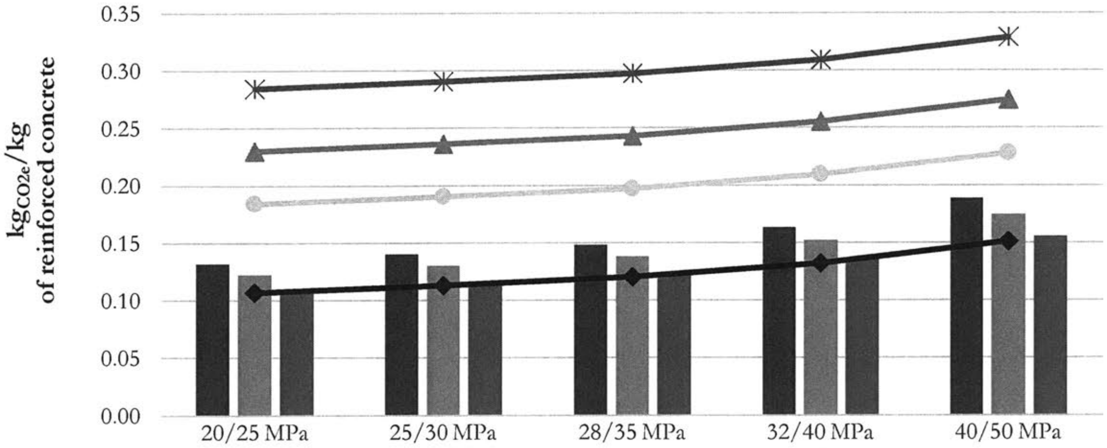


Figure 3.2: Variability of the results by strength and data source

Figure 3.3 illustrates the variations of the ECC by strength, percentage of fly ash, and percentage of rebar for reinforced concrete. These results were summarized by the present study with data from the ICE database to calculate the variations (Hammond and Jones, 2010). The methodology developed by Hammond and Jones (2010) to find the different contributions of cement replacement and rebar is recommended globally, but with data adapted with local LCA results for ingredients such as cement, fly ash, and reinforcing steel. The values for fly ash replacements assume a typical amount of reinforcement of 3%. ICE suggests adding 0.77 for each 100kg of rebar per m^3. The coefficients can vary from 0.11 to 0.33 kg_{CO2e}/kg depending on the amount of cement replacements or rebar percentages. It is therefore important to define the concrete mix precisely when assessing the environmental impact of concrete elements in building structures. Purnell and Black (2012) performed a detailed embodied carbon analysis of different concrete mixes and showed that there is a complex relationship between embodied carbon and concrete mix design, for example due to replacement of cement with pulverized fuel ash. Purnell and Black (2012) showed that an optimum strength for all concretes in terms of embodied carbon per unit of structural performance lies between 50 and 70 MPa.



	20/25 MPa	25/30 MPa	28/35 MPa	32/40 MPa	40/50 MPa
■ 0% fly ash	0.13	0.14	0.15	0.16	0.19
■ 15% fly ash	0.12	0.13	0.14	0.15	0.17
■ 30% fly ash	0.11	0.12	0.12	0.14	0.16
◆ 0% rebar	0.11	0.11	0.12	0.13	0.15
● 1% rebar	0.18	0.19	0.20	0.21	0.23
▲ 2% rebar	0.23	0.24	0.24	0.26	0.27
✳ 3% rebar	0.28	0.29	0.30	0.31	0.33

Figure 3.3: ECC for concrete by strength, fly ash and rebar percentage, data after (Hammond and Jones, 2010)

For approximate calculations of unreinforced concrete elements, 0.11 kg_{CO2e}/kg can be used for normal concrete (C20/25 - C28/35 and 30% fly ash) and 0.13 kg_{CO2e}/kg for high strength concrete (C32/40 - C40/50 and 30% fly ash). Vieira et al. (2016) give a review of LCA applied to the manufacturing of concrete and Purnell (2013) analyzes the carbon footprint of reinforced concrete varying between 0.05 and 0.5 kg_{CO2e}/kg depending on the strength.

3.1.3. Steel

The different available databases give different results for structural steel and reinforcement (rebar). ICE gives values of 1.46 kg_{CO2e}/kg for general steel and 1.4 kg_{CO2e}/kg for rebar (Hammond and Jones, 2010). GaBi proposes 1.7 kg_{CO2e}/kg for rebar with 65% recycled content (GaBi, 2016). Athena suggests 0.88 kg_{CO2e}/kg for structural steel and 0.42 kg_{CO2e}/kg for rebar (Athena, 2009). Figure 3.4 shows the variability of the structural steel and rebar results for different data sources. EcoInvent proposes 1.1 kg_{CO2e}/kg for sections (beams, columns), 2.6 kg_{CO2e}/kg for sheeting, 1.2 kg_{CO2e}/kg for studs and 2.5 kg_{CO2e}/kg for plates (EcoInvent, 2016). Table 3.3 illustrates the reasons for variation between the various coefficients.

Steel variations
Recycled content / recycling rate
Structural steel / rebar
Energy mix
Available scrap steel
Sections / Sheet / Reinforcement, etc. have a different manufacturing process

Table 3.3: Reasons for variations in the ECC of steel

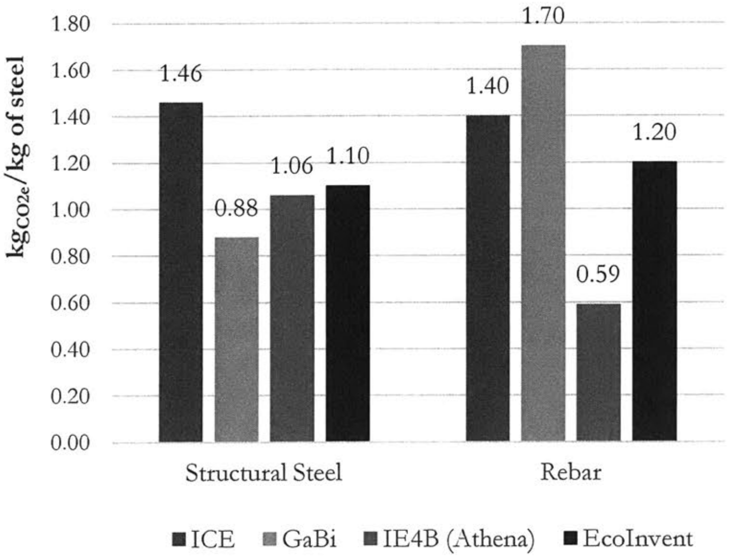


Figure 3.4: Variability of results by data source

For steel, a wide variation exists when comparing different regions due to the percentage of recycled content. Indeed, primary and secondary steel have a significantly different ECC. Moreover, steel used for rebar has a different fabrication process than structural steel, leading to different coefficients. This is illustrated in Figure 3.5.

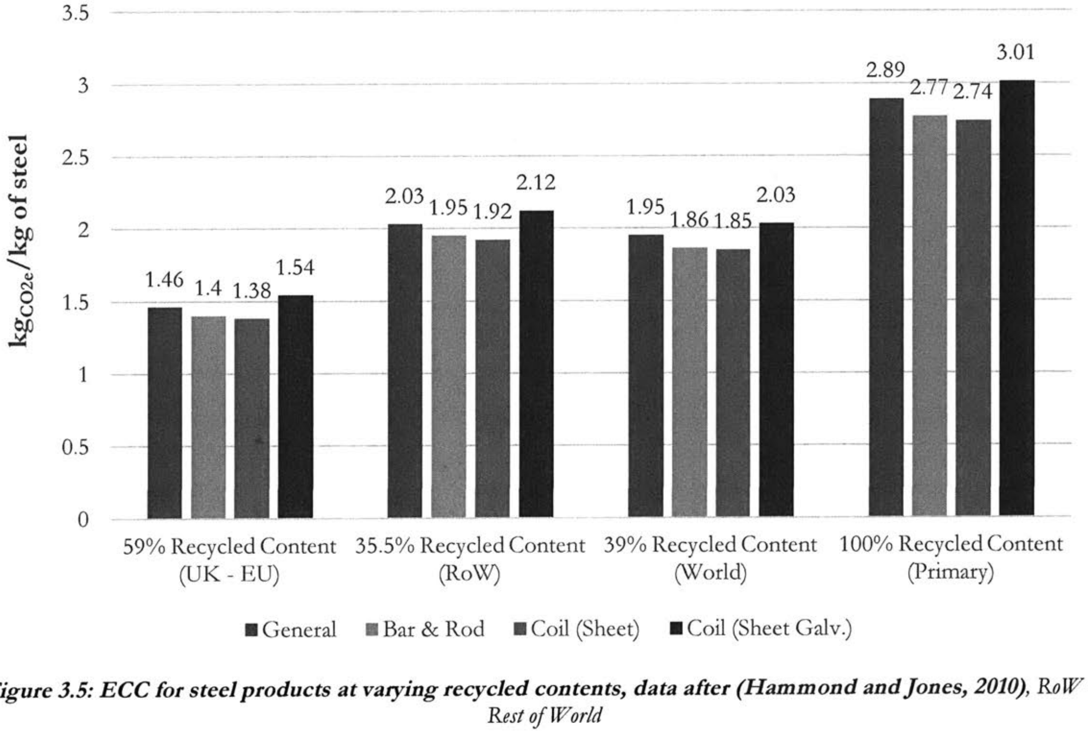


***Figure 3.5: ECC for steel products at varying recycled contents, data after (Hammond and Jones, 2010)**, RoW = Rest of World*

3.1.4. Timber

Timber, a renewable and biodegradable product, varies regionally due to a different amount of moisture content of the trees, variations in the consumptions of total energy to manufacture the same timber product, whether it is sawn lumber or engineered timber, and variations in the fuel mix (Hammond and Jones, 2010). The ICE database gives ECCs with and without biomass fuel. Indeed, to dry timber in a kiln, timber off-cuts are burnt to provide energy. This biomass fueled energy is considered carbon neutral if the timber comes from a sustainably managed forest (Weight, 2011). The ICE does not include carbon sequestration in the coefficients. As long as timber is sustainably sourced, only the ECC due to fossil fuel usage is accounted for in this dissertation. Timber from unsustainably managed forests such as old-growth rainforest should not be considered for structures at all, to avoid the climate and biodiversity catastrophes that could occur due to deforestation.

An important issue when calculating the ECC of timber is *carbon sequestration*. During their lifetime, trees absorb carbon emissions while growing. Photosynthesis uses carbon to produce wood resulting in carbon being half the weight of wood fibers (Kestner et al., 2010; Weight, 2011). Therefore, timber manufacturers advocate a negative number should be added to the ECC value of timber to account for the carbon sequestered in the timber product. Whether or not this should be taken into account depends highly on the end-of-life treatment of the timber product (Weight, 2011), as well as on the sustainability of the forest management (if no tree is planted when another is cut, it stops sequestering carbon at all; Law and Harmon, 2011).

When timber is burnt at its end of life, the carbon is emitted again into the atmosphere. To have a complete view of the environmental impact of timber, the ECC should therefore be cradle-to-grave: including both carbon sequestration and end-of-life emissions. The argument for including carbon sequestration even in the cradle-to-gate coefficients is that the carbon is kept out of the atmosphere for at least the lifetime of the building.

Another argument for timber as a construction material helping to sequester carbon is the management of sustainable forests. Indeed, forests growing without human intervention reach an equilibrium over long periods of time so that the GHGs absorbed equal the GHGs emitted. Sustainably managed forests yield useful timber while planning thinning for a continued net forest intake of CO_2. However, natural forests processes such as forest fires, forest succession, and decay can help soil renewal (Webster, 2012). Deforestation is responsible for 20% of anthropogenic GHG emissions (Law and Harmon, 2011). Afforestation (establishing a forest where there was none before) and reforestation (reestablishing a forest where there used to be one before) are climate change mitigation strategies to help the forest's intake of CO_2. Reduced deforestation, reforestation, afforestation, and new plantations are defined as one of the stabilization wedges for solving the climate problem for the next 50 years with current technologies by Pacala and Socolow (2004).

Often timber is used as an example of a material with very low carbon emissions (Skullestad et al., 2016). However, it is important to note two groups of timber: sawn lumber and engineered timber (Ramage et al., 2017). Sawn lumber indeed has a low ECC as it contains mainly transport emissions. The majority is manufactured in mainland Europe and

Scandinavia. Two types of sawn lumber are distinguished: softwood comes from coniferous species such as pine, fir, spruce, or cedar and tends to grow faster resulting in a lower density whereas hardwood comes from a deciduous tree such as maple, oak, walnut, or alder and tends to be slower growing resulting in a higher density. Most structural sawn lumber comes from softwood. Engineered timber is a composite material using hard- and softwoods combined with other components such as glue to make the structural elements more flexible. Examples are cross laminated timber (CLT) and glued laminated timber (Glulam). The layers of CLT are glued perpendicular to adjacent layers giving strength in two directions, making it ideal for walls, floors and roofs (Harris, 2015). The layers of Glulam are glued in the same direction, making it ideal for columns, beams and curved shapes (Ong, 2015). Whole timber is also used in structural application. Table 3.4 illustrates the potential reasons for the variations in the coefficients for timber. Different assumptions on part of these issues result in the variable results shown in Figure 3.6, with a comparison for timber as a structural material with Glulam, CLT, sawn hardwood and sawn softwood. Some sources do not include carbon sequestration, leading to significantly higher ECCs (Hammond and Jones, 2010).

Timber variations
Engineered, sawn or whole timber
Carbon sequestration
Sustainable forest management
End-of-life scenarios: landfill, reuse, recycling, use as fuel, etc.
Provenance, type of wood/forest
Transport & availability of local timber

Table 3.4: Reasons for variations in the ECC of timber

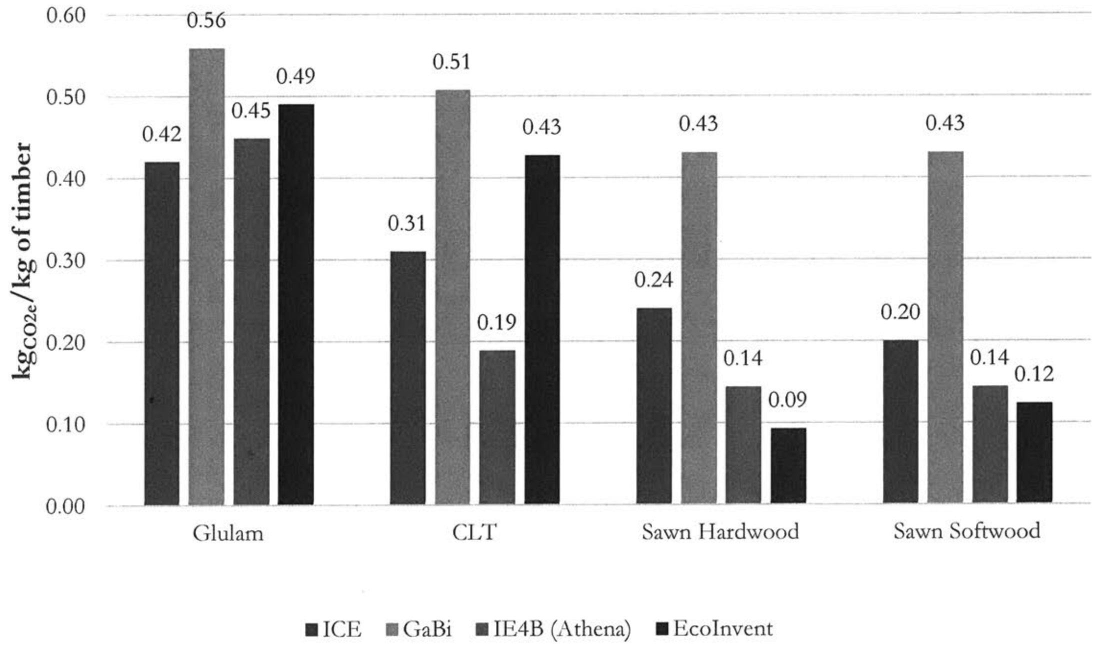


Figure 3.6: ECC of timber from various sources

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, and industry reports. The coefficients are given for different regions in the world, taking into account data from world cement and steel associations as well as regional forestry practices.

3.2.1. *Concrete*

For concrete, the coefficients not only vary as a function of material composition, but also on the location, due, for example, to different efficiencies of the kilns. Concrete is composed of aggregate, sand, water, cement, admixtures and air. Though cement only accounts for about 10% of the weight in concrete, it consumed 90% of the energy to produce concrete (Farny and Panarese, 1994; Purnell, 2013). Figure 3.7 illustrates the production of concrete. Most emissions are related to the cement production. Approximately 3,000 kJ is needed to produce 1 kg of Portland cement (Fernández, 2006), which has decreased from 6,000 kJ/kg a few decades ago due to newer kilns. The embodied carbon of concrete can significantly be reduced by replacing up to 50% of the Portland cement with fly ash, a byproduct of coal burning mainly going to landfill (Fernández, 2006). Currently, between 0.5 and 0.8 kg_{CO2e} is needed per kg of cement produced depending on the efficiency of the kilns in different regions (WBCSD, 2016).

Cured concrete is penetrated by CO_2 and chemically react to form carbonates, a process called carbonation (Webster et al., 2012). However, non-ideal real world conditions make the process too slow to address the urgent need for carbon reduction in the next decades. Carbonation equals a small percentage of the CO_2 emitted in the production and is therefore neglected in this dissertation.

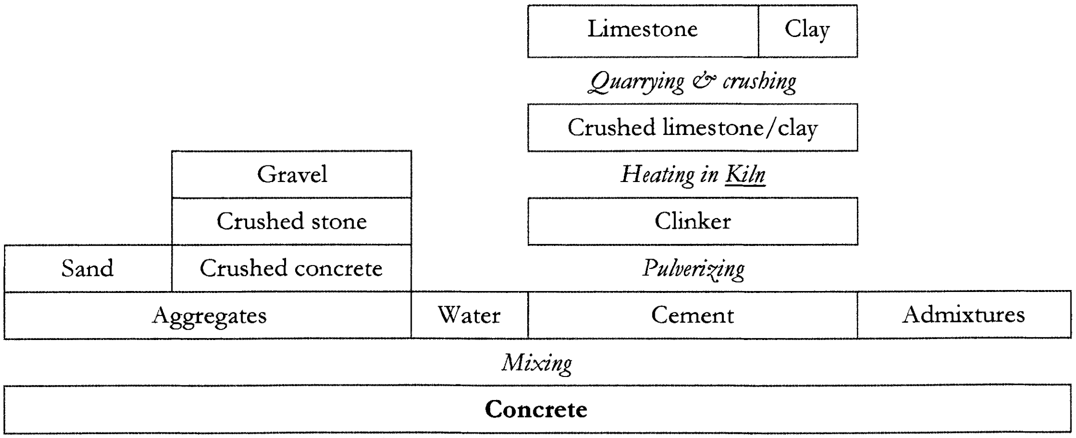


Figure 3.7: Production of concrete

A range of ECCs for concrete has been determined based on the cement production statistics in the report "Getting the Numbers Right" published by the World Business Council on Sustainable Development (WBCSD, 2016). Annual emissions and cement production data from 25 major cement corporations with kilns spread over 100 countries are collected in this database. The ECC of cement in each region in Table 3.5 is calculated by dividing the cement production carbon emissions of each country (published by the WBCSD) by the mass of grey and white cement produced. A weighted average of the ECC of cement for all regions results in 0.64 kg_{CO2e}/kg. For example, for High Performance Concrete (HPC) with strengths between 70 and 140 MPa the cement content averages around 0.205 $kg_{cement}/kg_{concrete}$ (ASTM C 1084, ACI 211.1). The aggregates, sand, water, and trace additives account for the remaining 10% of the embodied carbon in concrete, from the transportation of aggregate and sand from quarries to the concrete plant, adding between 0.01 and 0.02 kg_{CO2e}/kg to the ECC of concrete. For HPC, combining the embodied carbon from all ingredients, transportation to the manufacturer, and production is estimated around 0.14 kg_{CO2e}/kg.

	$kg_{cement}/kg_{concrete}$ →	0.135	0.196	0.205
Region	kg_{CO2e}/kg_{cement} ↓	**30/40 MPa**	**50 MPa**	**HPC**
Africa	0.63	0.09	0.14	0.14
Asia* & Oceania	0.68	0.10	0.15	0.15
Brazil	0.60	0.09	0.13	0.13
Central America	0.64	0.10	0.14	0.14
China	0.63	0.09	0.14	0.14
CIS (Ex-USSR)	0.72	0.11	0.16	0.16
Europe	0.62	0.09	0.13	0.14
India	0.59	0.09	0.13	0.13
Middle East	0.72	0.11	0.16	0.16
North America	0.79	0.12	0.17	0.18
South America**	0.54	0.08	0.12	0.12
World	**0.64**	**0.09**	**0.14**	**0.14**

**excluding China, India, CIS; **excluding Brazil*

Table 3.5: ECC for concrete in different parts of the world

The NRMCA (2016) published certified EPDs for ready mixed concrete with the following impact assessment results for the GHG emissions of different types of concrete. Cradle-to-gate results for 4001-5000 psi (27.59 – 34.47 MPa) concrete ranged between 233.8 and 391.2 kg_{CO2e}/m^3 which gives ECCs between 0.1 and 0.16 kg_{CO2e}/kg for low strength concrete. The value of 0.12 obtained for North American 30/40 MPa lies within this range. The results for 6001-8000 psi (41.38 – 55.16 MPa) concrete ranged between 372.8 and 628.9 kg_{CO2e}/m^3 which gives ECCs between 0.16 and 0.26 kg_{CO2e}/kg for high strength concrete. The value of 0.17 obtained for North American 50 MPa concrete lies within that range.

When high quality data is available such as these certified EPDs and the material specification is known, these ECCs should be used. The recommended ECCs given in this Chapter are the most likely range of values that can be used for approximate calculations. The recommended values in Table 3.5 (concrete), Table 3.6 (steel), and Table 3.8 (timber) are therefore still subject to uncertainties. Where regionally specific verified EPDs are available, they should be prioritized.

3.2.2. Steel

The ECC for steel is extremely dependent on the recycled content. Indeed, primary steel production emits higher amounts of GHGs than secondary steel. Gutowski et al. (2013a) estimated global average energy intensity of material production for steel (MJ/kg) among other materials. The primary steel needs 25 MJ/kg, whereas the secondary steel only requires 9 MJ/kg. Gutowski et al. (2013b) note that the scrap availability is an important issue for reducing the embodied impacts of steel.

A high value of end-of-life recycled rate is important, but recycled steel should also displace primary production, which is more challenging in a growing economy (Pauliuk et al., 2013). The current low recycling rates for steel are also due to improvements in yield and the rapid growth of steel. Figure 3.8 illustrates the production of steel.

Two methods exist to produce steel: from virgin iron ore (primary steel) or from recycled steel scrap (secondary steel). The first method is called Basic Oxygen Furnace (BOF) and requires more energy than the second method or Electric Arc Furnace (EAF). Therefore, the primary steel has a higher ECC than secondary steel. To calculate the ECC for steel, the ECC values of primary and secondary steel are weighted according to the recycled content of the steel product.

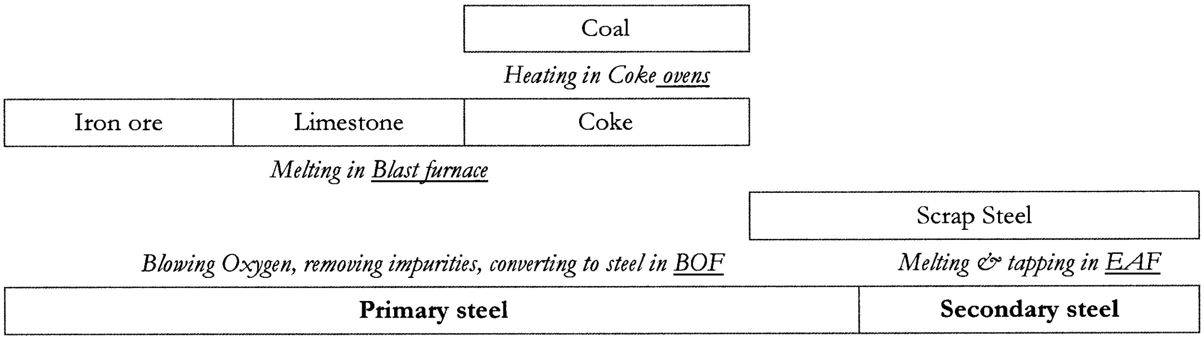


Figure 3.8: Basic Oxygen Furnace (BOF) for primary and Electric Arc Furnace (EAF) for secondary steel

The World Steel Association (2014) has a database for sustainability factors of steel collected from 150 primary steel producers over 66 countries, corresponding to 85% of global steel production and reports a global, weighted average EEC of 20.2 MJ/kg. Though uncertainty needs to be addressed, the calculation methodology is given for a certain set of assumptions to compute reproducible ECCs.

With a world emission factor of 0.6 kg_{CO2e}/kWh (IEA, 2016), the global, weighted average ECC of primary steel is 3.36 kg_{CO2e}/kg. If uncertainty is taken into account, this result gives a range rather than a single number. Based on these numbers for primary steel, the ECC of secondary steel can be calculated. The production of secondary steel requires 74% less energy and carbon than primary steel production according to the Bureau of International Recycling (BIR, 2016). The global, weighted average ECC of secondary steel is thus 0.87 kg_{CO2e}/kg. While 95% of structural steel and 70% of rebar is recycled, the *recycled content* in manufacturing steel is considerably lower, due to the lack of available scrap steel. Because more steel is produced than scrap steel is available, only a percentage of global steel production uses steel scrap feedstock currently (BIR, 2016).

Studies published by steel manufacturers advocate for the use of *recycling rates* at end-of-life (life cycle stage C) rather than recycled content at production (life cycle stages A1-A3), based on the disadvantage of growing economies where the steel production outskirts scrap availability (EUROFER, 2000). These ECC values of steel could be manipulated with scrap trade by importing scrap from developed to growing economies.

Meanwhile, the ECC values in this dissertation account for recycled content, as the recycling rates are only accurate when steel is produced from scrap in a closed cycle. The ECC of steel in this dissertation reflects the product-specific recycled content: for example, with 40% recycled content, rebar has an ECC of 2.37 kg$_{CO2e}$/kg and with 60% recycled content, structural steel (sections such as wide flange beams and hollow steel sections) has an ECC of 1.87 kg$_{CO2e}$/kg (World Steel Association, 2011).

		Primary	**Secondary**	**Structural Steel**		**Rebar Steel**	
Region	**kg$_{CO2e}$/kWh**	**kg$_{CO2e}$/kg**	**kg$_{CO2e}$/kg**	RC*	**ECC**	RC	**ECC**
Africa	0.71	3.96	1.03	56%	2.32	37%	2.86
Asia** & Oceania	0.67	3.78	0.98	62%	2.03	42%	2.61
China	1.05	5.89	1.53	24%	4.84	21%	4.97
CIS (Ex-USSR)	0.37	2.06	0.54	58%	1.18	38%	1.47
Europe	0.49	2.74	0.71	65%	1.42	43%	1.86
Latin America***	0.19	1.06	0.28	42%	0.73	28%	0.84
Middle East	0.67	3.77	0.98	90%	1.26	54%	2.26
North America	0.57	3.18	0.83	77%	1.37	51%	1.98
World	**0.60**	**3.36**	**0.87**	**60%**	**1.87**	**40%**	**2.37**

**RC = Recycled Content; **excluding China, India, CIS; ***excluding Brazil*

Table 3.6: ECC for steel in different parts of the world

As shown in Table 3.6, the ECC of steel is extremely depended on the region where it is produced, as the results are sensitive to the emissions factor (IPCC, 2016; IEA, 2016) of the energy mix (kg$_{CO2e}$/kWh) as well as to the recycled content determined by the available scrap steel in the corresponding regions (Wübbeke and Heroth, 2014; EurActiv, 2016; Recycling International, 2016; World Steel Association, 2017). The contribution of this section is to offer a transparent methodology to calculate the ECC of steel. With more accurate information on these key factors for a specific country, an adapted ECC can be found for structural steel and rebar.

To identify strategies for reducing CO_2 emissions from steel production, Milford et al. (2013) combined process emissions intensities with a global mass flow analysis to predict that the last required blast furnace will be built by 2020 if sectoral emissions are to be reduced by 50%. Scrap becoming more available in the future will significantly reduce the ECC of steel by 2050 if the steel and engineering industry works towards energy and material efficiency (Figure 3.9). Arens et al. (2016) find that currently available technologies only allow for 5% reduction of GHG emissions between 2014 and 2030. They suggest that alternative steelmaking processes need to be developed. In the meantime, incremental CO_2 reductions can be obtained through heat recovery from blast furnace slag and waste heat in electric arc furnaces, the use of by-products for the production of base chemicals, and the production of high quality steel from scrap-based secondary steelmaking. A team at MIT (Sadoway, 2017) discovered a new steelmaking process that could reduce emissions while increasing the purity in a cost-effective way if it was scaled up, while looking for ways to produce oxygen on the moon for NASA. The process is called molten oxide electrolysis and uses iron oxide (which is available in lunar soil) to make oxygen in abundance with steel as a byproduct (Allanore et al., 2013).

For more detailed ECCs, the EPDs commonly used in North America suggested by LEED come from the American Institute of Steel Construction (AISC, 2017) and give 1.16 kg_{CO2e}/kg for fabricated hot-rolled structural sections, 1.47 kg_{CO2e}/kg for fabricated steel plates, and 2.39 kg_{CO2e}/kg for fabricated hollow structural sections (HSS). This range is close to the ECC of 1.37 kg_{CO2e}/kg given for North American structural steel in Table 3.6.

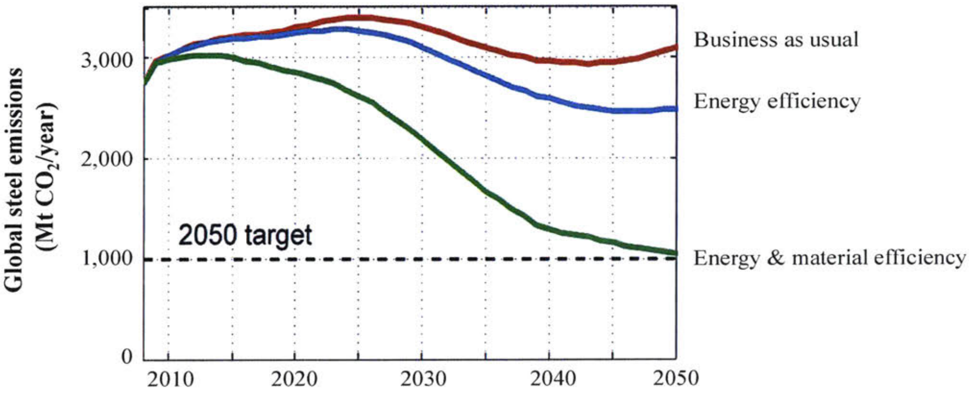


Figure 3.9: Can we meet the emissions target in the steel sector? (Milford et al., 2013)

3.2.3. *Timber*

The ECC of timber is lower for sawn lumber than engineered timber, as the latter requires extra adhesives and processing. Outputs from trees are not only the structural timber product, but also pulp chips, sawdust, shavings, wood fiber, bark, and wood fuel. The production of timber is illustrated in Figure 3.10. To calculate the embodied carbon of timber in different parts of the world, the methodology of the embodied through-life carbon dioxide equivalent assessment by Weight (2011) is followed. Two timber products are analyzed: sawn lumber and engineered timber.

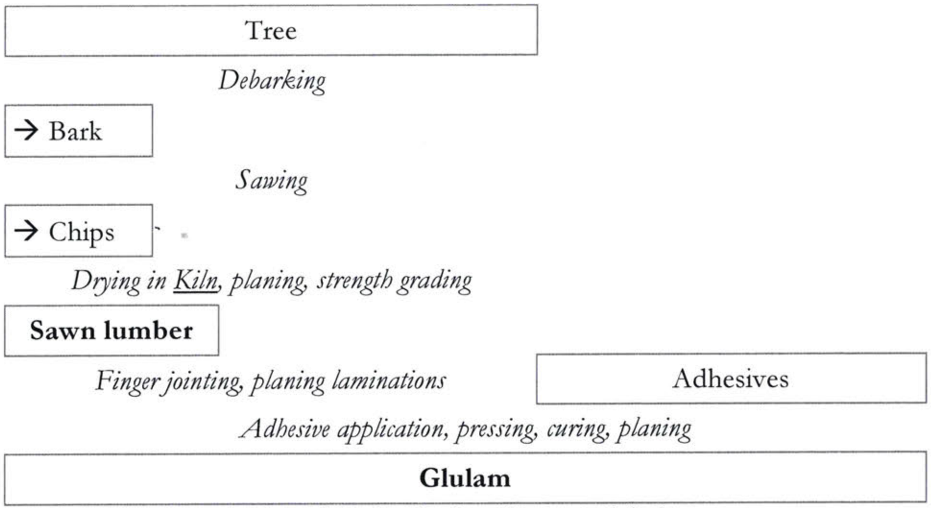


Figure 3.10: Production of structural timber

For the assumptions, the properties of Glulam are used for calculating the embodied carbon of engineered timber. Two scenarios for the end-of-life treatment are followed: landfilled and incineration for energy. Weight (2011) shows that 1 ton of wood is used to produce 292.5 kg of timber. Because the carbon content is 50-53% for softwood and 47-50% for hardwood (Ragland et al., 1991), the carbon content of wood in this calculation is 50%. By subtracting 12.75% from the 1 t of wood, corresponding to retained moisture, 50% * 87.25% *1000 kg = 436 kg of carbon contained is obtained for 1 t of wood. With the relative molecular mass of carbon being 12 and for oxygen being 16, each kg of carbon in the timber is drawn from 3.67 kg_{CO2e}. To produce 292.5 kg of timber, 3.67 kg_{CO2e}/kg_{carbon} * 436 kg_{carbon} = 1600 kg_{CO2e} has been sequestered. Normalizing by kg_{timber} and subtracting the allocation of carbon sequestration to co-products gives -5.2 kg_{CO2e}/kg_{timber} to add to the whole-life ECC of timber, *only if the wood is known to be from a sustainable source* (Weight, 2011).

Forestry processes include forestry management, sawmills, kiln use, and biofuel. Normalizing the results calculated by Weight (2011) gives 0.93 kg_{CO2e}/kg_{timber}. For transport, both the transport from sawmill to manufacturer as the transport from the manufacturer and the end-of-life treatment facility is taken into account. The road transport (sawmill to port, port to manufacturer, manufacturer to site, site to end-of-life waste treatment facility) distance of 1493 km and emissions of 0.2 kg_{CO2e}/t.km and sea transport (from Sweden) distance of 1100 km and emissions of 0.03 kg_{CO2e}/t.km give total transport emissions of 0.47 kg_{CO2e}/kg_{timber}. These contributions to the ECC of timber are held constant across different countries (Table 3.7). For more detailed calculations, this distance can be altered on a case by case basis, depending on the location of the construction site and the sourcing of the wood.

Sequestration	-5.18
Forestry Process	0.93
Transport	0.47
Landfill	3.68
Incineration for energy	1.06
Resin	0.02

Table 3.7: kg_{CO2e}/kg of different processes and products for timber, held constant across regions after data from (Weight, 2011) and (Wilson, 2010)

Weight (2011) shows that landfill emissions due to off-cuts from manufacturing and production at end-of-life of CO_2 and CH_4 are equivalent to 3.68 kg_{CO2e}/kg_{timber}, whereas incineration emissions minus the energy benefits due to incineration of the wood used as biomass are equivalent to 1.06 kg_{CO2e}/kg_{timber}. The waste indicators from the United Nations Statistics Division (UNStats, 2016) are used to determine how much timber is landfilled or incinerated in different parts of the world.

For the manufacturing of timber, a difference is made between sawn and engineered timber. The embodied energy used in manufacturing was converted to carbon using the same emissions factor (IPCC, 2016; IEA, 2016) of the energy mix (kg_{CO2e}/kWh) as for the steel ECC calculations.

For Glulam, the embodied carbon of resin was added. The amount of Melamine Urea Formaldehyde Resin (MUF) and Phenol Resorcinol Formaldehyde Resin (PRF) in a cubic meter of Glulam is described by Puettmann et al. (2013) in a CORRIM publication. Wilson (2010) gives LCI results of formaldehyde-based resins used in wood composites in terms of resources, emissions, energy and carbon. Taking 1 kg of Glulam, 0.00154 $\text{kg}_{\text{MUF}}/\text{kg}_{\text{Glulam}}$ at 1.775 $\text{kg}_{\text{CO2e}}/\text{kg}_{\text{MUF}}$ and 0.01592 $\text{kg}_{\text{PRF}}/\text{kg}_{\text{Glulam}}$ at 1.394 $\text{kg}_{\text{CO2e}}/\text{kg}_{\text{PRF}}$ give 0.2 $\text{kg}_{\text{CO2e}}/\text{kg}_{\text{Glulam}}$ to be added to the ECC of Glulam (Wilson, 2010). The results for the whole-life ECC of sawn and engineered timber are given in Table 3.8.

The ECC of timber is highly sensitive to the sourcing of the wood. The effect of deforestation can increase the figures by 5 $\text{kg}_{\text{CO2e}}/\text{kg}$ (Weight, 2011). Also, multiple scenarios are possible for the end-of-life treatment, resulting in different contributions to the ECC, as illustrated by Figure 3.11. Therefore, the examples of ECC computations given in Table 3.8 are only an approximation of the ECC of sawn and engineered timber based on the given assumptions on carbon sequestration, sustainable forest management, and end-of-life treatment.

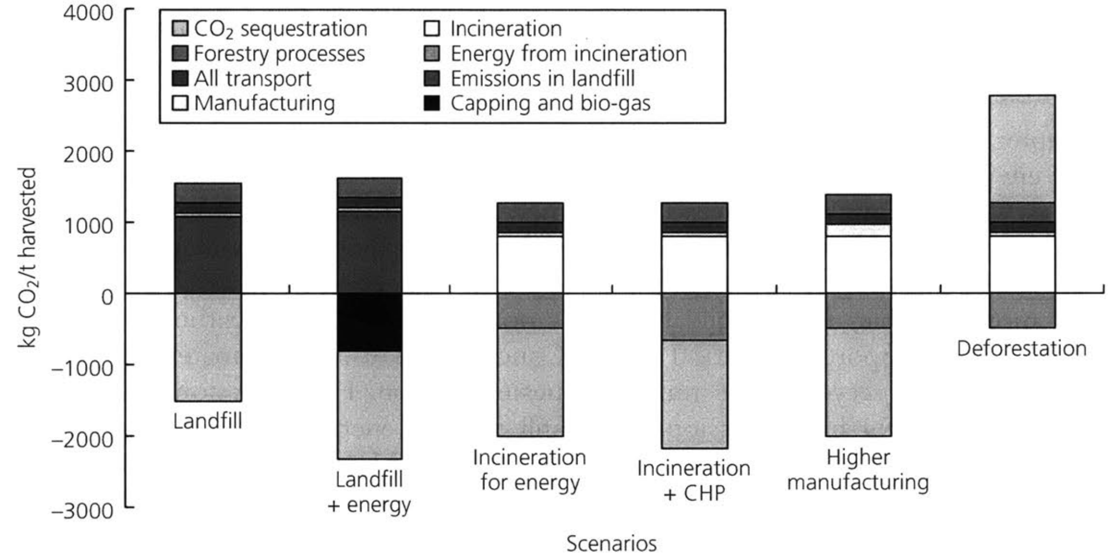


Figure 3.11: Whole life carbon flows for six end-of-life scenarios (Weight, 2011)

Region	Emissions factor (kg_{CO2e}/kWh)	End-of-life (%)		Manufacturing (kg_{CO2e}/kg)		Whole life ECC (kg_{CO2e}/kg)	
		Landfill	**Incineration for biomass**	**Sawn**	**Engineered**	**Sawn**	**Engineered**
Africa	0.71	92%	8%	0.26	0.85	-0.06	0.55
Asia & Oceania	0.67	69%	31%	0.25	0.81	-0.66	-0.08
Europe	0.49	64%	36%	0.18	0.58	-0.86	-0.42
Latin America	0.19	66%	34%	0.07	0.23	-0.93	-0.75
Middle East	0.67	96%	4%	0.25	0.81	0.03	0.61
North America	0.57	84%	16%	0.21	0.68	-0.31	0.19

Table 3.8: ECC for timber in different parts of the world with data from (UNStats, 2016)

However, because the coefficients in Table 3.8 are whole life ECCs instead of cradle-to-gate ECCs, alternative assumptions can be made to calculate cradle-to-gate ECCs of engineered timber and use them with steel and concrete cradle-to-gate ECCs.

3.3. Summary

First, this chapter assessed the state of the art in terms of ECCs, based on the ICE database from the University of Bath, the numbers used by the IE4B of the Athena Institute, GaBi, EcoInvent, and the Concrete Centre, showing a lack of uniform methodology to assess the environmental impact of structural materials. Then the detailed ECCs from the available databases were used to show the variability of concrete, steel and timber based on different strengths, rebar contents, steel types, or timber treatments.

Second, ECCs of concrete, steel, and timber were reviewed for different regions in the world. It is important to note that these ECCs should not be used to show a material is better than another. Non-aligned LCA data and high uncertainties prevent the meaningful comparison across materials. Moreover, by expressing the GHG emissions by kg of material, the ECCs are no indication of the environmental performance within a structure as the stiffness, volume, and strength vary widely from one material to another and even within the same material (depending on the concrete mix for example).

This chapter does not intend to answer the question which structural material has the "lowest" environmental impact, but aims to demonstrate the variability from one region to another as well as from one scenario to another. Also, the carbon footprint is only one impact factor next to others including toxicity, resource depletion, loss of biodiversity, etc. Different material industries and lobbies have often claimed their material is financially cheaper, more durable, more buildable, and more recently "lower carbon," as this is becoming a more important political focus. Concrete can use waste materials, steel can theoretically be fully recycled, and timber sequesters carbon. However, concrete still uses cement responsible for high emissions, steel still requires energy to re-melt and can lack available scrap steel, and timber can lead to deforestation and landfill emissions. This chapter has also shown that regional variability is high. As Purnell (2012) argued, the average embodied carbon of materials per unit volume or mass should not be used to make decisions for minimizing carbon in structures. Each case is unique.

The structural material ECCs in this chapter are placeholder numbers that can be used in approximate calculations to estimate the embodied carbon of a structure regionally at the concept stage, but are not stated in a definitive manner given the known uncertainty of these values. Other sources, such as nationally certified EPDs according to ISO 14025 will likely offer data with more advanced certainty in the future. The range of the estimated values in this chapter aligns with other LCA databases. This dissertation does not aim to perform another new LCA of individual materials, but to give a literature review on the material scale in order to determine what values can be used in calculating the embodied carbon of building structures. This chapter only intends to provide a transparent value for typical structural materials to perform calculations on the material, structural, building, and urban scale, as will be illustrated in the next chapters: Chapter 4 on the structural scale and Chapter 5 on the urban scale. Chapter 6 and 7 will then give guidelines on low carbon pathways on the material, structural, building, and urban scale.

4. Embodied carbon on the structural scale[3]

This chapter addresses the assessment of embodied carbon of structures through data collection and analysis in order to develop benchmarks. This is critical for both measuring the present-day material quantities and embodied carbon in building structures and for choosing optimal and responsible design options with a low environmental impact. This chapter discusses the development of the database of embodied Quantity outputs (deQo) in Section 4.1, the results of the database in Section 4.2, and their statistical analysis in Section 4.3.

4.1. Development of a database of building structures

This dissertation studies the Global Warming Potential (GWP) of building structures. The results are normalized by floor area in order to be compatible with other available metrics that are already calculated per floor area and because the floor area of most building projects is readily available. Normalizing entails dividing the total amount of carbon emissions by the declared unit, in this case the gross floor area. Benchmarks of embodied carbon in building structures can then be established. Section 4.1.1 discusses available benchmarking databases.

4.1.1. Existing benchmarking databases

To collect data on the operational energy of buildings, the United States Energy Information Administration (EIA) developed the Commercial Buildings Energy Consumption Survey (CBECS, 2017). A common metric for building energy consumption used in CBECS is the EUI expressed in annual energy use normalized by gross floor area (Nikolaou et al., 2015). What CBECS aims to establish in terms of benchmarking for the operational energy of buildings, deQo aims to define for the embodied carbon of building structures. This dissertation proposes the GWP expressed in kg_{CO2e}/m^2 as a metric for embodied carbon, similar to the EUI being the metric for operational energy.

The Athena Sustainable Materials Institute is incorporating Whole Building Life Cycle Assessment (WBLCA) benchmarks into IE4B (Athena, 2009). Indeed, rating schemes such as LEED now include credits to evaluate and improve the embodied carbon of a proposed building design compared that of a reference building with the same floor area and use. There is a lack of clarity on what constitutes an agreed upon reference building. Therefore, Athena Sustainable Materials Institute is developing a whole building database (Bowick, 2017) as a reference for LEED's new Building Life Cycle Impact Reduction credit (LEED, 2016). The National Institute of Standards and Technology (NIST), who also developed the BEES software, collected LCA and LCC information for commercial and multi-unit

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[3] The methodology for this chapter has been published in De Wolf, C., Yang, F., Cox, D., Charlson, A., Hattan, A., and Ochsendorf, J. (2016a) "Material quantities and embodied carbon dioxide in structures," *ICE Journal of Engineering Sustainability*, 169(ES4), 150-161, DOI: 10.1680/ensu.15.00033. The development of embodied carbon benchmarks for structures was done in collaboration with the Embodied Carbon Benchmark project led by Kathrina Simonen, with Barbara Rodriguez Droguett, at the University of Washington and supported by the Carbon Leadership Forum.

residential buildings for the Building Industry Reporting and Design for Sustainability (BIRDS, 2015) database.

The European Commission developed the European Sustainability and Performance assessment and benchmarking of buildings (SuPerBuildings) Project (Häkkinnen, 2012). The project summarizes the typical GHG emissions reported by various European countries as well as the data quality of the benchmarks. The European database is mainly composed of results from the German and French databases.

The German Sustainable Building Council or Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB, 2017) Certification System developed LCA benchmarks for theoretical archetypes of offices, industrial, and residential buildings. They offer a target value around 12 $kg_{CO2e}/(m^2\text{-}yr)$ and a limit value around 24 $kg_{CO2e}/(m^2\text{-}yr)$ over a life span of 50 years including structure and envelope. The reference value multiplied with this lifespan is 850 kg_{CO2e}/m^2. While DGNB uses archetypes, deQo collects data from real, existing buildings.

In France, the rating scheme Haute Qualité Environnementale (HQE, 2012) developed the project "Construisons Ensemble HQE Performance" to benchmark the LCA results for buildings according to EN 15978. Median values range from 8 to 13 $kg_{CO2e}/(m^2\text{-}yr)$ for the equipment, products, and materials over a life span of 50 years (Dodd et al., 2016). The reference values multiplied with the considered life span gives a range of 400 to 650 kg_{CO2e}/m^2. Where the German benchmarks are based on theoretical archetypes, the French benchmarks are based on the LCA results of the buildings applying for the HQE label. While HQE uses only buildings that applied for the environmental label and therefore might be biased, deQo collects all building structures whether they received a certification or not.

Existing benchmarks are not always aligned in terms of building components included. Therefore, the scope of deQo is structure only, excluding non-structural façades, mechanical equipment, and interior finishes.

4.1.2. Development of deQo

DeQo (2017) was developed to offer a uniform, transparent database of existing building structures. This relational database has an online interactive interface for collecting data on the SMQ and embodied carbon in structures from industry. The framework and features of the database are explained in detail in Appendix D.

The main aims of the relational database are the following:

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

In deQo, the GWP is defined as the cradle-to-gate embodied carbon results for the building structures illustrated in Equation 4.1. As the database collects data on building structures, the scope corresponds to the highest contribution to the whole life cycle impact. Moreover, the collection of SMQ allows for an easy transition to further life cycle stages and building layers. The database has been developed in a way that allows for the future expansion to a WBLCA database.

$$\mathrm{GWP} = \sum_{i=1}^{N} \mathrm{SMQ}_i \times \mathrm{ECC}_i \qquad \text{Equation 4.1}$$

where:

i	a particular component or material in the building structure $i = 1, 2, 3$, etc., N
GWP	Global Warming Potential (kg_{CO2e}/m^2)
SMQ_i	Structural Material Quantities (kg_m/m^2)
ECC_i	Embodied Carbon Coefficients (kg_{CO2e}/kg)

Common metrics to normalize results for buildings are the gross floor area (m^2), net floor area (m^2), area and lifespan (m^2-yr), number of occupants, and number of occupants per year. The results in this dissertation are normalized by gross floor area, but the other metrics are also collected and allow for the evaluation of data normalized by these other metrics.

Figure 4.1 shows the development steps of deQo. First, the goal and scope of deQo was defined through interviews and focus groups with industry partners and through the literature review discussed in Chapter 1 and Chapter 2. Several interviews were conducted with leading experts in embodied carbon assessment in structural engineering companies to evaluate the needs.

Second, contributing industry partners tested the interactive web-based interface created during the pilot phase. An advisory committee was constituted by two leading civil engineering companies: Arup (2017) and Thornton Tomasetti (2017).

Third, these industry partners began the initial data collection. The data collection was based on contributions from both companies as well as from published LCA literature, other structural design firms, and institutions such as the Council on Tall Buildings and Urban Habitat (CTBUH). The advisory committee then gave feedback on the parameters used to collect data, which led to improvements in the interactive interface.

Fourth, the SMQ and GWP results were displayed in aggregated form through box-and-whisker plots (See Figure 4.15, Section 4.2). A data quality matrix evaluated the data collected on a larger scale.

Finally, an uncertainty analysis determined potential errors and a statistical analysis evaluated the findings. A non-parametric statistical analysis of potential correlations was performed on the data.

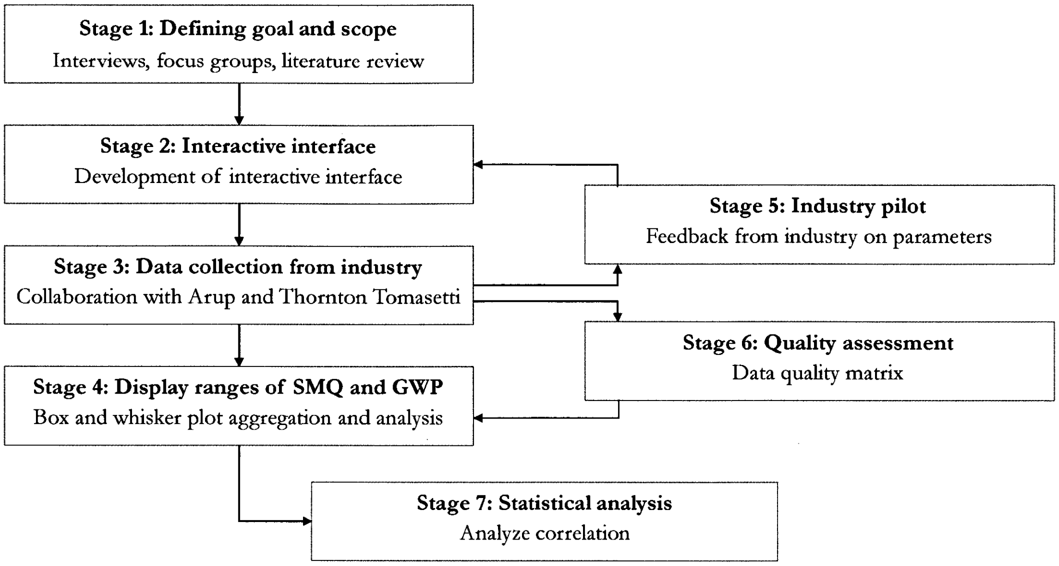


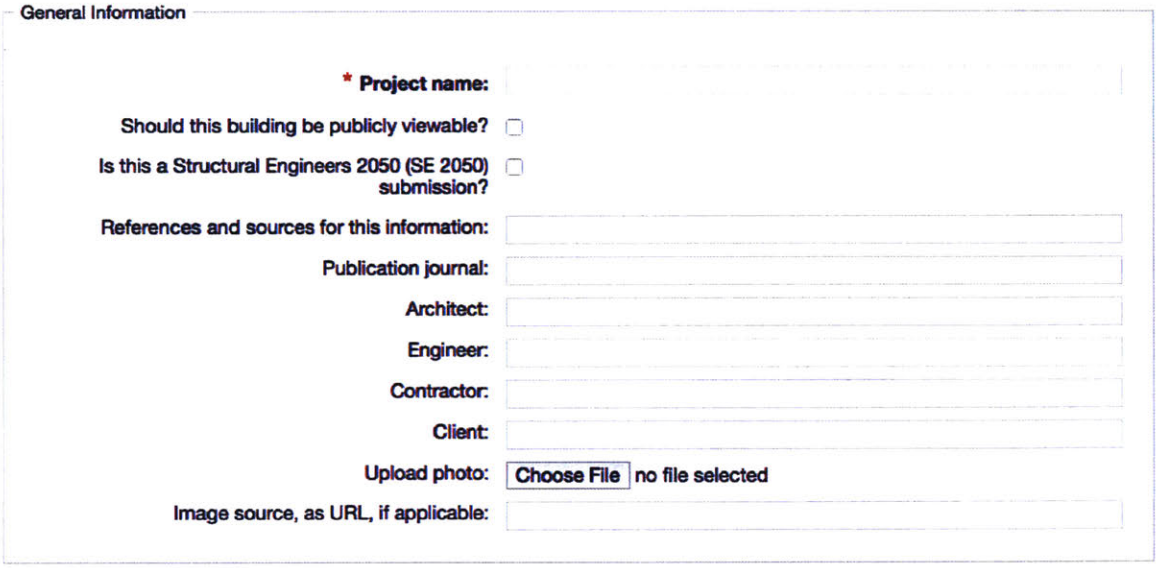
Figure 4.1: Development of deQo

This dissertation addresses the gap in literacy on structural material quantities and embodied carbon of building structures through the development of this database.

4.1.3. Contributing structural projects to deQo

After registering as a user, the interface of deQo can be used online to input data on building structures. The user fills in a form developed in cooperation with stakeholders such as structural design firms, the Carbon Leadership Forum (CLF), the Athena Sustainable Materials Institute, and the United States Green Building Council (USGBC). Red stars indicate mandatory fields; other fields are optional. Figure 4.2 illustrates the general information asked by deQo: Project name, Architect, Engineer, Contractor, Client, etc. The form also asks if the submission is made for the SE 2050 (2017) Commitment. This can later be used as a filter in displaying the results. This commitment will be explained in more detail in Chapter 6.

Figure 4.3 shows the fields for building location, building status, and building program type. The regions include Africa, Asia, Oceania, Europe, Middle East, North America, and South America. When the regions are selected, the corresponding country is chosen from a list of countries in the selected region. Then the city or detailed location of the construction site is entered manually by the user. The building status includes the construction completion year. The project phase is asked so that the results can be filtered by existing buildings (discussed in this dissertation) or theoretical buildings. The project phase can then be picked from the following phases: concept design, developed design, technical design, fabrication design, construction, and in-use. The building program type is chosen amidst the following categories: Residential, Commercial, Industrial, Infrastructure, Other Non-Residential, and Mixed use. The number of full time occupants is asked. When stadiums are selected as the building program type, the number of seats is also asked. For residential buildings, the number of housing units is asked.


General Information

* Project name:

Should this building be publicly viewable? ☐

Is this a Structural Engineers 2050 (SE 2050) submission? ☐

References and sources for this information:

Publication journal:

Architect:

Engineer:

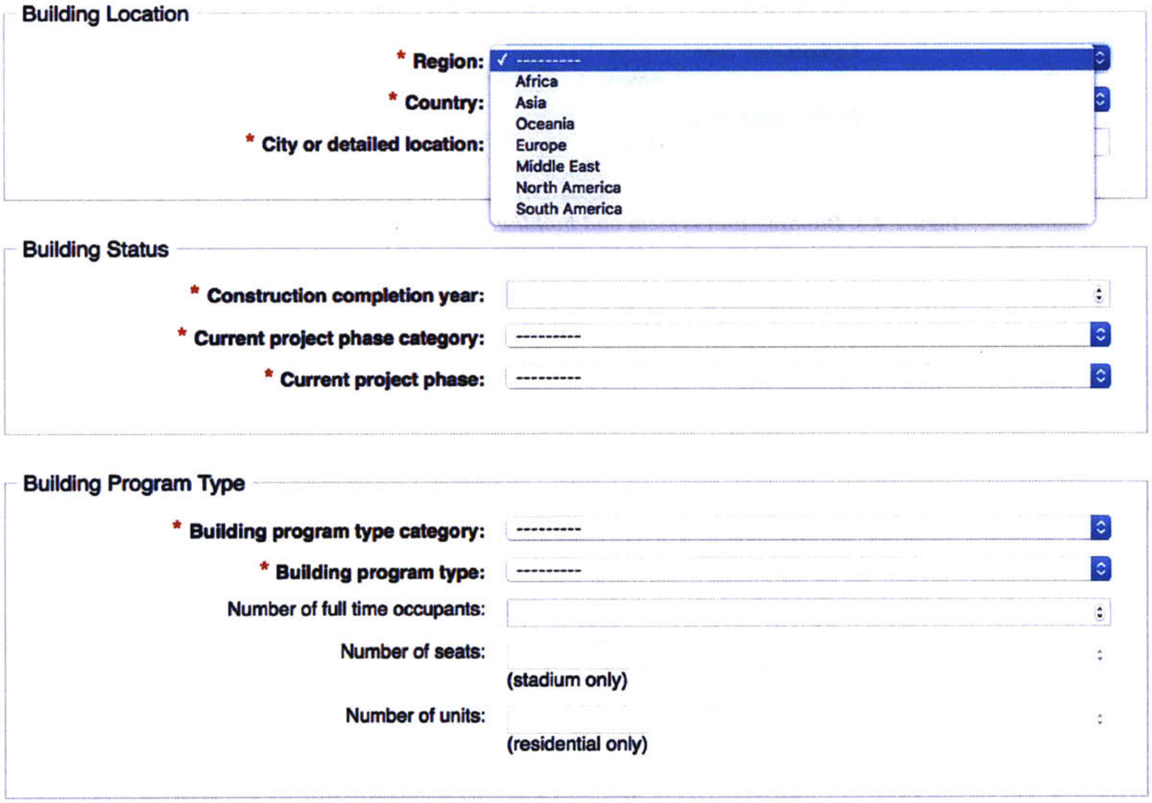
Contractor:

Client:

Upload photo: Choose File no file selected

Image source, as URL, if applicable:

Figure 4.2: General information asked in the interactive interface of deQo


Building Location

* Region: ✓ ---------
- Africa
- Asia
- Oceania
- Europe
- Middle East
- North America
- South America

* Country:

* City or detailed location:

Building Status

* Construction completion year:

* Current project phase category: ---------

* Current project phase: ---------

Building Program Type

* Building program type category: ---------

* Building program type: ---------

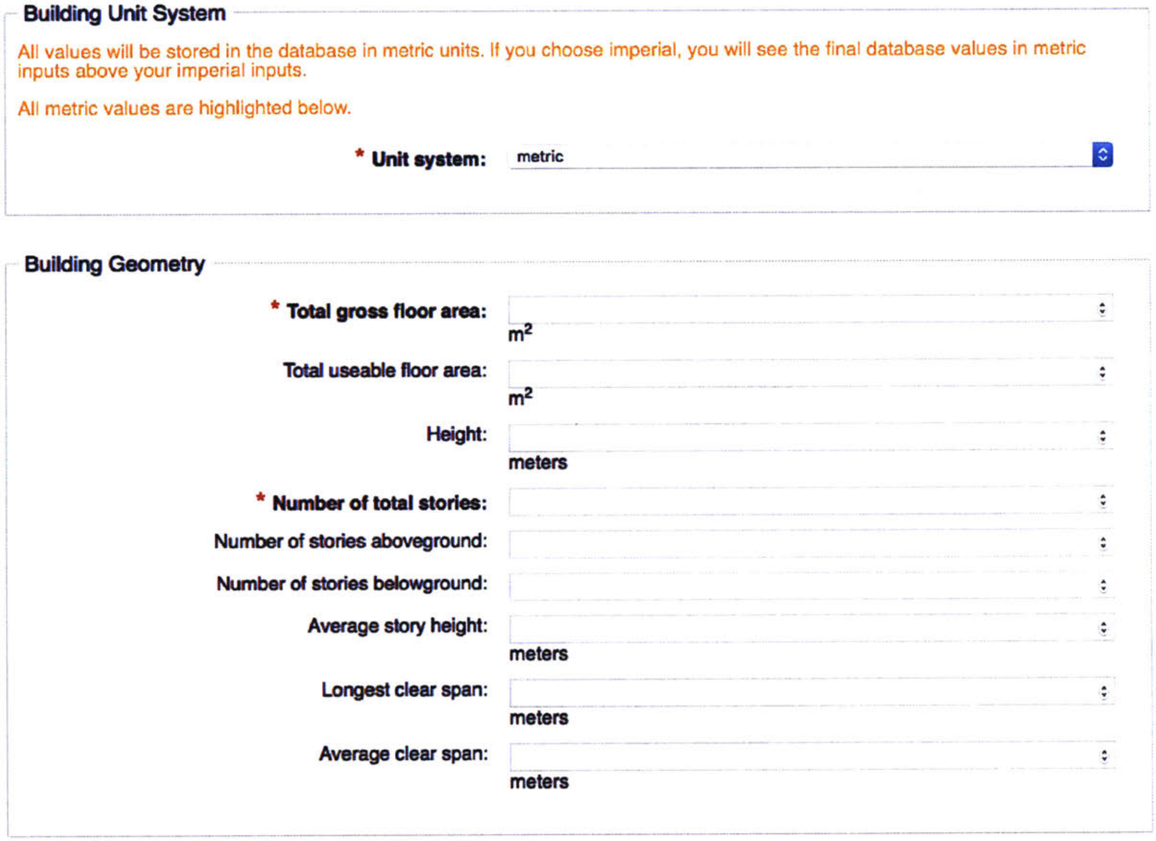
Number of full time occupants:

Number of seats: (stadium only)

Number of units: (residential only)

Figure 4.3: Building location, status, and program type asked in deQo

Then, the building unit system is requested (Figure 4.4) so that the user can enter data in metric (also known as the International System of Units or SI Units) or imperial (also known as British Imperial) units. The building geometry is collected with important fields such as the total floor area (m^2 or ft^2) and number of total stories. Other information such as average story height, longest and average clear span is optional.


Building Unit System

All values will be stored in the database in metric units. If you choose imperial, you will see the final database values in metric inputs above your imperial inputs.

All metric values are highlighted below.

* Unit system: metric

Building Geometry

* Total gross floor area: m2

Total useable floor area: m2

Height: meters

* Number of total stories:

Number of stories aboveground:

Number of stories belowground:

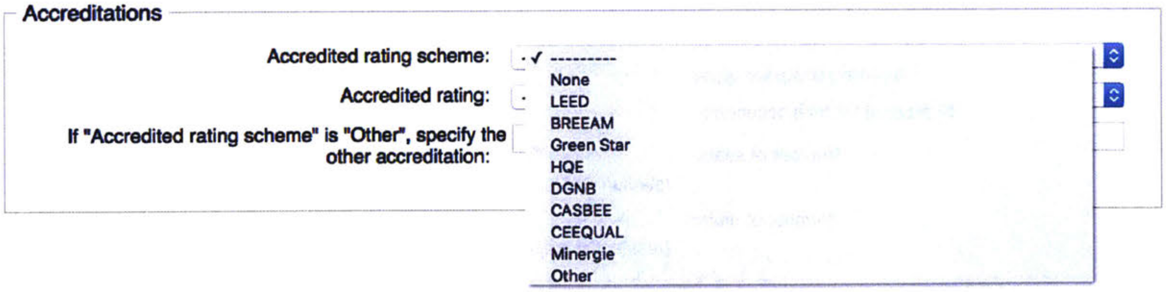
Average story height: meters

Longest clear span: meters

Average clear span: meters

Figure 4.4: Building unit system and building geometry asked in deQo

The affiliation with accreditation schemes is are also collected in deQo (Figure 4.5). For each accredited rating scheme, the corresponding accredited rating is selected. For example, for LEED, the user needs to input if it is LEED Certified, LEED Silver, LEED Golden or LEED Platinum. The user can also manually enter a rating if the rating scheme is not given in the list.


Accreditations

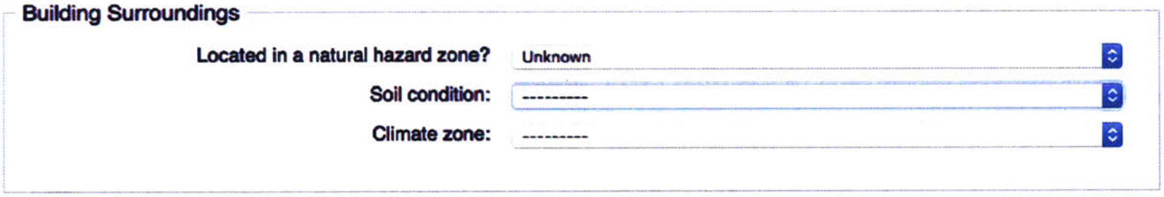
Accredited rating scheme: ✓ ---------

Accredited rating:

If "Accredited rating scheme" is "Other", specify the other accreditation:

Figure 4.5: Accreditations asked in deQo

Figure 4.6 shows the questions related to the building surroundings such as earthquake zones, soil conditions, and climate zones. This could potentially be filled in by default based on the detailed location if connected to weather, soil, and hazard zone databases.



Building Surroundings

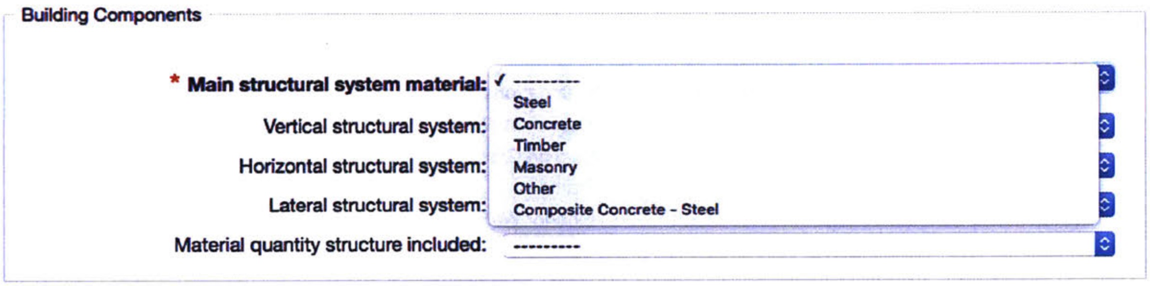
Located in a natural hazard zone? Unknown

Soil condition: ---------

Climate zone: ---------

Figure 4.6: Building surroundings asked in deQo

In Figure 4.7, the main structural material is requested. Then, the vertical, horizontal, and lateral structural systems are registered.



Building Components

* Main structural system material: ✓ ---------

Vertical structural system:

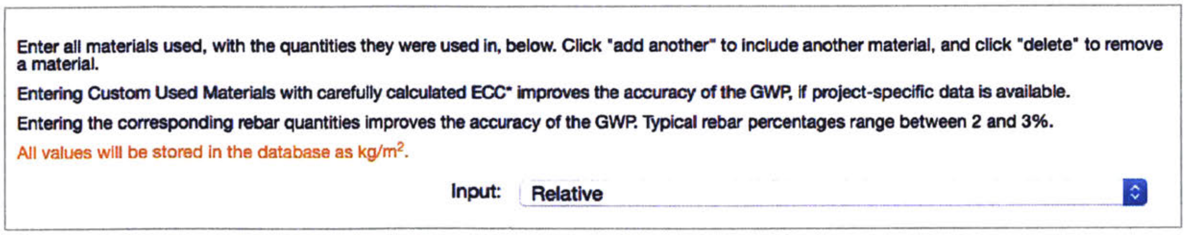
Horizontal structural system:

Lateral structural system:

Material quantity structure included: ---------

Figure 4.7: Building components asked in deQo

Then, the material quantities are collected. The user can input data in relative (kg/m^2) or absolute quantities (kg) (Figure 4.8). The absolute quantities are immediately divided by the entered floor area (m^2). The user can also choose to input material quantities by weight (kg) or volume (m^3). Two options are available to the user: select materials from the database (Figure 4.9) or enter custom materials (Figure 4.10). Both options need to define a material category: concrete, steel, timber, masonry, other, and rebar. For the predefined materials, the material specifications are picked by the user among a list of materials for the selected material category. These materials have predefined ECCs. The amount of materials is then entered and the structural building component corresponding to this quantity is selected (foundations, basement walls, slab on grade, frame, exterior walls, stairs and ramps, floor construction, roof construction, other). The non-structural building components are also given to potentially expand to a WBLCA database in collaboration with Athena Sustainable Materials Institute to be used by the LCA community for entire buildings. Materials can be removed or added. When concrete is selected as a material category, two extra options appear: precast concrete and adding reinforcement. When precast concrete is selected, the ECC is adapted according to Hammond and Jones (2010). The rebar can be added in percentage or as an extra material in kg or m^3.



Enter all materials used, with the quantities they were used in, below. Click "add another" to include another material, and click "delete" to remove a material.

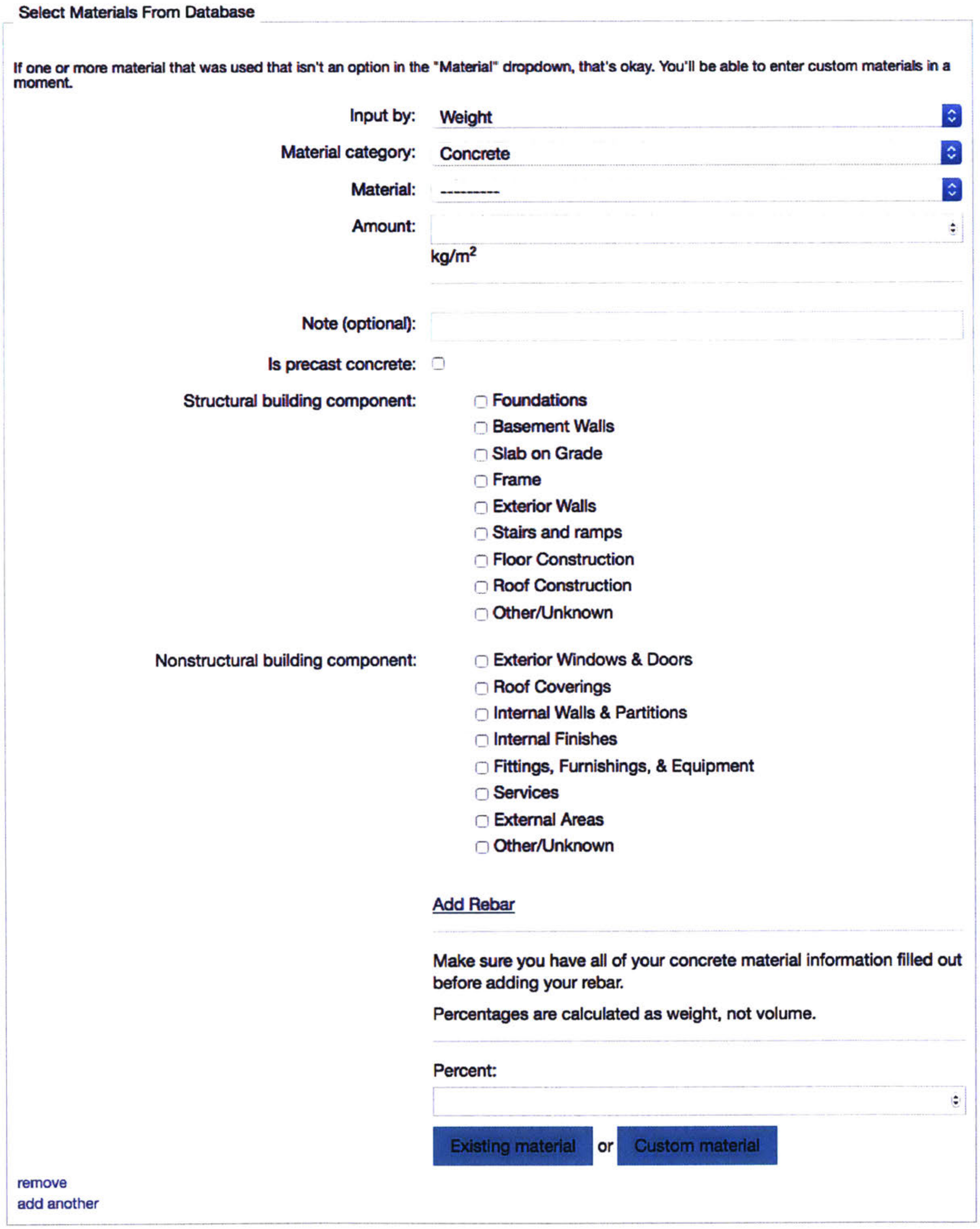
Entering Custom Used Materials with carefully calculated ECC* improves the accuracy of the GWP, if project-specific data is available.

Entering the corresponding rebar quantities improves the accuracy of the GWP. Typical rebar percentages range between 2 and 3%.

All values will be stored in the database as kg/m^2.

Input: Relative

Figure 4.8: Materials can be entered as relative or absolute quantities



Select Materials From Database

If one or more material that was used that isn't an option in the "Material" dropdown, that's okay. You'll be able to enter custom materials in a moment.

Input by: Weight

Material category: Concrete

Material: ---------

Amount:

kg/m^2

Note (optional):

Is precast concrete: ☐

Structural building component:
- ☐ Foundations
- ☐ Basement Walls
- ☐ Slab on Grade
- ☐ Frame
- ☐ Exterior Walls
- ☐ Stairs and ramps
- ☐ Floor Construction
- ☐ Roof Construction
- ☐ Other/Unknown

Nonstructural building component:
- ☐ Exterior Windows & Doors
- ☐ Roof Coverings
- ☐ Internal Walls & Partitions
- ☐ Internal Finishes
- ☐ Fittings, Furnishings, & Equipment
- ☐ Services
- ☐ External Areas
- ☐ Other/Unknown

Add Rebar

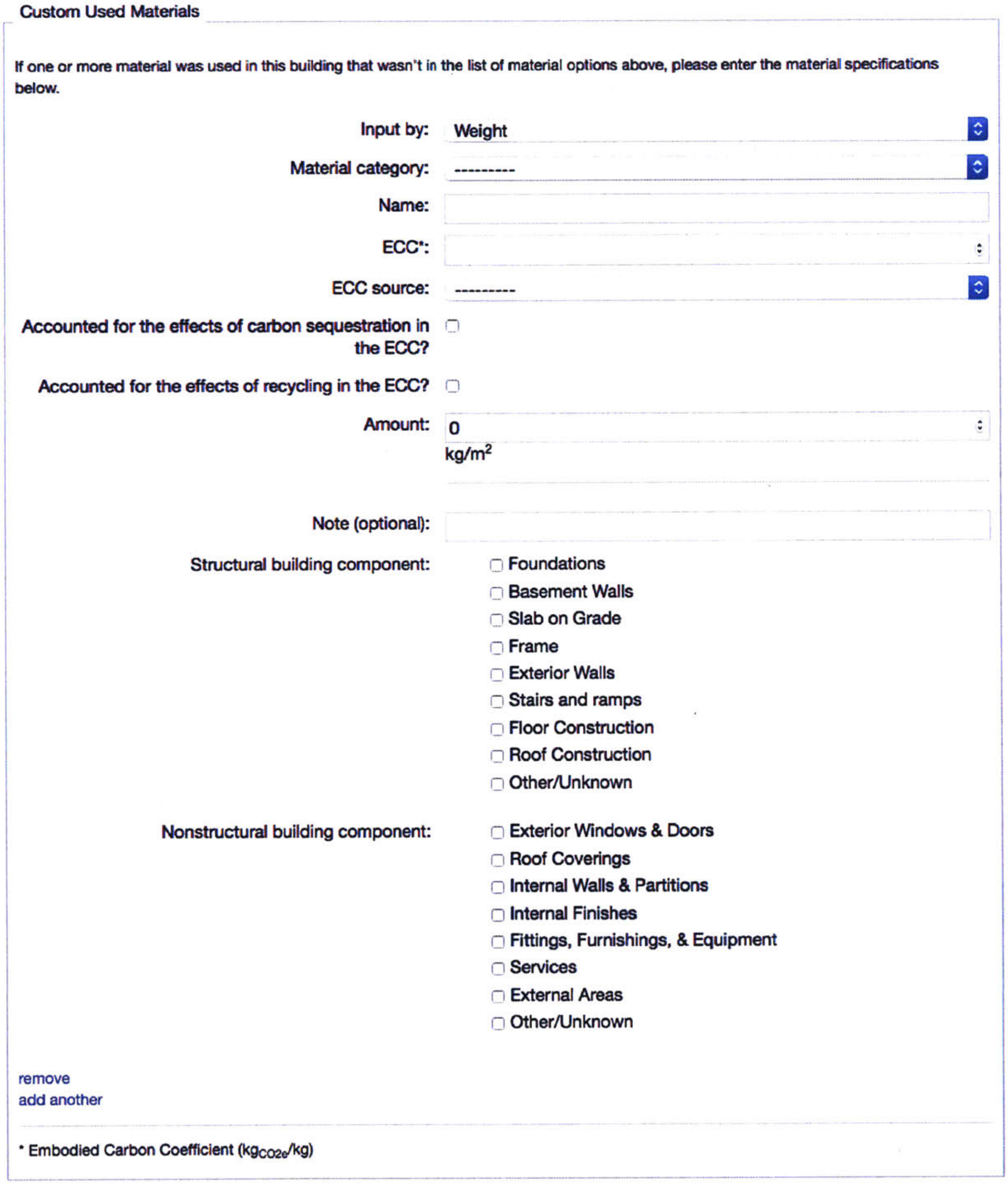
Make sure you have all of your concrete material information filled out before adding your rebar.

Percentages are calculated as weight, not volume.

Percent:

Figure 4.9: Selecting materials from the database

For the custom materials, the user must define the name and ECC of each material. The ECC source is selected from a list and questions such as whether carbon sequestration and recycling has been accounted for are asked to ensure comparability. These user-defined custom materials can be approved by the administrators of deQo in order to show up in the list of predefined materials.



Custom Used Materials

If one or more material was used in this building that wasn't in the list of material options above, please enter the material specifications below.

Input by: Weight

Material category: ---------

Name:

ECC*:

ECC source: ---------

Accounted for the effects of carbon sequestration in the ECC? ☐

Accounted for the effects of recycling in the ECC? ☐

Amount: 0 kg/m^2

Note (optional):

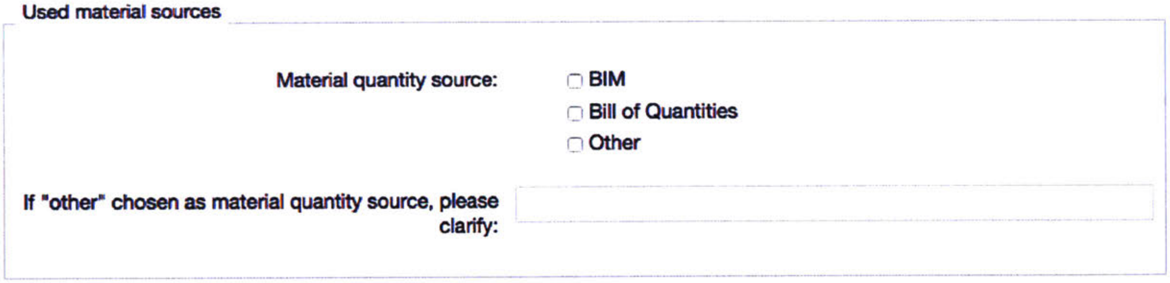
Structural building component:
- ☐ Foundations
- ☐ Basement Walls
- ☐ Slab on Grade
- ☐ Frame
- ☐ Exterior Walls
- ☐ Stairs and ramps
- ☐ Floor Construction
- ☐ Roof Construction
- ☐ Other/Unknown

Nonstructural building component:
- ☐ Exterior Windows & Doors
- ☐ Roof Coverings
- ☐ Internal Walls & Partitions
- ☐ Internal Finishes
- ☐ Fittings, Furnishings, & Equipment
- ☐ Services
- ☐ External Areas
- ☐ Other/Unknown

* Embodied Carbon Coefficient (kg_{CO2e}/kg)

Figure 4.10: Custom materials entered by the user

The source for the material quantities is also requested: BIM models, Bill of Quantities, or others (Figure 4.11).



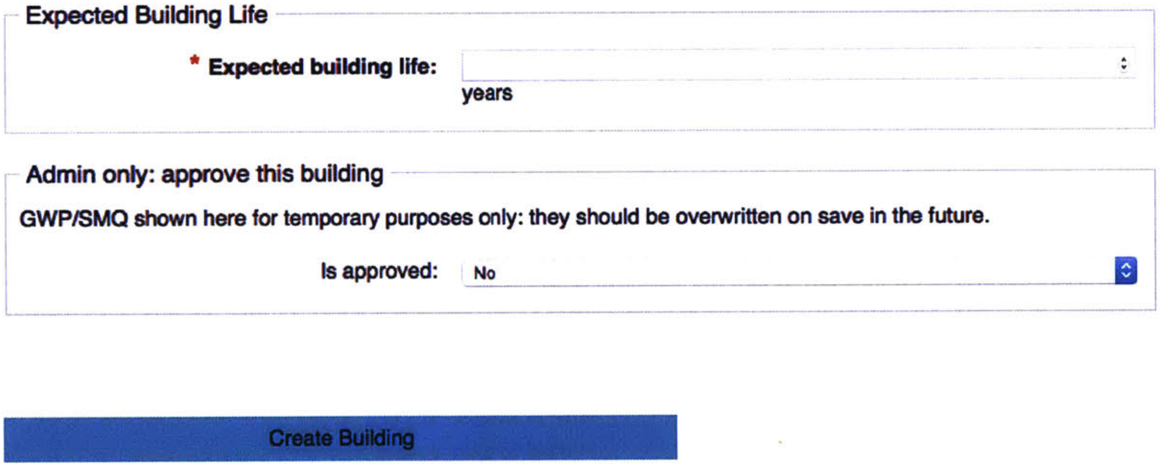
Used material sources

Material quantity source:
☐ BIM
☐ Bill of Quantities
☐ Other

If "other" chosen as material quantity source, please clarify:

Figure 4.11: Sources for the entered material quantities

Finally, the last question in the form is the expected building life (Figure 4.12). This will mainly be used when expanding the database to a WBLCA database. The administrators of deQo need to approve all buildings before they are included in the boxplots that show the ranges of SMQ and GWP for all buildings in the database. This enables administrators to eliminate erroneous data and perform an uncertainty analysis before including the project in the end results.



Expected Building Life

* Expected building life: years

Admin only: approve this building

GWP/SMQ shown here for temporary purposes only: they should be overwritten on save in the future.

Is approved: No

Figure 4.12: Expected building life and end of the form in deQo

4.2. Results of deQo Survey

This section details 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 and Thornton Tomasetti through the deQo interface.

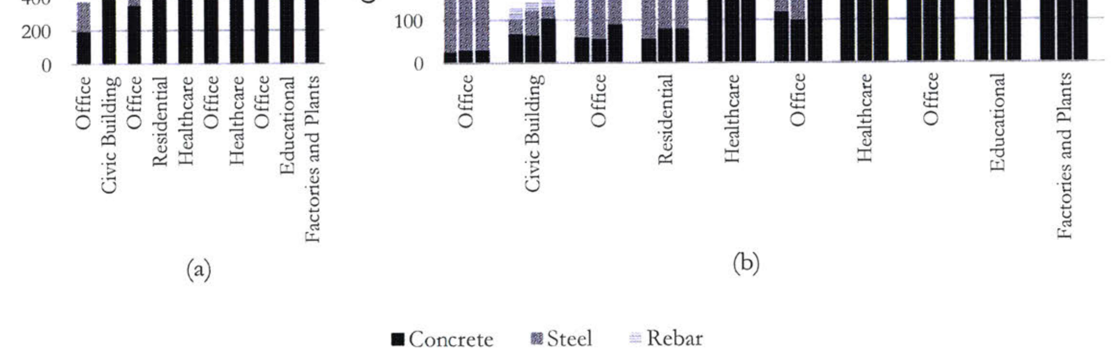
Figure 4.13.a illustrates the approach for ten sample projects of the deQo database in Europe and North America, with the concrete, structural steel and rebar quantities, ranked from low to high SMQ. The results for the GWP of the ten building projects can be obtained by multiplying the material quantities with the appropriate ECCs according to the location of each building. Though there is some correlation between quantities and carbon outputs, the structural systems and material choices also matter for lowering the GWP of the building projects. Because steel has a higher ECC than concrete, the contribution of the

different materials to the total GWP result shifts compared to the material quantity analysis. Hence, these GWP charts give a better understanding of the environmental impacts of the structures.

To illustrate the sensitivity of the embodied carbon end results to the assessor's choice of ECC, Figure 4.13.b shows results for three cases:

- using the ECCs defined in Chapter 3 corresponding to the strength and region of the material specification;
- using the lowest ECCs corresponding to the NRMCA and AISC published EPDs for North American projects and to the ICE database for European projects;
- using the highest ECCs corresponding to the NRMCA and AISC published EPDs for North American projects and to the ICE database for European projects.

The GWP results show a relatively high sensitivity to the choice of ECC (Figure 4.13). The variation can be as small as 5 kg_{CO2e}/m^2 and as high as 150 kg_{CO2e}/m^2. This motivates the approach of this dissertation to collect material quantities rather than the end result for embodied carbon in buildings, as is done in recent benchmarking projects such as WRAP (2017) and the Embodied Carbon Benchmark (ECB) Study (Simonen et al., 2017a; Simonen et al., 2017b). As demonstrated in Chapter 3, the field of embodied carbon on the material scale still needs to mature in the manufacturing industry. Chapter 6 will illustrate the national and regional efforts for collecting uniform EPDs that will define more accurate ECCs for each product in different countries. The database developed in this dissertation, deQo, provides material specifications where the user enters material quantities. When the construction industry and embodied carbon field will have matured towards more accurate ECCs for all structural materials, it will be possible to have more accurate ranges for the embodied carbon of building structures. Therefore, this dissertation will always show the ranges of material quantities alongside the ranges of calculated embodied carbon. This provides greater transparency for users.



(a) (b)

Figure 4.13: SMQ (a) and GWP with sensitivity to ECC (b) for 10 case studies in deQo

Due to intellectual property concerns, the following results for 600 projects obtained from industry are shown in aggregated format. The compiled results are encompassed in a confidential database to protect privacy and non-disclosure agreements. To protect the intellectual property rights of the data, data visualization can aggregate the data in ranges when publishing the results and take out the results for ranges that contain less than a certain amount of buildings (Howard and Sharp, 2010; Mathew et al., 2015).

The projects are not only analyzed by program type, but also by main material for the structural system (concrete, steel, timber, masonry, composite), size (floor area), height (skyscraper versus low-rise), number of occupants, span, or rating scheme certification (Figure 4.14).

Program Category
Program

Accredited Rating Scheme
Accredited Rating

Region
Country

Main Structural Material

Number of stories
Number of Occupants
Floor Area (m²)

Average clear span
Longest clear span

Figure 4.14: Different ranges plotted with deQo

The box-and-whiskers graphical representation facilitates the visualization of the ranges, with median, upper and lower quartiles, minimum and maximum, and outliers. It was first introduced by Tukey (1977). Figure 4.15 illustrates how a Tukey box-and-whisker plot is constructed.

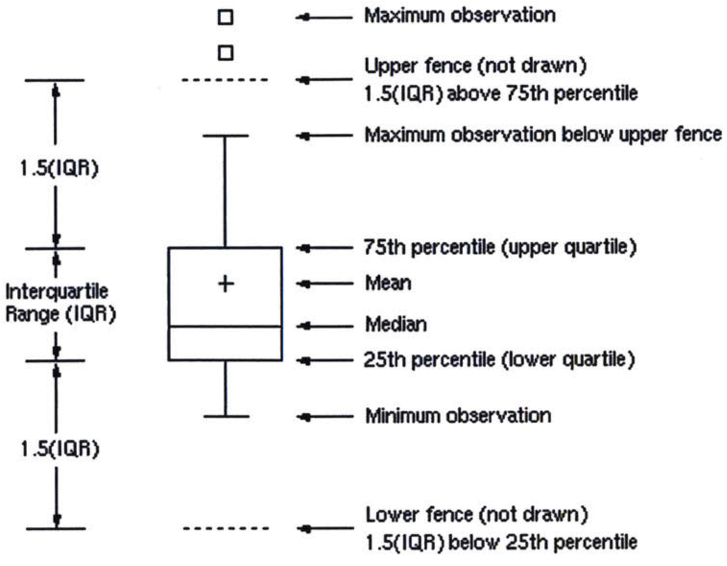


Figure 4.15: Schematic box-and-whisker plot (SAS/STAT(R), 2017)

Figure 4.16 illustrates what is displayed in a boxplot. Next to the median, the quartiles at 25% and 75% are calculated (Q1 and Q3 respectively). The interquartile range (IQR) is calculated by subtracting Q1 from Q3. The upper whisker marks the maximum value of observations under the upper fence Q3+1.5*IQR. The lower whisker marks the minimum value of the observations above the lower fence Q1–1.5*IQR. The outliers are all projects that are outside the upper and lower fences.

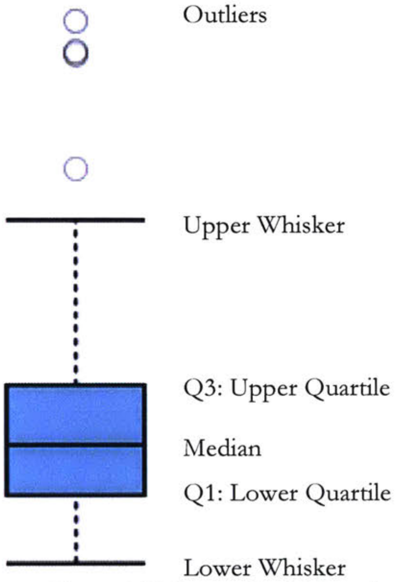


Figure 4.16: Box-and-whisker plot

4.2.1. Embodied carbon for different building uses

Figure 4.17 shows the SMQ, normalized by floor area and expressed in kg of material per square meter; and Figure 4.18 the GWP, normalized by floor area and expressed in kg_{CO2e}/m^2. The boxes give the standard ranges around the median indicated by the middle line. The buildings have been classified per program type. The number below the different programs indicates the number of projects in that category. Residential buildings have the lowest SMQ with a median value of 605 kg/m^2 and the lowest GWP with a median value of 265 kg_{CO2e}/m^2 while industrial buildings have the highest SMQ with a median value of 1,682 kg/m^2 and the highest GWP with a median value of 784 kg_{CO2e}/m^2. Normalized by floor area, industrial buildings typically use three times more structural material than residential buildings. Only four industrial projects were observed in the database, including heavy plants and factories.

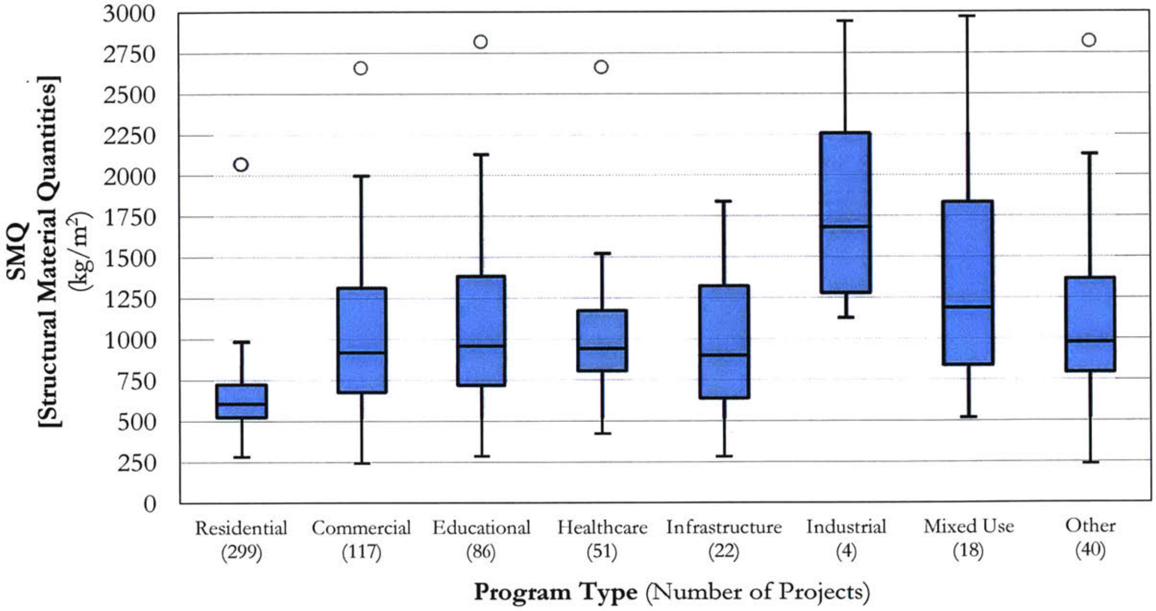


Figure 4.17: SMQ of buildings per program type

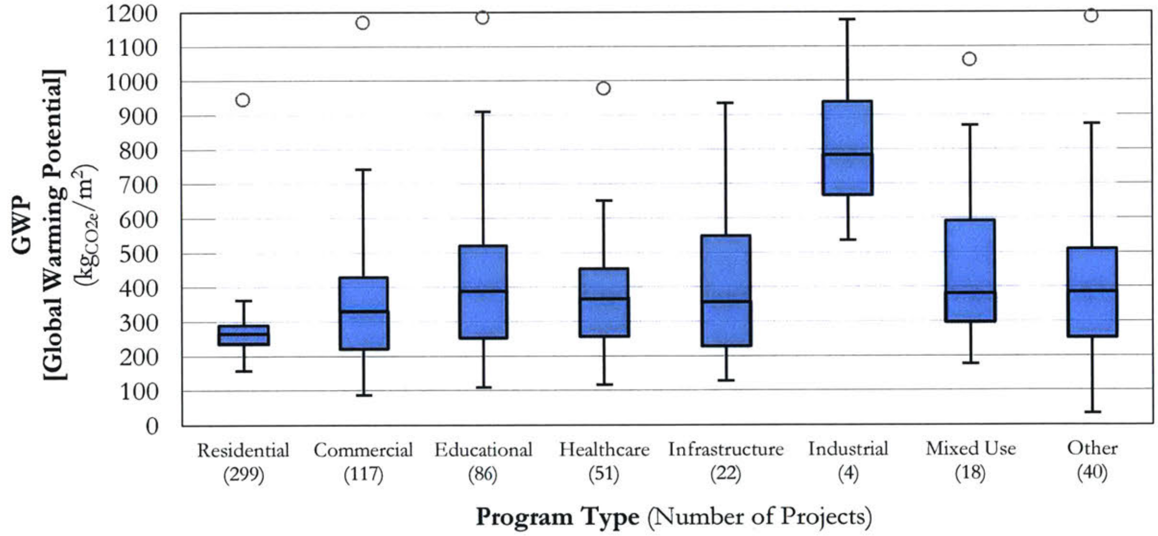


Figure 4.18: GWP of buildings per program type

4.2.2. Structural material systems

In Figure 4.19 and Figure 4.20, the x-axis shows the main material used in the structural system. In these figures, the outliers have been omitted. It should be noted that the "structure types" concrete, steel, timber, masonry, and concrete-steel are describing the main structural material. Nevertheless, the total SMQs and the total GWP include all the materials present in the structure. For example, a reinforced concrete structure will count towards the ranges for concrete structural systems, but its results include both the concrete and rebar quantities and the embodied carbon for the entire structure. Steel structures typically have lower material quantities than concrete structures, but the higher ECC of steel leads to a similar GWP among typical concrete, steel, and composite concrete-steel structures. The masonry and timber structures typically have smaller ranges, which are below the medians of concrete and steel structures. However, it is still possible to achieve low carbon buildings with all structural material systems, as the lower bounds for all structural material systems lies around 244 kg/m^2 for the SMQ (steel building) and around 47 kg$_{CO2e}$/m^2 for the GWP (timber building).

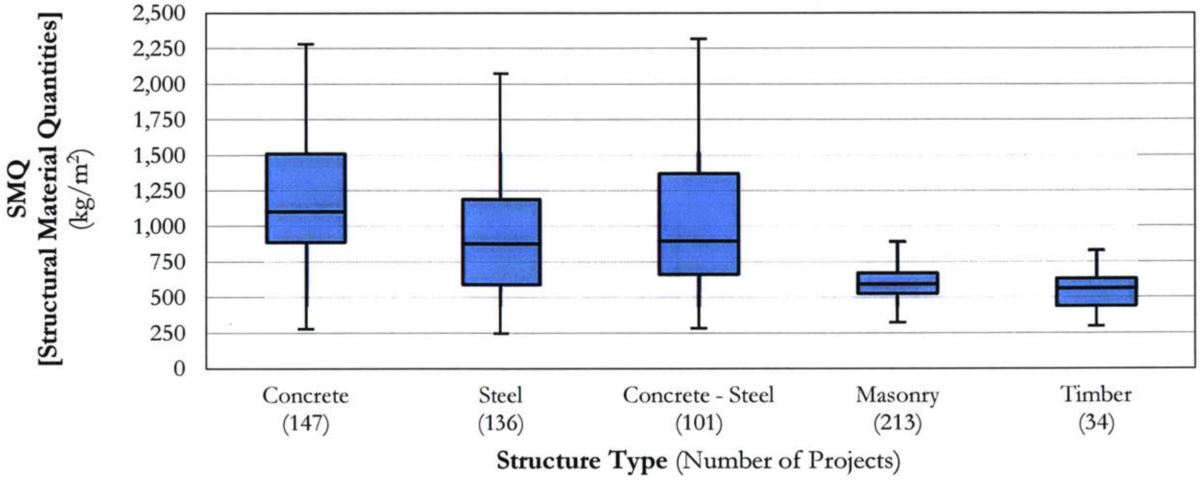


Figure 4.19: SMQ of buildings per structure type

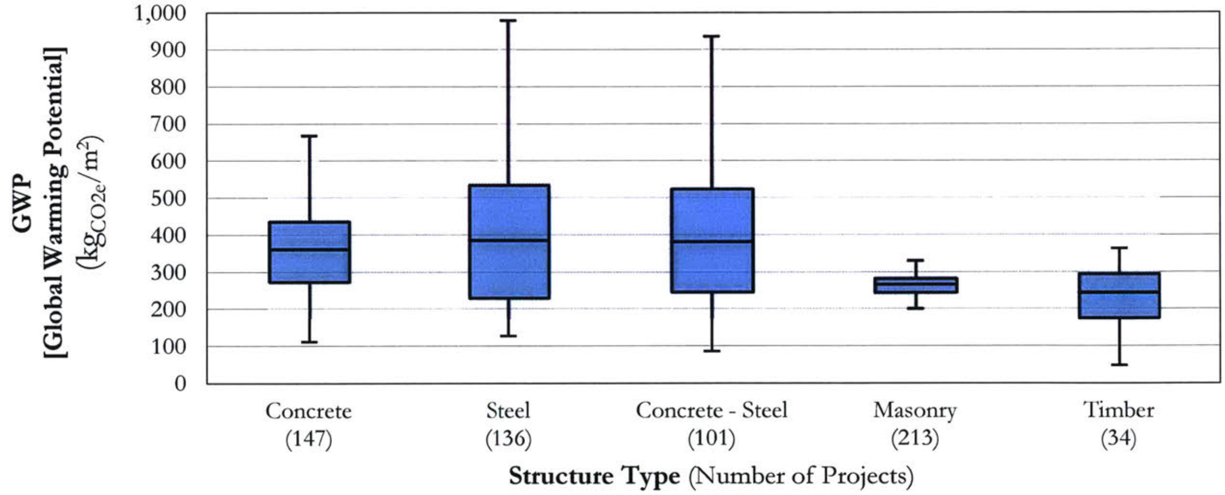


Figure 4.20: GWP of buildings per structure type

4.2.3. Embodied carbon versus size

Sorting the categories by total gross floor area can also enable the comparison of different project sizes, as shown in Figure 4.21 and Figure 4.22. The results were divided into groups according to the total gross floor area. The results show a significant increase in SMQ and GWP with the size of buildings. While small buildings (< 1000 m^2) typically range between 250 and 290 kg$_{CO2e}$/m^2, large buildings (>100,000 m^2) typically range between 276 and 495 kg$_{CO2e}$/m^2.

Compared to the results published in De Wolf et al. (2016a) of the first 200 projects added to the database, the smaller buildings increased from 31 to 230 building projects. The trends in the boxplots are still comparable, but the ranges became tighter for categories that have new building data. Moreover, a data quality assessment was performed to avoid extreme outliers from the data collected in 2016.

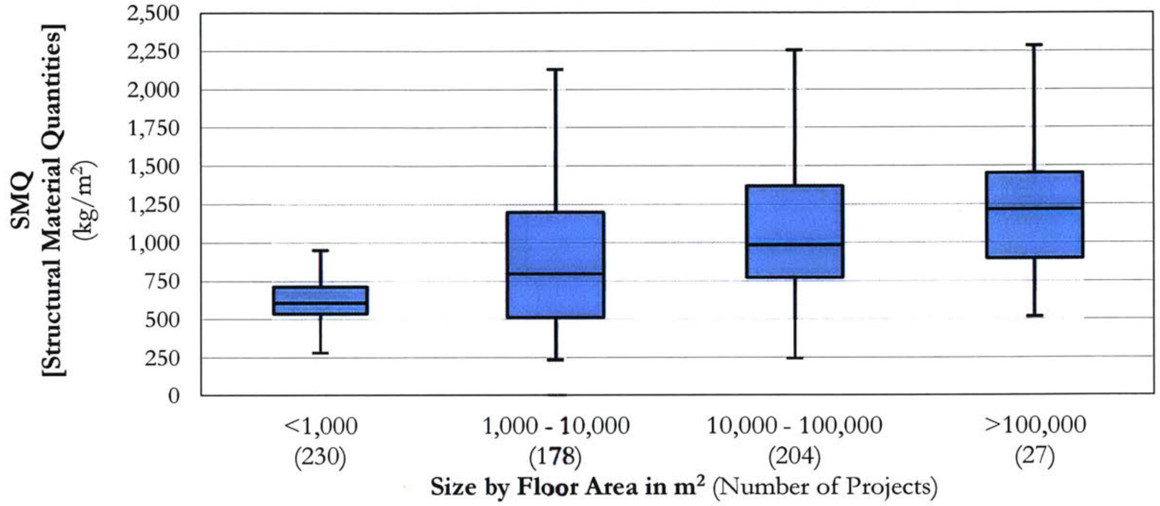


Figure 4.21: SMQ of buildings by size

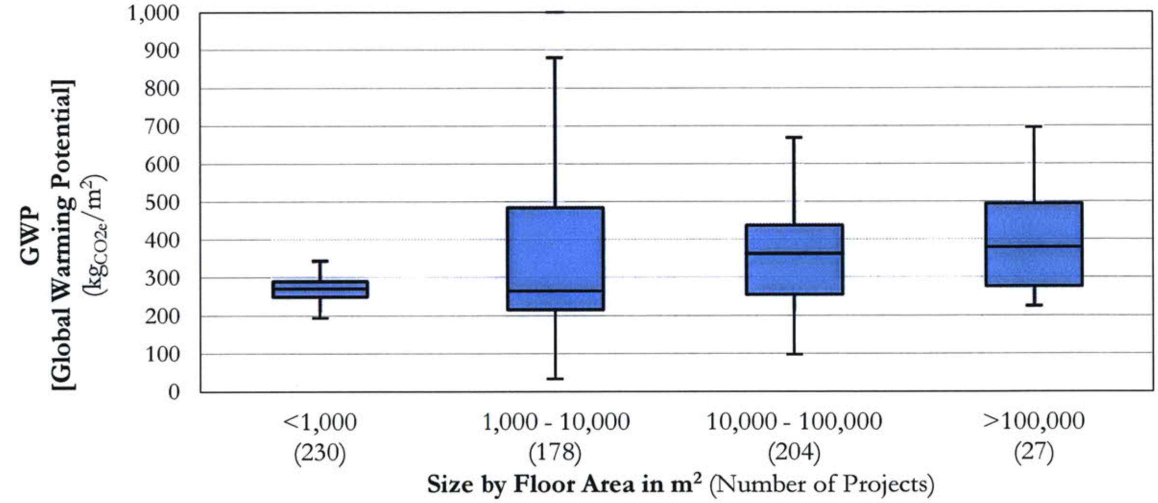


Figure 4.22: GWP of buildings by size

4.2.4. Embodied carbon versus height

Figure 4.23 and Figure 4.24 show the ranges classified by number of floors to illustrate the influence of height on the SMQs and GWP of buildings. A similar approach to the previous graphical representation was followed to analyze the results by height, dividing them into groups according to number of floors. We can recognize the trend Fazlur Khan predicted; the bigger and the higher the building, the more material is used on average per square meter after more than 10 stories (Khan and Rankine, 1981).

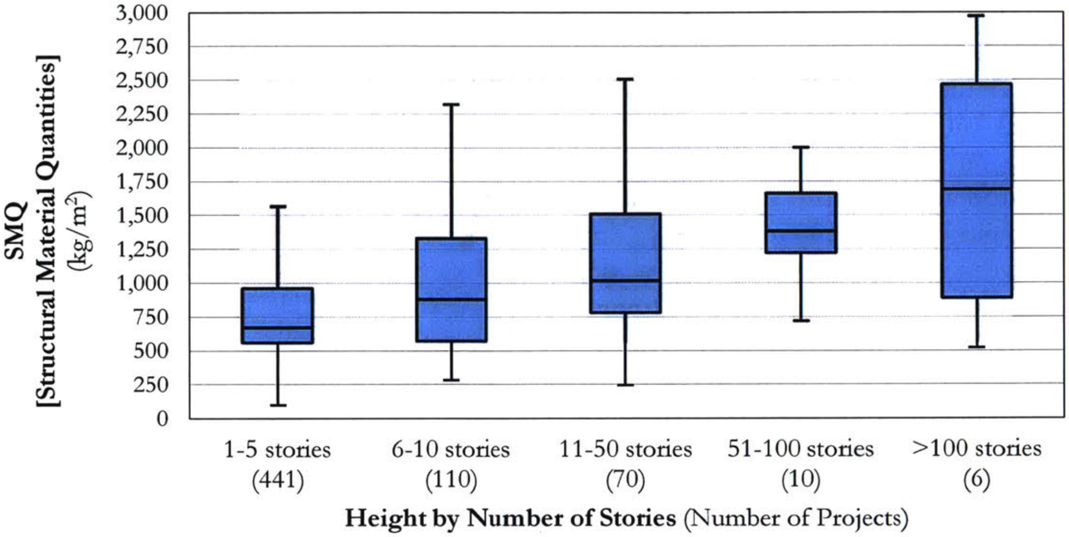


Figure 4.23: SMQ per height by number of stories

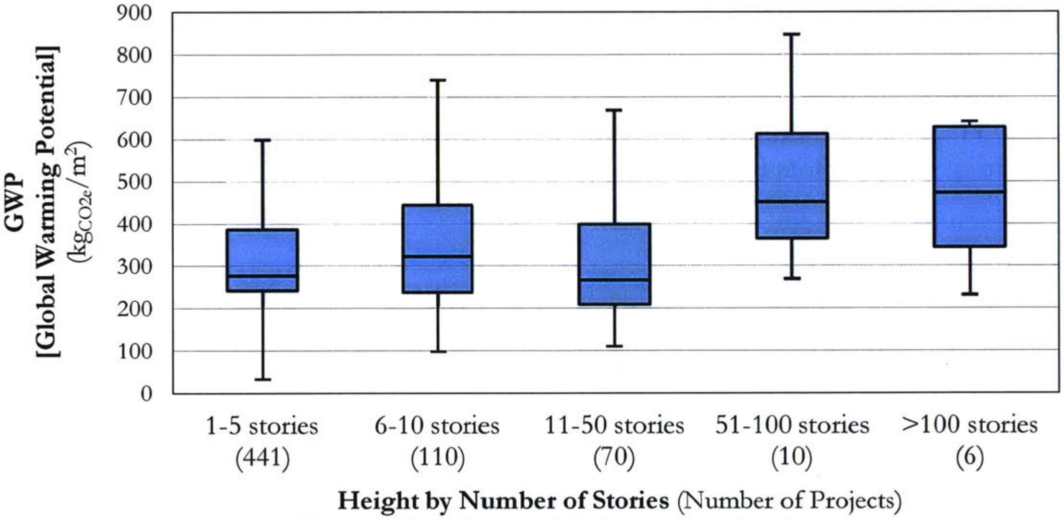


Figure 4.24: GWP per height by number of stories

The buildings collected in deQo typically range between 650 and 1350 kg/m^2 for the SMQs and between 200 and 550 kg$_{CO2e}$/m^2 for the GWP. From all buildings collected, 95% have an SMQ lower than 1900 kg/m^2 and a GWP lower than 850 kg$_{CO2e}$/m^2. These ranges are an important step towards benchmarking the environmental impact of building structures.

The survey of existing buildings reveals that industrial buildings have the highest amount of material and environmental impact, whereas multi-family, low-rise residential buildings have the lowest amount of material and environmental impact. The survey demonstrated that the highest material weight comes from concrete and steel structures. The ranges for concrete, steel, and composite concrete-steel structures are wide. As steel has a higher ECC than the other materials, the results for the GWP of the existing projects show a higher or similar embodied carbon for steel structures, even though this structure type had lower material quantities compared to concrete structures. The SMQ also went up with height and size of the buildings.

As shown in Figure 2.1 (Chapter 2), the embodied carbon results in literature vary widely. Often, the results are given for a low amount of building structures analyzed. Sinha et al. (2016) showed timber buildings ranged around 40-70 kg_{CO2e}/m^2 and concrete buildings ranged around 160 to 240 kg_{CO2e}/m^2. The results given by deQo show ranges between 47 and 362 kg_{CO2e}/m^2 for timber and between 111 and 668 kg_{CO2e}/m^2 for concrete building structures. Eaton and Amato (1998) give values between 200 and 350 kg_{CO2e}/m^2. Vukotic et al. (2010) give ranges from 130 to 220 kg_{CO2e}/m^2. Allwood and Cullen (2011) show structures can vary between 400 and 4000 kg_{CO2e}/m^2 depending on the design decisions. For whole buildings, the DGNB results averaged around 850 kg_{CO2e}/m^2 while HQE results averaged around 345 kg_{CO2e}/m^2. From the collected buildings in deQo, building structures typically ranged around 400 kg_{CO2e}/m^2. The average of over 600 buildings in deQo is 353 kg_{CO2e}/m^2 with a standard deviation of 194 kg_{CO2e}/m^2.

As the data are scattered, the ranges are often wide. The GWP does not always show major differences from one category to another. The results show that the best way to reduce the embodied carbon of structures is by improving the material efficiency on a case-by-case basis, rather than by selecting a particular structural system above another. The main goal of this dissertation is to provide a baseline for comparing a design to the range of existing buildings for similar structural systems and use, rather than deciding if one is better than the other. This enables engineers and architects to assess the position of their new design within the existing range and therefore improve its environmental design. A more detailed representation of the boxplots is given in Appendix E.

4.3. Statistical analysis

4.3.1.1. Uncertainty and data quality matrix

There are different sources of uncertainty. Part of this uncertainty is related to the material quantities. There is a lack of standardization for the description of what goes in the structure and how the floor area is defined. Therefore, an uncertainty analysis is necessary to make sure comparable data is collected. The other uncertainty is related to the ECCs. LCA data can come from different LCI sources. Some LCI data only captures the GHG emissions. LCA methodology can include cradle-to-gate to cradle-to-grave life cycle stages. The scope can include sub- and superstructure only. To address this second uncertainty, deQo collects quantities of materials rather than the end results for embodied carbon alone as is the case for current databases such as WRAP (2017). While other databases collect GWP results, deQo collects SMQ. This solves a number of uncertainties in the long term.

A database of SMQs is therefore very powerful: collecting SMQs enables the update of ECCs as they become more accurate. The next step, already implemented in deQo, will be to break out the quantities to count the different sublayers such as foundations, basement walls, slab on grade, frame, exterior walls, stairs and ramps, floor construction, roof construction, etc. When expanding to the whole building, non-structural components such as exterior windows, doors, roof coverings, internal walls, partitions, internal finishes, fitting, furnishings, equipment, services, and external areas will also be included. Element modules will be defined according to Uniformat used in life cycle costing, similarly to the life cycle stage modules in EN 15978.

Ciroth et al. (2013) developed the uncertainty factors for the pedigree matrix to assess the data quality for LCI. Generally, there is a shortage in sensitivity and uncertainty analyses in industry. The most performed data quality assessment in current practice, if any, is to cross-reference with other sources and validate with other projects previously calculated. For greater transparency, the type of source for the ECCs (EPDs, scientific papers, ICE database, etc.) and the collected SMQs should be listed. This added value of transparency is a major contribution of deQo. The collected data points of each project were evaluated with a data quality matrix.

The data quality pedigree matrix is used to measure uncertainty due to the use of estimates, lacking verification, incompleteness in the sample, or extrapolation from temporally, spatially and technologically different conditions, for example when applying the ECC of the United Kingdom to a building in Sweden. The pedigree matrix for assessing the quality of data sources is illustrated in Table 4.1 based on the work of from Weidema (1998) and Ciroth et al. (2013).

Indicator score	**1**	**2**	**3**	**4**	**5 (default)**
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East)
Further technological correlation	Data from enterprises, processes and materials under study	Data from identical technology but from different enterprises	Data from materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Table 4.1: Pedigree matrix to assess the quality of data sources, from (Weidema, 1998) and (Ciroth et al., 2013)

A similar approach was taken to evaluate the different data sources (in Table 4.2) and each individual data point in deQo (with an extra indicator verifying if the data point is an outlier or an error). The six indicators are reliability, completeness, temporal correlation, geographical correlation, technological correlation, and distribution. For each data point that corresponded to a score higher than 3 for any indicator, it was sourced back to identify the cause of the outlier or error. This process helped improve the robustness of the database, as the sources of errors were addressed in how the database was further implemented.

Indicator score	**1**	**2**	**3**	**4**	**5 (default)**
Reliability	Verified SMQ based directly on Revit/BoQ; Verified ECC based on ISO method for LCA	Verified SMQ based directly on Revit/BoQ; Non-verified ECCs	Non-verified data partly based on Revit/BoQ and LCA	Qualified estimate (e.g. by industrial expert or Building LCA researcher)	Non-qualified estimate
Completeness	Representative data for all parameters	Representative data for all mandatory parameters	Representative data for 50% of mandatory parameters	Representative data for <<50% of mandatory parameters	Representativeness unknown or data from a small number of case studies
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from country under study	Average data from region under study	Data from area with similar production conditions	Data from area with slightly similar conditions	Data from unknown or distinctly different area
Further technological correlation	Consistent data (building layers, life cycle stages)	Consistent data	Consistent building layers	Structural layers included	Unknown building layers
Distribution (only for data points)	Within 2σ of median	Within 3σ of median	Outlier within 1 order of magnitude	Outlier outside order of magnitude	0 or > 2000 kg_{CO2e}/m^2

Table 4.2: Pedigree matrix to assess the quality of data sources contributing to deQo, adapted from Table 4.1

Data sources and data points with indicator scores of 1 or 2 for all indicators were automatically accepted in deQo. Data sources and points with a score of 5 for at least one of the indicators were automatically deleted from deQo. Data with indicator scores of 3 or 4 were studied in more detail to evaluate errors. The results of the data quality matrix for different data sources (not identified due to intellectual property protection) are given in Table 4.3. The data quality matrix for the individual data points is given in Table F.1 in Appendix F.

	Reliability	**Completeness**	**Temporal**	**Geographical**	**Technological**
Industry Partner 1	1	1	1	2	1
Industry Partner 2	1	1	2	2	2
Industry Partner 3	1	1	1	2	2
Industry Partner 4	2	1	1	1	1
LCA study 1	1	2	4	1	2
LCA study 2	1	2	3	1	3
LCA study 3	2	1	1	4	2
LCA study 4	1	2	2	2	3
LCA study 5	1	1	2	3	2
LCA study 6	3	1	1	1	4

Table 4.3: Pedigree matrix to assess the quality of data sources contributing to deQo, adapted from Table 4.1

4.3.2. Results of correlation

To perform statistical analysis on the data collected through deQo, the correlation between the different variables and results for all buildings is studied. The correlation analysis will show the degree to which the parameters are linearly (and later non-linearly) related through an index designed to give an idea how closely two variables move together (Wonnacott and Wonnacott, 1990). The parameters size, height, and span are shown in correlation with either SMQ or GWP. The parameters analyzed are the following: the floor area (m^2) as a measure of the size of the building, the number of stories as a measure of the height of the building, the typical span (m) and the longest clear span (m). The analysis of the results shows that the linear correlation between size and number of stories with the SMQ and GWP results is relatively small. The linear correlation between typical span and GWP is the highest, with an r of 0.72. All coefficients are positive, meaning that with a higher value of the parameter, the SMQ and GWP tend to be higher as well.

Non-linear correlations have also been studied, with the coefficient of determination R^2 to indicate the proportion of the variance in the dependent variable (SMQ, GWP) that is predictable from the independent variable (size, number of stories, typical span, longest span). The typical clear span is the average distance between span supports. As the slab thickness tends to vary with the clear span, an analysis was conducted to see the influence on the embodied carbon results. The quadratic polynomial correlation between the typical span and the results is illustrated in Figure 4.25. R^2 is 0.57 for SMQ and 0.54 for GWP for a quadratic correlation and R^2 is 0.58 for SMQ and 0.54 for GWP for a cubic correlation. A smaller polynomial correlation is observed for the longest clear span. Generally, the values of R^2 are low, which is to be expected considering the wide variability of the data on existing buildings.

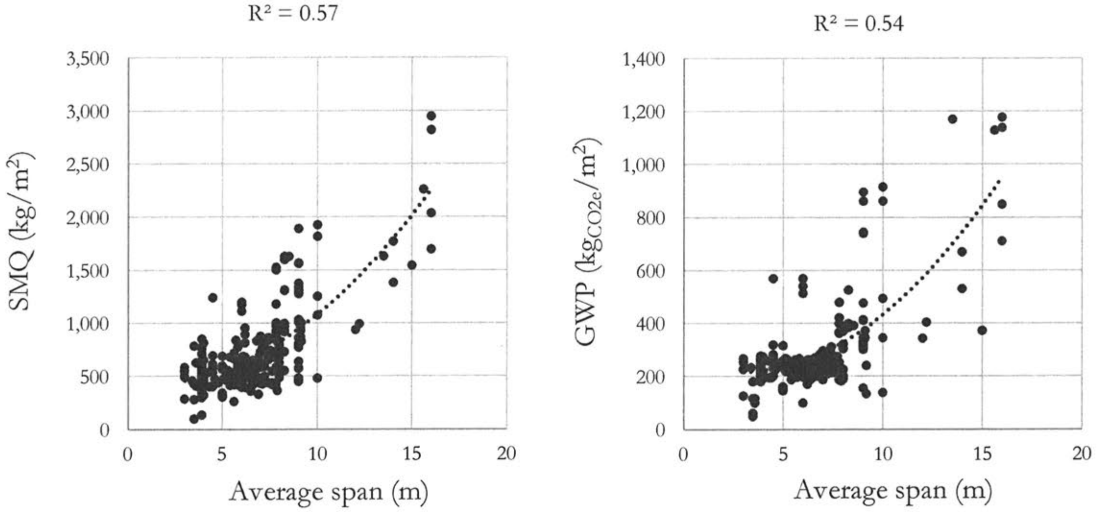


Figure 4.25: Second degree polynomial correlation between average span and SMQ (a) and GWP (b)

This polynomial correlation is to be expected following a simple theoretical study of strength and stiffness limits. Figure 4.26 illustrates the equations for a simple beam and a uniform load. Equation 4.2 gives the bending moment for a uniformly loaded simple beam. To compare with strength and stiffness limits, Equation 4.3 gives the corresponding maximum strength and Equation 4.4 gives the corresponding maximum deflection.

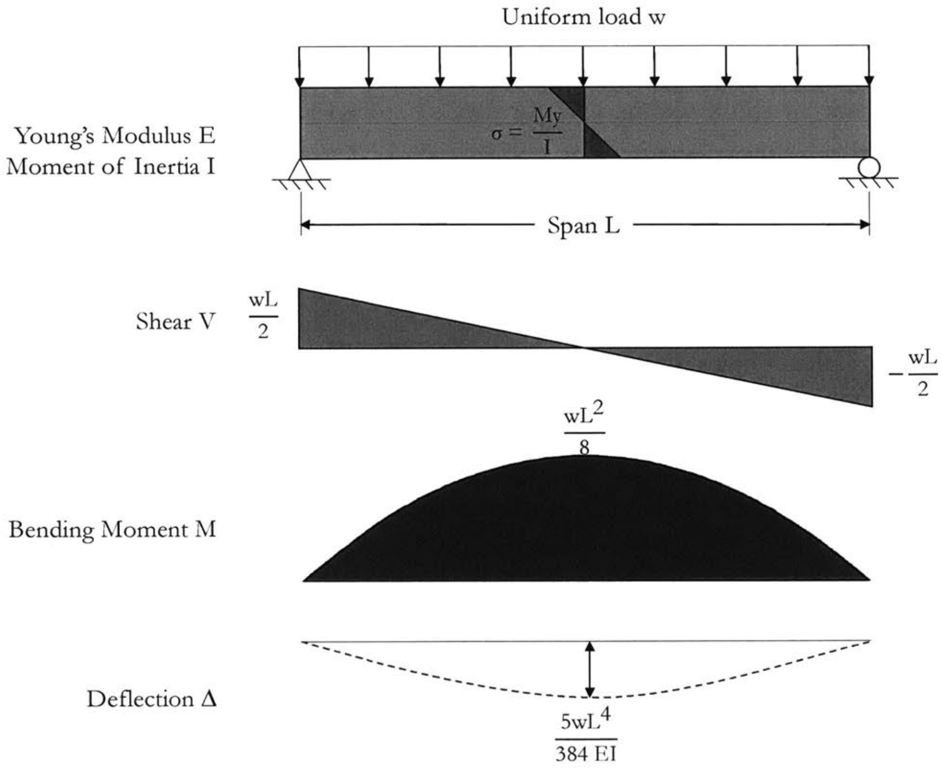


Figure 4.26: Shear, bending moment, and deflection of a uniformly loaded simple beam

$$M = \frac{wL^2}{8} \qquad \text{Equation 4.2}$$

where:

M	Bending moment (kNm)
w	Uniform load (kN/m)
L	Span (m)

$$\sigma = \frac{My}{I} \qquad \text{Equation 4.3}$$

where:

σ	Stress (MPa)
M	Bending moment (kNm)
y	Distance from neutral axis to outer surface where maximum stress occurs (m)
I	Moment of inertia (m^4)

$$\Delta = \frac{5wL^4}{384\,EI} \qquad \text{Equation 4.4}$$

where:

Δ	Deflection (m)
w	Uniform load (kN/m)
E	Young's modulus (MPa)
I	Moment of inertia (m^4)

The results from deQo show that SMQs increase with the span and that the correlation can be expressed through quadratic or cubic equations. These types of correlation are to be expected as the SMQs are related to strength and stiffness considerations for different spans. Based on the strength and stiffness equations, the weight of materials per square meter of floor area could be expressed as a quadratic or cubic function of the span. The SMQs are linked to the moment of inertia I. However, this is beyond the scope of this dissertation as these theoretical equations are highly dependent on the choice of section types, but they could be analyzed in future work. Figure 4.27 and Figure 4.28 give the results for the typical clear span in the buildings in deQo.

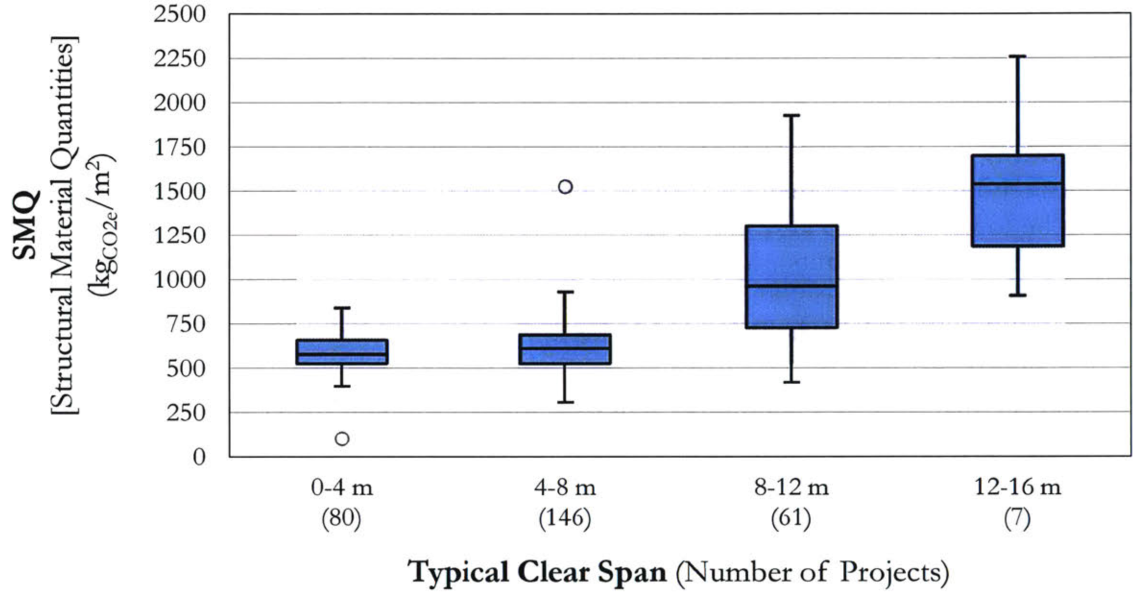


Figure 4.27: SMQ per average clear span

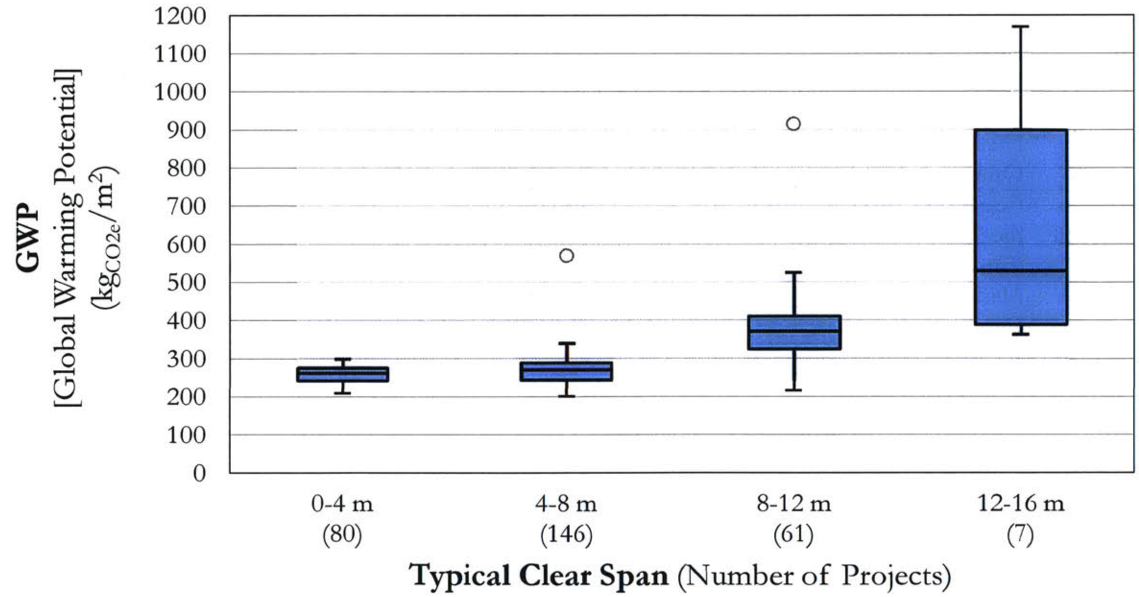


Figure 4.28: GWP per average clear span

The results of the statistical analysis of the database can be summarized as follows:

- The correlation between size by gross floor area and height with SMQ/GWP is smaller than expected.
- There is a clear correlation between span and GWP. The higher the span, the higher the SMQ and the higher the GWP.
- Other parameters need additional data collection to establish any correlation.

As the data is scattered, it is difficult to establish correlations. Data Envelopment Analysis (DEA) could help with establishing the benchmarks for different types of buildings (Cook et al., 2014).

4.3.3. Benchmarking

The following findings can lead to a baseline for benchmarking. The SMQs of building structures tend to be lower than 1900 kg/m^2 and the embodied carbon of building structures tends to be lower than 850 kg$_{CO2e}$/m^2, with the exception of industrial buildings (agricultural buildings, factories and plants). Most building structures range between 650 and 1350 kg/m^2 for the SMQs and between 200 and 550 kg$_{CO2e}$/m^2 for the GWP. The average GWP is 353 kg$_{CO2e}$/m^2 and the standard deviation is 194 kg$_{CO2e}$/m^2.

Structural engineers can use the plotted ranges as a way of testing where their design projects are compared to existing buildings of similar categories. To be within the 25% lowest existing buildings, the targeted embodied carbon values lie between the minimum and the lower quartile. Table 4.4 illustrates the targeted ranges (below Q1) for embodied carbon in different types of buildings versus the typical range (interquartile range). Reference buildings can be found in these ranges for benchmarking.

		Targeted range (kg$_{CO2e}$/m^2)	**Typical range (kg$_{CO2e}$/m^2)**
Program Type	Commercial & Residential	90 – 220	220 – 430
	Infrastructure	130 – 230	230 – 550
	Industrial	540 – 670	670 – 940
	Educational	110 – 250	250 – 520
	Healthcare	120 – 260	260 – 450
	Other	35 – 260	260 – 500
Main Structural Material	Concrete	110 – 270	270 – 440
	Steel	120 – 230	230 – 540
	Timber	50 – 170	170 – 300
	Masonry	150 – 210	210 – 260
	Composite	90 – 250	250 – 520
Number of floors	1 – 10	30 – 230	230 – 440
	11 – 50	110 – 210	210 – 400
	51 – 100	270 – 370	370 – 610
	> 100	230 – 340	340 – 630
Size (m^2)	<10,000	30 – 230	230 – 490
	10,000 – 100,000	100 – 250	250 – 440
	> 100,000	220 – 280	280 – 500

Table 4.4: Range for embodied carbon by program, main structural material, number of floors, and size

For more information on special structures, the embodied carbon results of stadiums and tall buildings have been discussed in the Master thesis preceding this PhD (De Wolf, 2014) and the results for bridges are published in De Wolf et al. (2015).

4.4. Summary

The results discussed above estimate the material efficiency and environmental impact of buildings in a transparent way. The database collected over 600 existing projects from worldwide architectural or structural engineering companies. The results for building structures are normalized material weights ranging between 620 and 1350 kg/m^2 and normalized embodied carbon values ranging between 200 and 530 kg$_{CO2e}$/m^2. The average of all results is 353 kg$_{CO2e}$/m^2 and the standard deviation is 194 kg$_{CO2e}$/m^2.

The results were analyzed by program type, by structural system, by size, by height, and by average or longest clear span. First, the program analysis has shown that industrial buildings have the highest impact. Then, the comparison of different structural systems and building types has shown that timber and masonry structures have the lowest impacts. Moreover, the survey has shown that material efficiency diminishes with increasing size and height of a building. Finally, the results showed a strong positive correlation between the structural span and the SMQ and GWP results.

The major contribution of this research is to pave the way to a more unified and transparent method for collecting material quantities, defining accurate ECC ranges and calculating the GWP of building structures. An understanding of the emissions of buildings could become as intuitive as the CO_2 emissions of cars. For comparison, driving from Philadelphia to Boston (480 km) would generate approximately 100 kg of carbon, whereas the construction of One World Trade Centre or the "Freedom Tower" generated approximately 100,000,000 kg of carbon (Tweeten and Maltby, 2014). Normalized by square meter, the GWP of the Freedom Tower would be over 300 kg$_{CO2e}$/m^2.

In summary, this chapter created new benchmarks using a transparent methodology for evaluating the embodied carbon of building structures.

5. Embodied carbon on the urban scale[4]

To extend the results to the urban scale, this chapter compares embodied and operational carbon simulations in the Al-Qādisiyyah neighborhood in Kuwait. The objectives of urban simulation of embodied carbon in buildings are discussed in Section 5.1. Then, Section 5.2 explains the methodology used for assessing the embodied carbon of a neighborhood. This methodology is applied to a case study of a Middle Eastern neighborhood in Section 5.3. Finally, the potential savings in terms of embodied carbon emissions are illustrated in Section 5.4. This chapter includes both *structure* and *envelope*, in order to look at the trade-off between operational and embodied impacts.

5.1. Objectives of urban embodied carbon simulation

5.1.1. Life cycle energy in Middle Eastern cities

From the material to the urban scale, different design scenarios are evaluated in terms of both operational and embodied energy and GHG emissions in this chapter. Middle Eastern countries including Kuwait are looking to enhance the sustainability of their built environment, since there is an urgent need to expand and build new cities (UNDP, 2017). Apart from carbon emissions, Kuwait is dealing with two additional stress factors on their building energy supply infrastructure: on the one hand the electric grid is already struggling at peak times to satisfy ever-increasing energy demands on summer afternoons, especially from air conditioning. On the other hand, there are hundreds of thousands of Kuwaiti citizens waiting for new housing; Kuwaiti cities have to further grow to give shelter to a growing population. Meir et al. (2012) review the regional constraints, needs, and trends for green building standards in the Middle East. Kuwait's air-conditioning demands account for 50% of its building energy consumption (Elgendy, 2010). Cooling and lighting alone account for 85% of the peak electric power and 60% of annual electrical consumption (Meir et al., 2012). Hajiah (2010) illustrates two codes for energy conservation limiting electricity consumption for air-conditioning: MEW/R-5 General Guidelines for Energy Conservation in Buildings and MEW/R-6 Code of Practice for Energy Conservation in Buildings for different building types (Al Jandal, 2010; Elgendy, 2010).

This chapter analyzes the current performance of Middle Eastern cities and different design alternatives to improve both embodied and operational impacts, including retrofitting the envelope, using less material, and choosing low carbon materials such as concrete with cement replacements and rammed earth. The scenarios presented in this chapter were selected to show what can be enforced via conventional building codes. The role of building

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[4] The results of this chapter are under review in De Wolf, C., Cerezo, C., Murthadhawi, Z., Hajiah, A., Al Mumin, A., Ochsendorf, J., Reinhart C. (2017c) "Life cycle building impact of a Middle Eastern residential neighbourhood," *Energy* (under review) and were developed in close collaboration with Carlos Cerezo, Christoph Reinhart, Zainab Murthadhawi, Ali Hajiah, Adil Al Mumin, and John Ochsendorf. This research was conducted as part of the Kuwait-MIT signature project on sustainability of Kuwait's built environment under the direction of Prof. Oral Buyukozturk and was supported by the Kuwait Foundation for the Advancement of Sciences. Carlos Cerezo performed the operational carbon simulations while the author of this dissertation performed the embodied carbon simulations.

codes today is to provide safety and to enforce regulation on design, construction practices, and quality. This research analyzes the potential and magnitude of carbon reduction that could be implemented through traditional energy policy measures such as building codes and green building rating systems. The results demonstrate whether adding an embodied carbon analysis in this context would make a sizable impact for new residential neighborhoods by 2030.

Simulations are performed using an Urban Building Energy Model (UBEM) tool called Urban Modeling Interface (UMI), developed at MIT (UMI, 2016; Reinhart et al., 2013; Reinhart and Cerezo, 2016). The results illustrate the distribution of both embodied and operational carbon for the different scenarios in order to suggest improvements to the current building code. The tradeoff between embodied and operational impacts is discussed by changing the envelope properties of a residential Kuwaiti neighborhood, Al-Qādisiyyah. This district represents most other residential districts in Kuwait as it covers different types of residential buildings. The neighborhood contains housing built before and after the building codes and includes both governmental houses and private villas. Therefore, Al-Qādisiyyah covers a suitable variation of typical Kuwaiti residential building types. It is a suburb of Kuwait City, Kuwait, one of the hottest cities in the summer on earth (exceeding 45°C regularly) due to the hot desert climate. The selection of this area is based on its connection between a high-density neighborhood (Hawalli) with a low-density neighborhood (Al Mansoureya). The neighborhood is organized into nine blocks around the grocery store, clinic, mosque, etc. For this simulation, a residential block of the neighborhood was taken with an area smaller than 0.2 km^2 (410 m x 480 m). The population of the block is 2867 people for 194 residential buildings. The buildings in this block are a mix of age (old and new), type (private and governmental), and architectural styles (modern, Mediterranean, Moorish, etc.) representative of neighborhoods all over Kuwait.

By looking at a real, existing neighborhood, this chapter offers simulations with actual diversity of building construction, materials and components. Using an urban model rather than a single building offers the variation and range of buildings of an existing neighborhood to address the problem on an urban scale. The current performance of typical villas in the neighborhood is wasteful due to high demands in air conditioning and little insulation. Most structures are composed of reinforced concrete, which typically has a higher embodied impact than more traditional materials such as rammed earth or adobe.

The simulations illustrated in this chapter focus on achieving the goal of lowering the environmental impacts by 2030. The year 2030 is humanity's deadline for keeping global warming within a two-degree range (UNFCCC, 2015; Architecture 2030, 2017; AIA 2030, 2017). The start date of the construction of new neighborhoods is considered in 2020, in order to establish what the life cycle impacts are after 1, 10, and 50 years, respectively in 2020, 2030, and 2070. To offer guidelines for the 2030 sustainability goals set by the governments in the Middle East (UNDP, 2017), a time frame from 2020 to 2030 (10 years) has been analyzed as well as a time frame until 2070 (50 years).

The United States building code cannot be applied in Middle Eastern neighborhoods, as both demands and climate are different. Countries such as Kuwait need to build a large amount of new buildings to keep up with the demands created by population growth, but governments do not have many tools to shift thought towards low carbon city design. The code from other countries cannot simply be copied, due to the different conditions in this region. Moreover, the energy in oil-rich countries is often too cheap to create an individual incentive to lower the embodied and operational energy consumption. A new building code is therefore necessary to lower the environmental impact of Middle Eastern buildings.

5.1.2. *Contributions from the material to the urban scale*

The objectives can be summarized through the following three general questions:

1. How can benchmarks for embodied impacts be defined for a residential neighborhood in the Middle East?
2. What is the whole life cycle impact of potential energy upgrades in buildings in a Middle Eastern neighborhood?
3. How can we lower the carbon emissions of new cities in the Middle East?

First, this chapter analyzes the embodied carbon of the Al-Qādisiyyah Kuwaiti neighborhood as a typical Middle Eastern residential district. To this end, the embodied impacts of the common construction materials in Kuwait are reviewed. To answer the first key question, embodied carbon is defined through collecting material quantities and Embodied Carbon Coefficients (ECC, expressed in kg_{CO2e}/kg) appropriate to the Middle East. The material quantities in this neighborhood were surveyed in three primary ways: through spreadsheets shared by municipalities, drawings from typical Kuwaiti villas (PAHW, 2016), and thickness measurements on construction and demolition sites. Then the embodied carbon was calculated by multiplying ECCs with quantities of the corresponding materials.

To answer the second question, a fully integrated analysis of operational and embodied impacts is applied to different scenarios of energy upgrades. Examples of these upgrades are added insulation or photovoltaic (PV) panels (for improved operational impacts) and variations in concrete mixes, the use of natural materials, and optimized material quantities (for improved embodied impacts). Both operational and embodied impacts are simulated in the UBEM tool UMI (2016) in order to illustrate their mutual relationship.

Ultimately, to answer the third question, this chapter contemplates how knowledge advancements can help governments to manage the construction of new cities. Alternatives are recommended to lower the embodied carbon of the neighborhood. Neighborhood scale simulations with UMI measure how much we can lower the embodied carbon of the built environment with these new design options. This chapter probes the possibility of simulating the Global Warming Potential (GWP, expressed in kg_{CO2e}/m^2 of floor area) on the urban scale by way of an example neighborhood.

This chapter focuses on low-rise residential buildings. Further research also looks at high-rise, high density buildings. Moreover, this work is a bottom-up approach focusing on building structure and envelope. Neither the internal fit-out nor the urban infrastructure are taken into account. The results are therefore only partially representative of material flows and carbon emissions estimated with a top-down urban metabolism approach (Ferrao and Fernández, 2013).

5.2. Methodology of urban embodied carbon assessment

5.2.1. *Embodied impact calculations*

Two key impacts are analyzed in this chapter: embodied and operational impacts. The impacts are expressed in carbon (kg_{CO2e}). Two key variables are needed: the material quantities (MQ, expressed in kg/m^2 of floor area) and the ECC (kg_{CO2e}/kg). Equation 5.1 illustrates how the embodied carbon is obtained by multiplying MQ with their corresponding ECC. Presently, there is no clear standard for accurate ECC values. Moreover, information on material quantities for buildings is scarce.

$$\text{Embodied Carbon}_{\text{building}} = \sum_{m=1}^{M}\sum_{l=1}^{L} MQ_i \times ECC_i \qquad \text{Equation 5.1}$$

where:

m	a particular material or component in the building m= 1, 2, 3, etc., M
l	the number of replacements within the lifespan of the building for each material l = 1, 2, 3, etc., L
MQ	material quantities (kg)
ECC	corresponding Embodied Carbon Coefficients (kg_{CO2e}/kg)

The World Business Council for Sustainable Development (WBSCD, 2015) gives embodied carbon values for cement in the Middle East. El Mostafa (2014) also studied the embodied carbon of concrete in Kuwait. Pearlmutter et al. (2007) analyse the life cycle energy of alternative materials for desert buildings. In the Middle East, they recommend hollow concrete blocks (1216 MJ/m^3), autoclaved aerated concrete (1536 MJ/m^3), stabilized soil blocks (938 MJ/m^3), fly-ash blocks (184 MJ/m^3), and stone (1890 MJ/m^3), without giving the related carbon dioxide equivalent. The emission conversion factor for the Middle East of 0.672 kg_{CO2e}/kWh was published by the International Energy Agency (IPCC, 2016; IEA, 2016). The embodied carbon for aerated concrete blocks, the cement replacement for low carbon concrete, rammed earth, sand base, and sandlime bricks were defined by Pearlmutter et al. (2007).

Middle Eastern Environmental Product Declarations (EPD) for rammed earth, cellulose, and ceramic tiles are compared with data from Pearlmutter et al. (2007), the ICE (Hammond and Jones, 2010), Granta Designs (2016) or the EcoInvent database (2016). The adoption of different databases can influence the results. The sensitivity to usage of the datasets can vary due to interpolation errors, indirect access to ECC values, misinterpretation of the units, or boundary definitions, but mostly due to the geographical variation of the different available datasets. It is difficult to compare projects in different parts of the world to one another. Therefore, this chapter aims to define "regional" coefficients for the used materials applied to the Middle East or Kuwait, using world averages when no reliable local information is available.

The ECCs can be changed manually in UMI by the user who is performing the simulations, once more accurate EPDs are available. Table 5.1 gives the coefficients used in the simulation in this chapter. The time step for replacement schedules is also presented.

	Material	ECC (kg$_{CO2e}$/kg)	Region	Time Step (years)
Structure	Cement block	0.79	Middle East	45
	Cement mortar	0.79	Middle East	45
	Concrete block	0.19	Kuwait	45
	Concrete block aerated	0.48	Middle East	45
	Reinforced concrete	0.33	Kuwait	45
	RC foundation	0.37	Kuwait	100
	Steel rebar	2.26	Middle East	45
	Concrete, cement repl.	0.14	Middle East	45
	Rammed earth	0.07	Middle East	45
Insulation	Fiberglass board	5.23	World	15
	XPS board	3.29	World	15
	Cellulose	0.04	World	15
Others	Ceramic tile	1.05	World	15
	Sand base	0.07	Middle East	15
	Plaster	0.39	World	15
	Glazing (windows)	12	World	15
	Sandlime brick	0.22	Middle East	15

Table 5.1: ECCs used in the simulations

Material quantities applicable to Kuwait were collected: wall and floor thicknesses were measured from published plans of Kuwaiti villas and spreadsheets from the municipality of the neighborhood. Geographic Information Systems (GIS) data formed the basic layer to build the 3D model in UMI. Detailed aerial photographs for the entire block were taken with a drone. Finally, a visit to the Kuwaiti neighborhood and construction sites enabled the definition of MQ in typical residential buildings in Kuwait. Quantities of materials of a typical villa in Kuwait are taken from plans available through the Public Authority for Housing Welfare (PAHW, 2016), construction and demolition site visits, as well as bill of quantities shared by the municipality of the neighborhood. Figure 5.1 shows an example of the plans of a Kuwaiti villa. Typical structural material quantities in the Middle East were defined by collecting data through the database of embodied Quantity outputs (deQo). The thicknesses of envelope material were measured on construction and demolition sites. The lengths of external walls were modeled based on the plans of typical Kuwaiti villas.

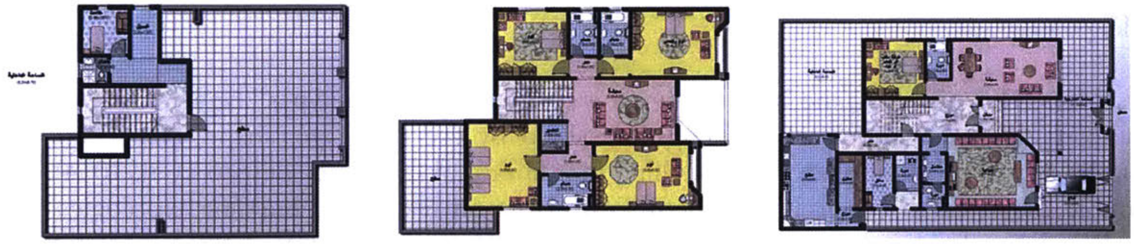


Figure 5.1: plans available through the Public Authority for Housing Welfare (PAHW, 2016)

To calculate the impacts of the PV panels, all roof surfaces in the neighborhood are considered, discarding those too small to install panels on them. The solar radiation on this remaining roof surface of 67,800 m^2 was calculated. Assuming almost flat panels in 50% of the roofs based on the aerial photos of the roofs, to take into account shadings, objects on the roof, etc., the resulting panel area is 33,900 m^2 with 15% efficiency (Fthenakis et al., 2008). The panels were simulated in EnergyPlus and produce a total of 3770 MWh of electricity, annually. The panels are crystalline silicon modules of about 1 m^2 per panel. To produce 1 m^2 of crystalline silicon PV panels, 250 kWh of electricity is needed (Fthenakis et al., 2008). The total amount of embodied energy for the 33,900 m^2 of solar panels is therefore 8475 MWh. With a conversion factor for oil and gas consumption to produce this electricity of 0.672 kg_{CO2e}/kWh for the Kuwait energy mixture (IPCC, 2016; IEA, 2016), 1 m^2 of panels correspond to an embodied carbon of 170 kg_{CO2e}. The initial embodied energy needed to produce the panels can be generated by them after an energy payback time (EPBT) of less than two and a half years. This number is on the lower bound compared to previous studies, due to the high use of electricity for air conditioning to cool Kuwaiti houses. For the Netherlands, Meijer et al. (2003) evaluated that the EPBT was 3.5 years. In Switzerland, Jungbluth (2005) evaluated that the EPBT ranged from three to six years.

5.2.2. Urban modeling

For the calculation of both embodied and operational impacts, an urban simulation model of 194 residential, low-rise buildings was built for the Al-Qādisiyyah neighborhood using UMI, based on research findings from Cerezo et al. (2015). The purpose of building this model is to create a baseline of the current performance in terms of material usage, embodied and operational impacts. For the operational impacts, UMI simulations use UBEM bottom-up techniques, modeling heat and mass flows in and around buildings (Reinhart and Cerezo, 2016), instead of a more traditional top-down modeling approach. As introduced before, UBEMs require the description of climatic conditions, building geometry, plus all building and occupant non-geometric parameters. Regarding weather information, they typically rely on standard files which store data on climatic conditions such as hourly solar radiation, dry bulb temperature, relative humidity, and wind speed in a single citywide annual weather dataset for Typical Meteorological Year (TMY) (Crawley et al., 1999; Liu et al., 2015; Bueno et al., 2012; Mavrogianni et al., 1999). For the case study, weather data was obtained in EPW/TMY format from a nearby weather station. Building 3D massing for urban areas is also available for UBEM in varying levels of detail, and is typically generated from GIS datasets of building footprints extruded to measured building heights, as it was in the case of Al-Qādisiyya. Non-geometric building parameters however, present a larger challenge, since the required information for their characterization is unknown to the modeler on the urban scale.

To address this problem, the building stock is divided into "archetypes" or sets of common characteristics for a group of buildings, classified by use type, age, shape, etc. These are typically stored as a template for modelling in a library or database (Cerezo et al. 2014). An example of an extensive archetype definition effort on residential building typologies was developed by the European Union in the TABULA (2012) project, later applied in the definition of an UBEM by Nouvel et al. (2015) in the SIMSTADT tool. In the absence of databases on constructions, systems, and occupant behavior, the archetypes are created in collaboration with local experts, building codes and building stock energy data (Haldi and Robinson, 2011; Page et al. 2008; He et al., 2015).

A review of previous UBEM efforts by Reinhart and Cerezo (2016) has shown that archetype-based deterministic models can maintain errors below 15% in the simulation of the aggregate energy use of a neighbourhood. For the UBEM of Al-Qādisiyyah, all residential buildings were classified into four main archetypes according to their official construction year, and their level of renovation as surveyed by the team:

(1) Original government villas built between the 1960s and 80s in 32% of the district;
(2) Retrofitted original villas in the 1990s or 2000s (16%);
(3) Villas, private or government sponsored, from the 80s and 90s under the 1983 Energy Conservation code (42%);
(4) Recent structures built after the 2010 Energy Code accounting for a 10%.

At the time of this study, no other information was available for classification, but further in depth surveys of the neighbourhood could allow for the introduction of archetypes based on cooling systems or resident types in further research. In these four archetypes, all building-related parameters were defined deterministically, based on gathered data from available literature and site visits (Table 5.2).

Parameter	Period	Value
Wall / Roof U value (W/m2K)	60s (Original)	2.53 / 1.56
	60s (Retrofitted)	2.53 / 0.53
	80s-00s (1983 Code)	0.62 / 0.53
	10s-Now (2010 Code)	0.32 / 0.40
Glazing U value (W/m2K) / SHGC	60s (Original)	5.96 / 0.86
	60s (Retrofitted)	2.89 / 0.76
	80s-00s (1983 Code)	2.89 / 0.17
	10s-Now (2010 Code)	2.33 / 0.65
Infiltration rate (ach)	60s (Original)	0.8
	60s (Retrofitted)	0.5
	80s-00s (1983 Code)	0.5
	10s-Now (2010 Code)	0.3
Cooling system COP	60s (Original)	2.4
	60s (Retrofitted)	2.4
	80s-00s (1983 Code)	2.4
	10s-Now (2010 Code)	2.9
Window to Wall Ratio (%)	All Periods	10 - 60% (By building)
Occupancy (pp/m2)	All periods	0.012
Lighting Power (W/m2)	All periods	12.3
Plug Multiplier (-)	All periods	1.0
Plug Power (W/m2)	All periods	6.3 - 10.8 (By # floors)
DHW Peak (m3/m2/h)	All periods	0.00013
Cooling Set point (°C)	All periods	22
Heating Set point (°C)	All periods	18

Table 5.2: Archetype simulation parameters in UMI

In this case, constructions, glazing and shading types, coefficients of performance (COP) and infiltration levels were chosen according to expert assumptions, published energy models of Kuwaiti homes (AlAjmi and Hanby, 2008; Assem and AlRagom, 2009; PAHW, 2016) and requirements from the 2010 (Kuwait MEW, 2010) and 1983 (Kuwait MEW, 1983) Energy Codes. Occupant related parameters, such as occupancy or plug loads, were assigned based on available literature and local expertise (Table 5.2), while the associated diversity hourly schedules were developed by residential room type based on a survey of 50 similar residences (AlMumin et al., 2003) and average room sizes for government provided housing. Once the four archetypes were assigned throughout the neighborhood, the UMI tool was applied for the generation of the calculation and simulation model. For calculating the operational carbon, UMI develops energy simulations in EnergyPlus for each building, based on the data sources and archetypes previously defined. Each building is defined as a 3D model representing the massing and shading context (Figure 5.2) and is assigned a set of parameters such as construction layers or occupancy schedules depending on its building archetype. To produce the simulation model for the neighborhood, the methodology for modeling Boston from Cerezo et al. (2016) has been adopted.

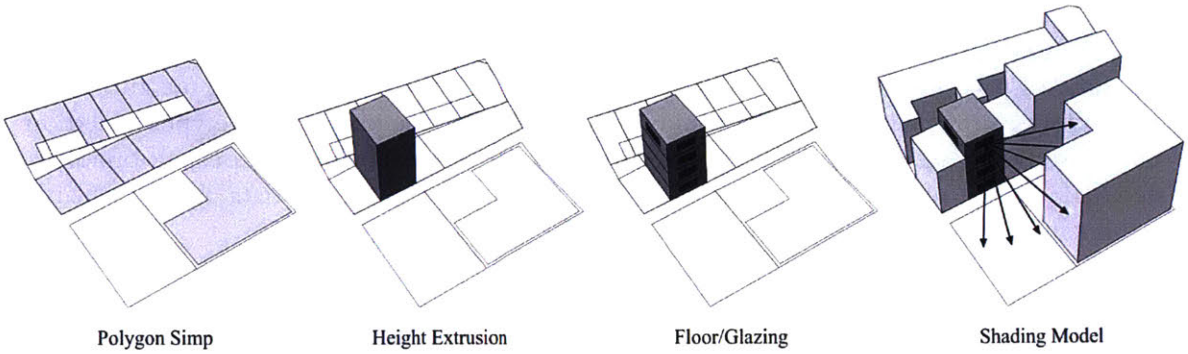


Figure 5.2: 3D geometry generation method in UMI (Cerezo et al., 2016)

The scenarios simulated in this chapter are further explained in Section 5.3.1. To efficiently generate the urban building energy model and to perform the life cycle calculation, four main steps were followed.

First, the building archetype model parameters were defined in a template JSN format text file. The data about constructions (for embodied impacts) and user behavior (for operational impacts) was retrieved from available publications, building standards, and local expert knowledge (Cerezo et al., 2015).

Second, the baseline neighborhood model was generated in the UMI simulation tool by combining available building geometry stored in GIS format with the archetype template files. This initial model represented the current conditions for the Al-Qādisiyyah neighborhood (used for the "current performance" scenario elaborated in Section 5.3.1) The UMI tool generated the 3D geometry and combined the datasets into a full model, used for the calculation of both embodied and operational impacts.

Third, the baseline urban model was annually calibrated with measured operational energy demands to reduce uncertainty in simulation input parameters. Figure 5.3 illustrates the measured buildings from the Al-Qādisiyyah neighborhood and the resulting Energy Use Intensity (EUI) distribution used for calibration. Soko et al. (2017) validated the accuracy of simulated energy compared to measured energy use for the neighborhood through a "Bayesian" calibration methodology, which estimates the unknown occupant behavioral parameters.

Fourth, three new building scenarios were evaluated in terms of embodied and operational energy and carbon simulations for new neighborhoods over up to 50 years. The resulting UMI simulation model can therefore be used to inform energy and carbon policy, building code, and urban planning decisions in Middle Eastern countries, by providing lifecycle carbon impacts for urban areas.

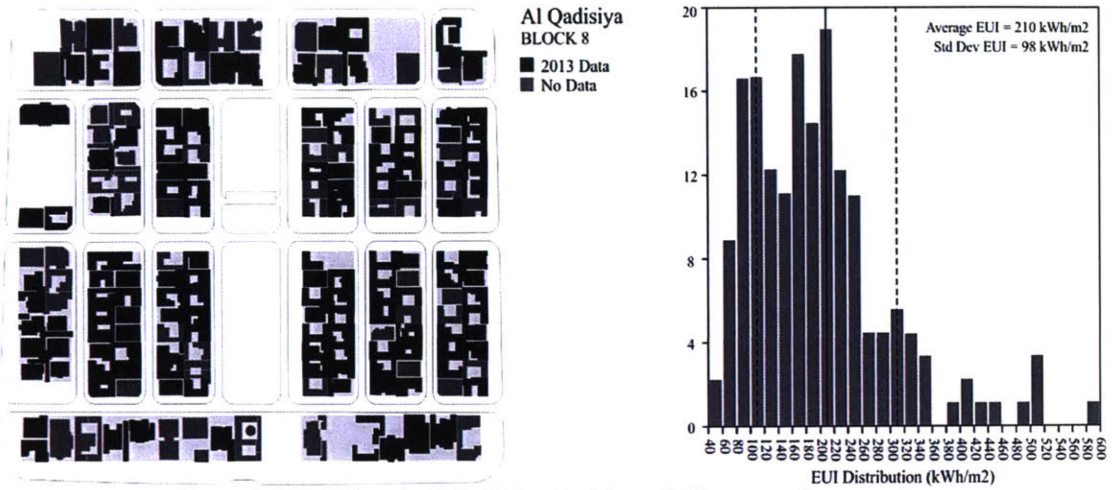


Figure 5.3: Buildings in Al-Qādisiyyah with available metered energy data

5.3. Case study: Middle Eastern neighborhood

5.3.1. Scenarios for embodied carbon in Kuwait on the neighborhood scale

This section illustrates the embodied carbon results from the UMI simulations. Different scenarios are simulated. First, the current performance of a new neighborhood built in the same way as the actual neighborhood is analyzed as a baseline. Then, the carbon is calculated for a new neighborhood built with envelope upgrades done for enhancing the operational carbon of the neighborhood. Next, two low carbon design strategies are applied: using less materials, and using low carbon materials with current technologies (cement replacement in concrete) and rammed earth walls. Finally, a fourth scenario adds PV panels to the low carbon design.

Figure 5.4 illustrates the simulations for embodied carbon for the first scenario. The values obtained for embodied carbon are normalized by the floor area of each corresponding building. A histogram shows the distribution across all buildings of the Al-Qādisiyyah neighborhood for each scenario in Figure 5.5. The normal distribution was calculated for these obtained results, based on the mean and standard deviation of all building results for each scenario. The probability density function is then compared across the four scenarios in Figure 5.6.

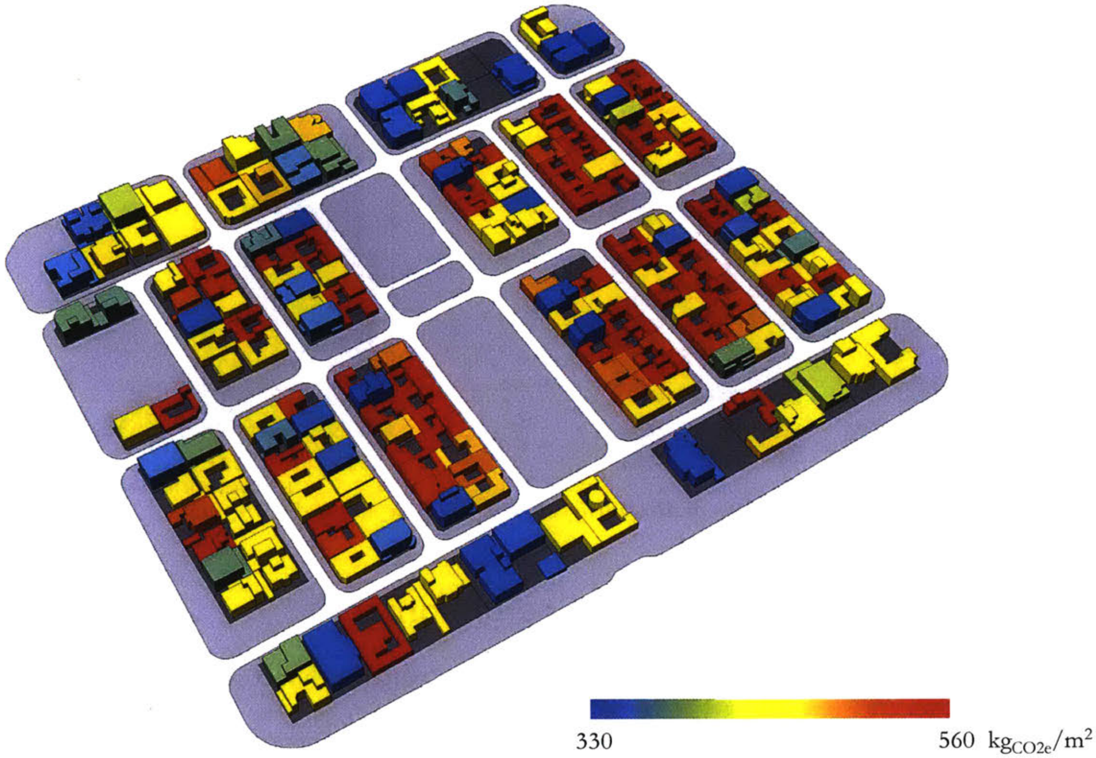


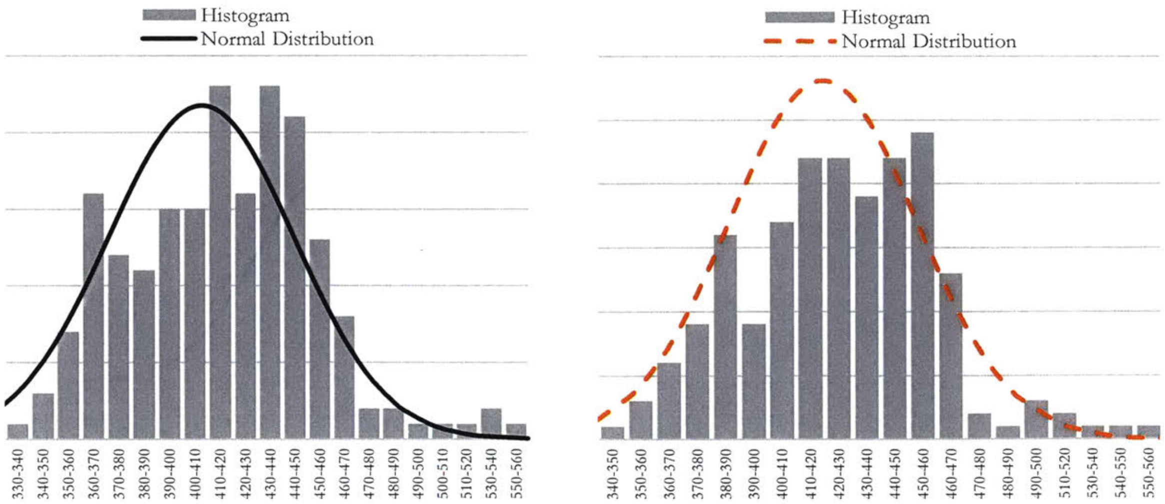
Figure 5.4: Illustration of the UMI simulation of Al-Qādisiyyah

First, the current performance in terms of material quantities is simulated in UMI as a baseline. The main material used in current neighborhoods is reinforced concrete, followed by sandlime bricks. The material quantities are relatively high. The current performance results range from 330 to 560 kg$_{CO2e}$/m^2 (Figure 5.5.a).

For the second scenario, the retrofitting and energy upgrades were applied to the current building stock, in order to improve the operational carbon. The embodied carbon slightly increases due to added insulation materials, etc. The upgraded performance results range from 340 to 560 kg$_{CO2e}$/m^2 (Figure 5.5.b).

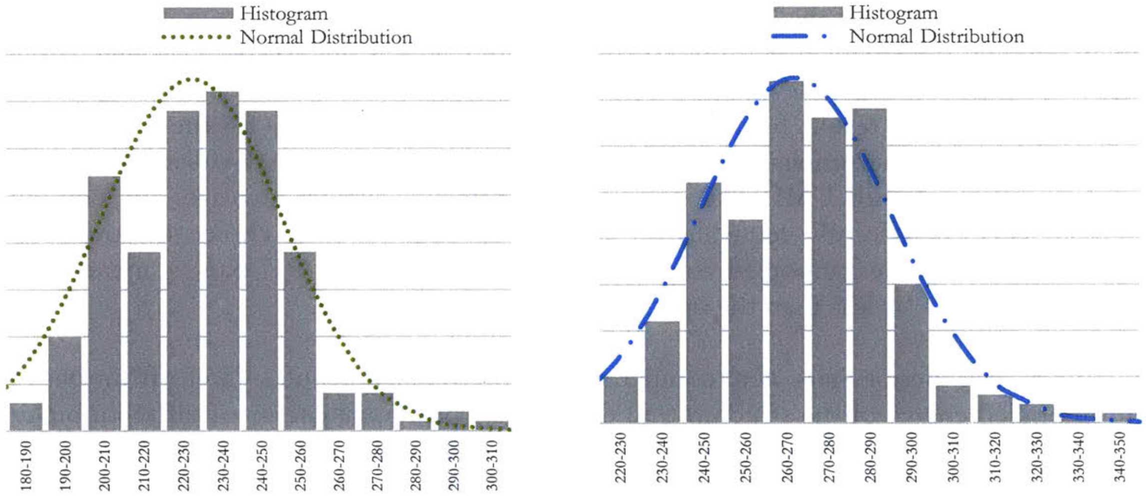
The third scenario offers a new design alternative, using current technologies, including cement replacement in concrete for the slab. The cement can be partially replaced by fly ash or volcanic ash. The concrete and sandlime brick walls are replaced with rammed earth, which has an extremely low ECC. Rammed earth is a construction material used in traditional architecture in Kuwait. The low carbon materials results range from 180 to 310 kg$_{CO2e}$/m^2. This shows that material efficiency alternatives can lower the embodied carbon by more than 200 kg$_{CO2e}$/m^2 (Figure 5.5.c).

The fourth scenario adds PV panels where possible to the neighborhood. The PV and low carbon materials results range from 220 to 350 kg$_{CO2e}$/m^2 (Figure 5.5.d).



Embodied Carbon Ranges (kg_{CO2e}/m^2)
Current Performance
(a)

Embodied Carbon Ranges (kg_{CO2e}/m^2)
Upgraded Envelope Performance
(b)



Embodied Carbon Ranges (kg_{CO2e}/m^2)
Low Carbon Materials
(c)

Embodied Carbon Ranges (kg_{CO2e}/m^2)
PV + Low Carbon
(d)

Figure 5.5: Histograms and normal distribution of four scenarios

The four scenarios are compared to each other in Figure 5.6. The distribution of the results demonstrates that a low carbon design alternative can significantly lower the embodied impacts; the low carbon scenarios result in savings of over 200 kg_{CO2e}/m^2 compared to the current and upgraded performance scenarios. The envelope upgrade (scenario b) only slightly increases the embodied impacts, whereas the choice of low carbon materials significantly lowers the impacts. The next section will compare the embodied results with the operational impacts.

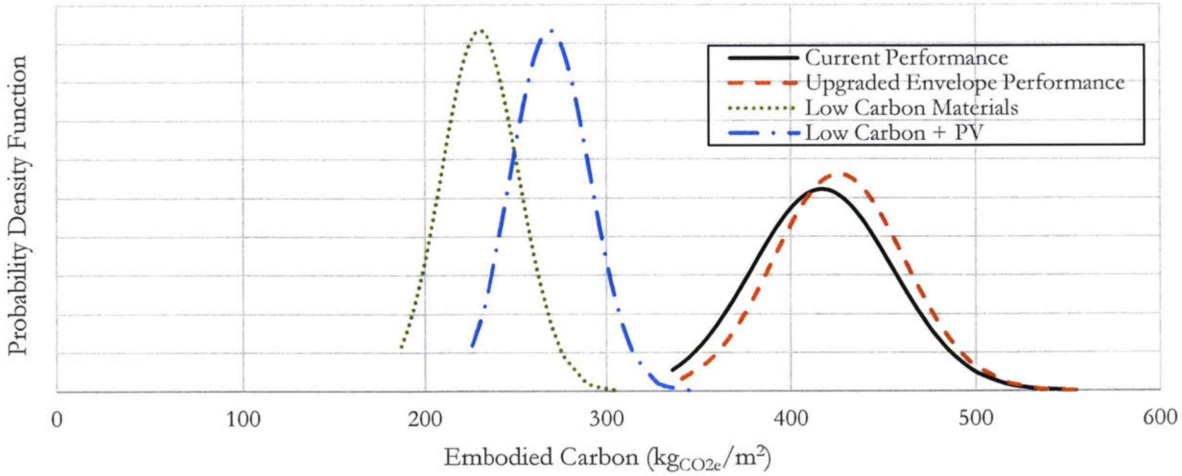


Figure 5.6: Embodied carbon for four scenarios

5.3.2. Embodied carbon versus operational carbon in the neighborhood

This section will discuss the tradeoff between embodied and operational carbon over time. Simulations have shown that 21% of Kuwait energy use is due to lighting, 22% is due to equipment and plug loads, 1% is due to space heating, 51% is due to space cooling, and 6% is due to water heating. The equipment and plug loads were not considered in the results. Figure 5.7 shows the results for all buildings in Al-Qādisiyyah by 2030 for the embodied and operational carbon accumulated over 10 years. This graphic shows the distribution of all buildings analyzed with UMI. The upgraded performance slightly increases the embodied impacts while significantly reducing the operational impacts. The choice of low carbon materials reduces the embodied impacts considerably. Adding PV panels increases the embodied impacts by less than the operational savings they induce.

As a reference, these results were compared with approximations of a Pareto front between the embodied energy of the structure and the annual operational energy of different building designs in Abu Dhabi, United Arab Emirates (Brown and Mueller, 2016). For different structural designs, Brown and Mueller obtained an annual operating energy between 2.3 and 3 GJ/m^2 in Abu Dhabi and an embodied energy of the structure between 0.6 and 1.8 GJ/m^2. To convert these numbers to carbon, the energy mix coefficient of Kuwait of 0.672 kg_{CO2e}/kWh has been used (IPCC, 2016; IEA, 2016). This gives an annual operating carbon between 429 and 560 kg_{CO2e}/m^2 and an embodied carbon of the structure between 112 and 336 kg_{CO2e}/m^2. The annual operational carbon obtained through UMI in Kuwait is between 75 and 300 kg_{CO2e}/m^2. Adding non-structural materials to the embodied carbon results obtained by Brown and Mueller yields results of the same order of magnitude as those obtained with UMI in this dissertation – between 350 and 500 kg kg_{CO2e}/m^2.

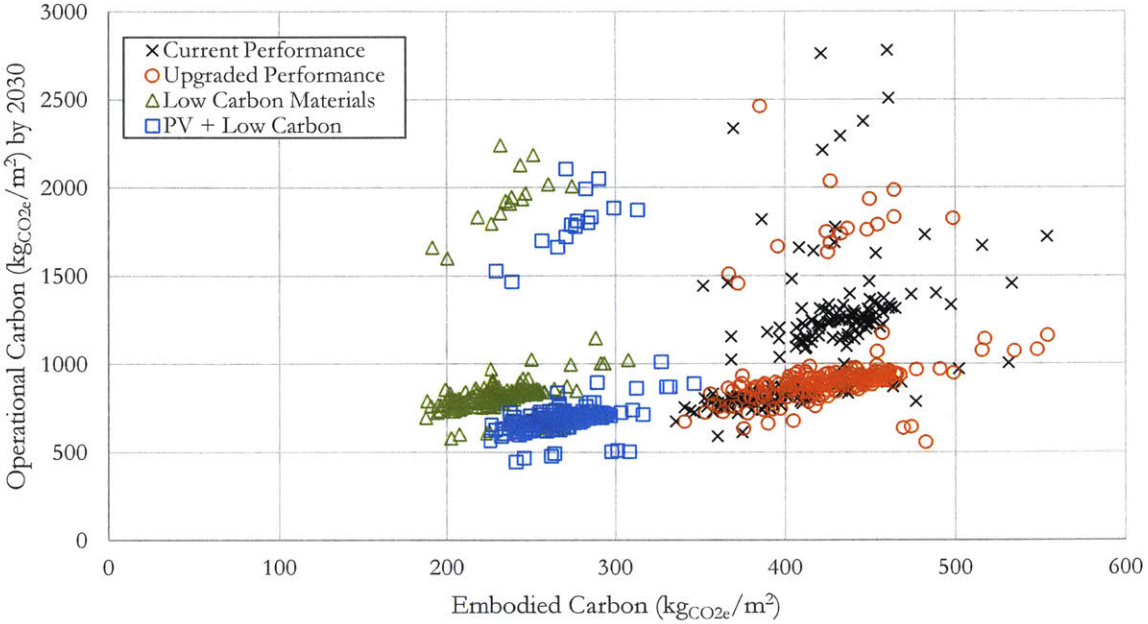


Figure 5.7: Operational and embodied carbon emitted by all buildings in Al-Qādisiyyah by 2030

Figure 5.8 and Figure 5.9 plot embodied and operational carbon for the different scenarios after 10 and 50 years respectively. The results, normalized by floor area, are aggregated for the entire neighborhood. The embodied impacts are equivalent to less than a few years of operational impacts, due to the high loads of air conditioning in Middle Eastern climates. Note that the four scenarios assume that new cities are built so that all buildings in the neighborhood are constructed in the first year (2020). This makes sense as Kuwait is looking to build new neighborhoods and cities to accommodate its high housing demand. The partial replacement of materials is visible through the vertical jumps in the results.

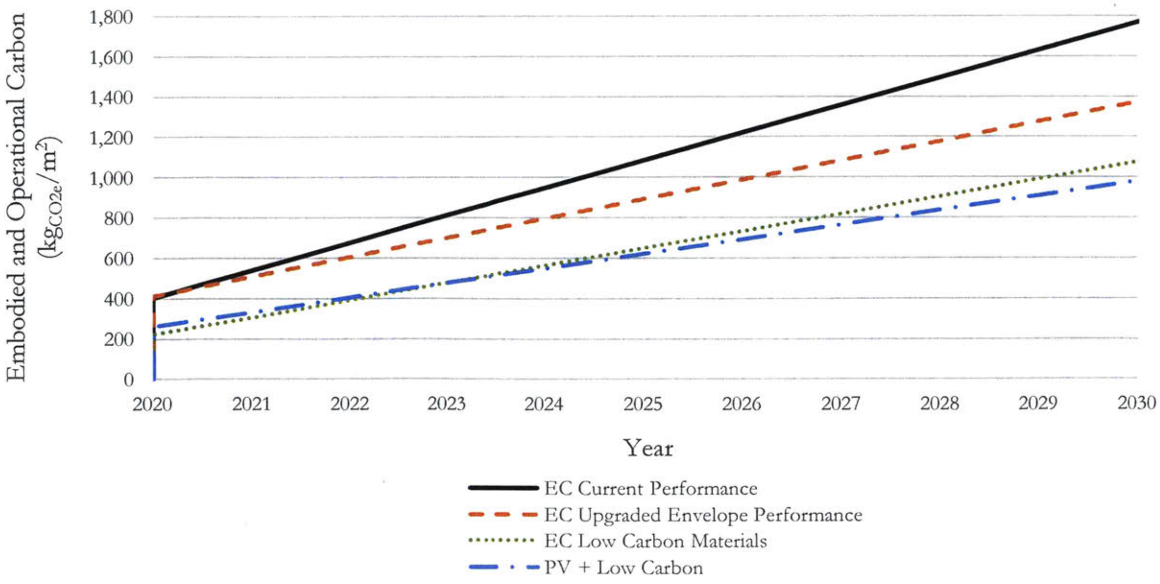


Figure 5.8: Embodied and operational carbon by 2030

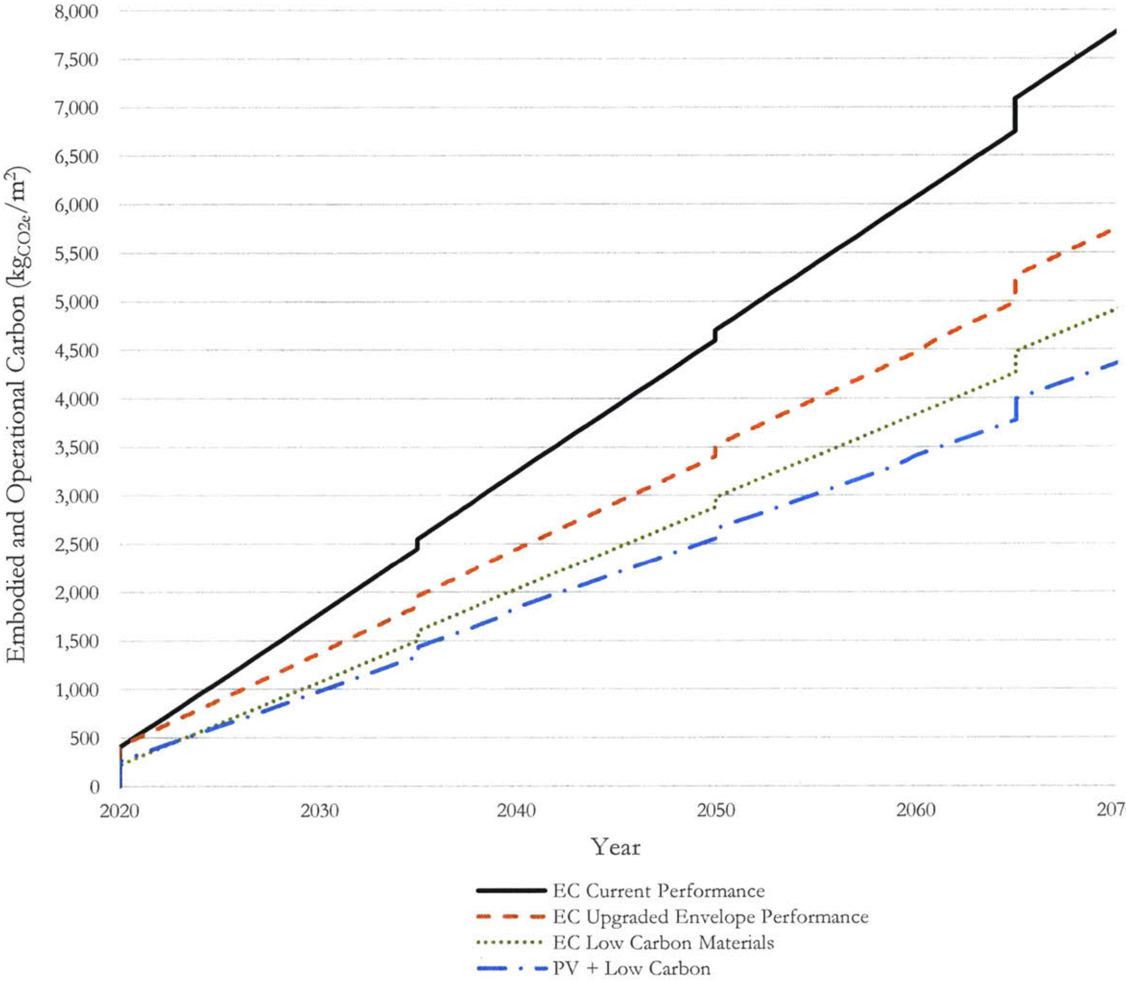


Figure 5.9: Embodied and operational carbon over 50 years

Figure 5.10 illustrates the whole life cycle impacts 1, 10 and 50 years after construction, in order to evaluate the contribution of embodied and operational impacts to the carbon emissions of the neighborhood, normalized by floor area. The different patterns show the average operational versus embodied impacts of all buildings in the neighborhood, the years indicate the accumulated impacts up to 2020, 2030 and 2070, the whiskers illustrate the distribution for the sum of both embodied and operational impacts of all buildings to show the lower and higher case studies amidst all buildings simulated in the neighborhood model. Included in this range are 95% of the results for each of the 194 buildings simulated. The evolution of the accumulated GHG emissions from the first year till the 2030 target and the year 2070 after a 50-year lifespan show the importance of reducing the embodied carbon now, as the IPCC warned carbon reduction is needed in the next decade (IPCC, 2014). The results also express that embodied and operational impacts are not necessarily a tradeoff: the last two scenarios are both lower in embodied and operational impacts compared to the original scenario of current performance.

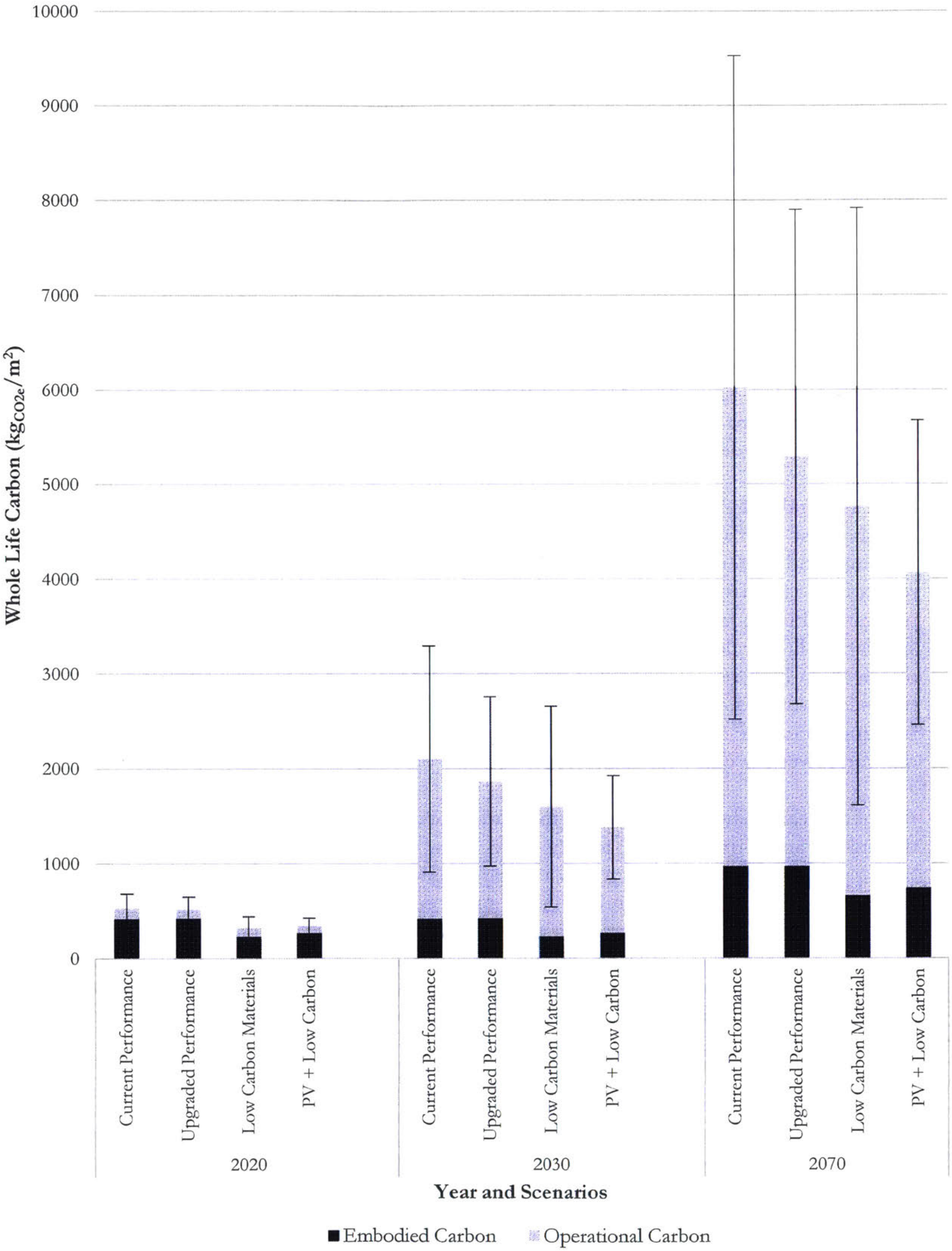


***Figure 5.10:** Whole life cycle carbon since the construction after 1, 10, and 50 years of use, whiskers encompass 95% of results (2 standard deviations) to illustrate distribution*

5.4. Embodied savings of a neighborhood

The results show that using less material and choosing low carbon materials can reduce emissions by 200 kg_{CO2e}/m^2. Note that this is assuming the new construction of a neighborhood. Using PV panels slightly increases the embodied impacts, but are paid back within two and a half years by savings in the operational impacts in the Middle East. Overall, two suitable strategies exist for reducing the embodied carbon and for improving the sustainability of Kuwait's built environment: using less material quantities and improving the concrete mix with cement replacement, using rammed earth walls and cellulose insulations. While the PV and low carbon materials scenario yield good results in terms of embodied carbon, designers need to first pursue better envelopes for new construction in order to move towards a more balanced embodied and operational carbon equation. The neighborhood Al-Qādisiyyah contains 194 units of housing. The savings in operational carbon were also significant with low carbon materials and an improved envelope upgrade. Considering that Kuwait and many other Middle Eastern countries are planning to build entire new cities to accommodate the population growth, considerable savings in embodied carbon can be made at the neighborhood level.

The case study of Al-Qādisiyyah in this chapter can be generalized over the Middle Eastern area as most Gulf Cooperation Council (GCC) countries share similar conditions in use of structure and materials. More research is needed to evaluate how design, needs, rules, and regulations vary from one country to another. Many neighborhoods have mixed building programs. Future work should include public buildings next to residential buildings when simulating life cycle impacts on the urban scale. Moreover, the Gulf region is investing massively in high rise construction based on reinforced concrete, steel and glass. The use of rammed earth and cellulose insulation in this chapter is recommended in low-rise residential buildings. Further analysis is needed to evaluate how cement replacement in the concrete mix can lower the embodied carbon of high-rise buildings.

Further research should include the measures governments can take to adapt the behavior of the inhabitants. Indeed, the results only show limited savings through changes in the building codes. One can reach substantially higher carbon reductions if internal loads are reduced. In order to significantly reduce emissions, the question of internal equipment load caps should be enforced at least as far as installed lighting power density, equipment power density, and peak plug loads go. However, traditional modes of governments can regulate building design more easily than occupant behavior, so adapting the code to include embodied and operational carbon is an efficient strategy to make savings in the built environment by 2030.

5.5. Summary

This chapter analyzes the benchmarks for embodied impacts of a Middle Eastern residential neighborhood, while investigating the impact of envelope upgrades on the whole life cycle impact of buildings. The UBEM simulation results for the different scenarios show that the carbon emissions of new cities in the Middle East can be lowered by making savings in the envelope performance, in the choice of low carbon materials, and in the use of PV panels.

Taking embodied carbon into account can improve savings, as shown by the third scenario. The fourth scenario showed the benefits of adding PV panels in countries with climates similar to the Middle East. If governments would add the embodied carbon aspect to the code, the embodied carbon savings by 2030 would be of the same order of magnitude as the operational carbon savings in that time frame. The results in the case studies discussed in this chapter could therefore affect policies in the Middle East, instead of taking over codes from other places such as the United States which are not adapted to the local construction demands. Indeed, it is rare for codes to integrate embodied carbon, but doing so will enable immediate carbon savings in areas where new cities need to be built for meeting the growing population's housing demands.

This chapter offers an environmental impact analysis of the built environment through an urban model. The added benefit from looking at a neighborhood is the distribution of the building results. The diversity of building design, occupant behavior, and shape of the buildings leads to distributions giving a broader overview of what policies can achieve for entire cities. To look at a whole city, the sensitivity to the different geometries of the different buildings can be analyzed, due to the diversity of results.

In conclusion, this chapter offers an urban simulation methodology to calculate the embodied carbon of buildings on a neighborhood scale applied to the case study of Al-Qādisiyyah, thanks to the collection of ECCs and material quantities in typical Middle Eastern residential buildings. Comparing the embodied and operational impacts for the analyzed study leads to recommendations for strategies that Middle Eastern cities can apply to the construction of new neighborhoods in order to lower their environmental impact.

PART III • LOW CARBON PATHWAYS

Part I introduced the gaps in literature and industry in the nascent field of measuring carbon emissions of building structures. Part II offered an integrated assessment approach on the material, structural, and urban scale.

Part III will use the data collected and results of the comparative analyses to establish strategies in order to lower the embodied carbon impact of structural design. First, the findings on the structural scale are expanded to the whole building scale. Then, the lower bounds of the data collected through deQo are analyzed. Exemplary projects are studied to identify the pathways structural designers can follow to lower the environmental impact of structures. Furthermore, industry strategies for encouraging structural designers to lower the embodied carbon of their projects are discussed. Finally, recommendations are given for low carbon pathways in structural design on the material, structural, and urban scale.

6. Discussion on low carbon pathways[5]

Chapter 6 discusses the results obtained in Part II in order to define new low carbon pathways for structural design. Section 6.1 expands from the structural to the whole building scale to address the remaining barriers for low carbon design. Section 6.2 both illustrates exemplary projects from deQo and proposes pathways to lower the environmental impact of building structures. Section 6.3 then suggests how the construction industry as a whole can tackle the challenges for reducing the embodied carbon of building structures.

6.1. Whole life carbon in buildings

The research in this section was developed at the University of Cambridge in the context of the Innovate UK funded project "Whole Life Carbon in Buildings (WLCiB)" in collaboration with leading LCA practitioners in the United Kingdom.

6.1.1. Barriers to embodied carbon assessment

The assessment of the embodied carbon of buildings in practice still faces numerous barriers. Through a pilot study and focus groups, uncertainties were identified (Table 6.1). Omissions or inconsistencies in embodied carbon calculation in industry practice can be divided in four categories after (Gieskam et al., 2016):

- Institutional and habitual practice
- Economy
- Technical Performance
- Knowledge Perceptions

Through interviews with industry experts described in Section 1.5.1 and the literature review, uncertainties in current embodied carbon assessment approaches were identified. These uncertainties can be classified in at least one of the four categories defined by Giesekam et al. (2016) and are summarized in Table 6.1.

The first four uncertainties are the reliability of the sources for ECCs, the collection of SMQs, the data quality assessment, and the comparison with operational impact; those were tackled in Part II. To reduce these uncertainties, available data sources for ECCs were compared and a transparent method for calculating regional ECCs was developed in Chapter 3. By focusing on the structural part of the building, the collection of clear material

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[5] The results of this chapter are published in several journal papers. Section 6.1 is published in De Wolf, C., Pomponi, F., and Moncaster, A. (2017a) "Measuring embodied carbon of buildings; a review and critique of current industry practice." *Energy and Buildings*, 140(1) April 2017, 68-80, DOI: 10.1016/j.enbuild.2017.01.075. This work was developed in close collaboration with Dr. A. Moncaster and Dr. Pomponi during a research stay at the University of Cambridge, supported by Innovate UK. The further research of this project is in preparation for the *2018 Special Issue of Energy and Buildings*. The results of Section 6.2 are published in De Wolf, C., Ramage, M., and Ochsendorf, J. (2016b) "Low Carbon Vaulted Masonry Structures." *Journal of the IASS*, 57(4), December n. 190, 275-284. The proposal for a SE 2050 Commitment Initiative was drafted by a committee of the Carbon Leadership Forum including: Amy Hattan, Thornton Tomasetti; Catherine De Wolf, MIT; Duncan Cox, Thornton Tomasetti; Frances Yang, Arup; and Kathrina Simonen, University of Washington.

quantities is possible. The direct SMQs can then be multiplied with verified ECCs which can be updated over time. A thorough data quality assessment can be completed on collected material quantities, as illustrated in Chapter 4. Applying those results in UMI allows the comparison of embodied and operational impacts, as shown in Chapter 5.

The remaining issues are discussed when applying the presented methodology to the whole building scale in Section 6.1. Indeed, most of these challenges are related to the non-structural layers of the building. The building layers and life cycle stages are discussed in 6.1.2 and 6.1.3. The other uncertainties are discussed in 6.1.4.

		Institutional Habitual	*Economic*	*Technical Performance*	*Knowledge Perceptions*
Chapter 3 • Material Scale	Reliability of sources for ECCs				✓
Chapter 4 • Structural Scale (4.1)	Material quantity collection: BIM, contractor, BoQ				✓
Chapter 4 • Structural Scale (4.3)	Data quality assessment		✓	✓	
Chapter 5 • Urban Scale	Comparison with operational energy and water use	✓			✓
Chapter 6 • Building Scale (6.1.2)	Building layers: sub/superstructure, façade, finishes, services	✓			
Chapter 6 • Building Scale (6.1.3)	Life cycle stages: transport, construction use, end-of-life	✓		✓	
Chapter 6 • Building Scale (6.1.4)	Life span considered	✓			
Chapter 6 • Building Scale (6.1.4)	Normalization: floor area definition (kg_{CO2e}/m^2)	✓			
Chapter 6 • Building Scale (6.1.4)	Decarbonization of the grid taken into account	✓			✓

Table 6.1: Remaining uncertainties divided in four categories after (Giesekam et al., 2016)

To expand embodied carbon assessment to the whole building instead of the structure only, four case studies from industry were compared to each other. On the one hand, the contribution of structure is compared to that of the other building layers. On the other hand, the contribution of the production stage is compared to that of the other life cycle stages. The case studies were given to three leading assessors from industry in the United Kingdom, who performed the embodied carbon assessment of the case studies based on the cost plan and Bill of Quantities (BoQ). This study therefore also looked at the sensitivity of the current practice to the choices made by the assessors. The four case studies are picked to give a representative view of the built environment: an office building, a residential building, a retail building, and an infrastructure project. The results are given in percentages to preotect the intellectual property rights of the data and the anonymity of the clients. This section addresses uncertainties related to the building layers (6.1.2) and life cycle stages (6.1.3) included, as well as the life span considered, the normalization, and grid decarbonization (6.1.4).

6.1.2. Building layers

Brand (1995) considers the building in time instead of in space. Applying the "shearing layers of change," he emphasizes the different rates of change of building layers. He defines six layers, which are an expansion of the four S's defined by Duffy (1990): site, structure, skin or façade, services, space plan or internal layout, and stuff or furniture. Each layer changes at different lifespans, with the site (timeless) and structure (30 – 300 years) being the least changed. This is why cradle-to-gate stages are the most important life cycle stages when looking at building structures. Other layers such as the façade (20 years), services (7 – 15 years), internal layout (3 – 30 years), and furniture (daily or monthly) are replaced more frequently. Gate-to-grave stages should therefore be considered carefully, especially for frequently changing layers.

Based on the international principles of elemental classification for buildings (BCIS, 2012), different building layers have been defined as illustrated in Table 6.2. This standard classification of functional elements for buildings is also used for building costs and specification. These definitions were given to the assessors so that they could classify the impacts of the case studies by building layer.

Building Layer	Function	Including
Substructure	Transmitting the *loads* to the ground	Foundations Basement Retaining Walls Basement Walls Ground Floor
Superstructure	Transmitting the *loads* to the substructure	Frame Upper Floors Roof Stairs and Ramps Load-bearing External Walls
Façade / Cladding	Separating *inside and outside* & represents the building *externally*	Non-Bearing External Walls External Wall Finishes External Windows and Doors Solar / Rain Screening
Internal Walls / Partitions + Fittings / Furnishings	Defining the *space plan*	Internal Walls & Partitions Internal Windows and Doors Balustrades and Handrails Moveable Room Dividers Cubicles Internal Wall, Floor and Ceiling Finishes Fittings, Fixtures and Furniture (including cupboards, wardrobes, shelving, benches, seating, counters) Soft furnishing (including curtains) Works of art Non-mechanical and non-electrical equipment
Services/MEP	Regulating the *supply and discharge* of water, energy, and air; taking care of *accessibility* of spaces / individual homes	Sanitary Appliances Services Equipment Disposal Installations Water Installations Heat Source Space Heating and Air Conditioning Ventilating System Electrical Installations Fuel Installations Lift and Conveyor Installations Fire and Lighting Protection Communications and Security Installations Special Installations
External works	Preparing *surroundings* of the building	Roads, Paths and Paving Hard and Soft Landscaping Site, Minor Building, and Demolition Works External drainage and services

Table 6.2: Building layers after (BCIS, 2012)

Figure 6.1 illustrates the results of all assessors for the four case studies, showing a wide variability, due to different assumptions on life cycle stages, ECCs, transport distances, construction emissions, maintenance scenarios, and end-of-life predictions. The structure is often a major part of the embodied carbon emissions. The external works and services were omitted. The office building containing a curtain wall is the only building where structural layers are not the main contributor to the total embodied carbon. Indeed, the curtain wall represents a high initial embodied carbon and needs regular replacement and maintenance during the office's lifetime. In a typical infrastructure project, the structural layers represent close to all of the Life Cycle Embodied Carbon (LCEC).

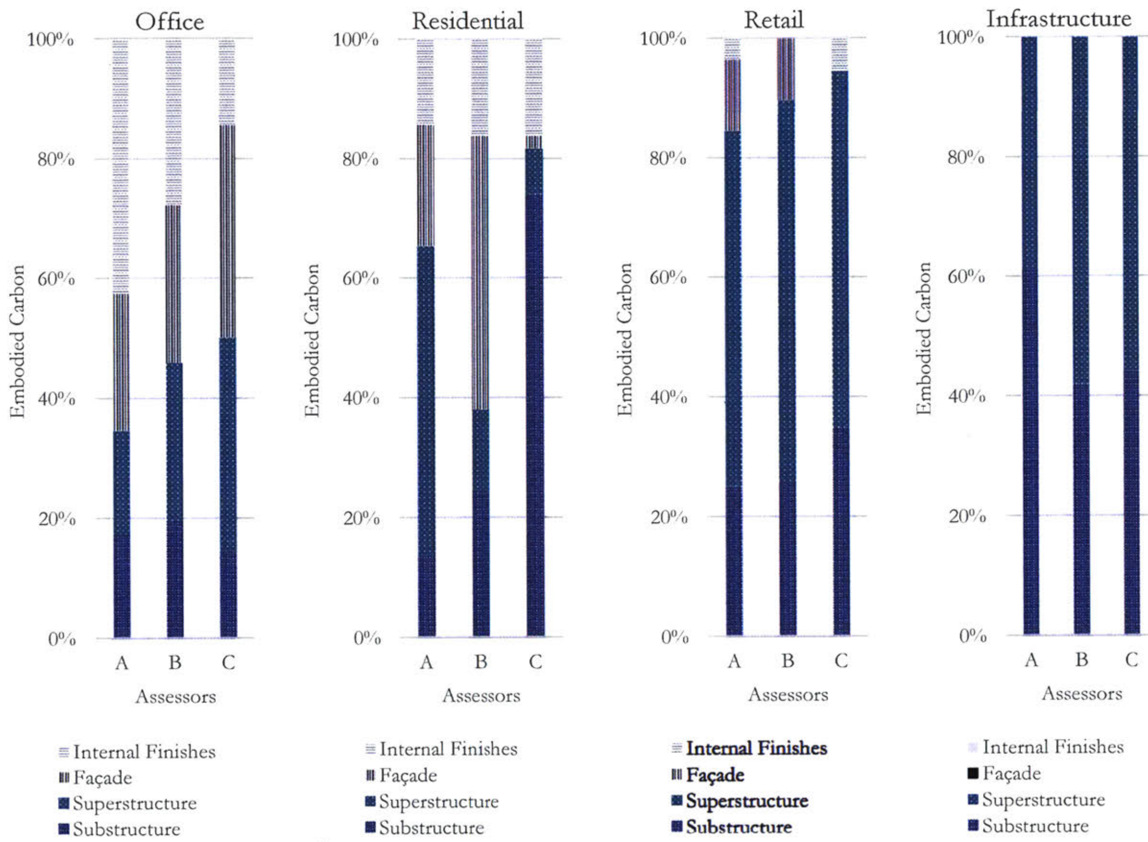


Figure 6.1: Contribution of different building layers to total embodied carbon

6.1.3. Life cycle stages

The life cycle stages according to EN 15878 (EN, 2017) were discussed in Section 1.4.5. Interviewed practitioners (identified by letters as described in Table 1.4 of Chapter 1) believe that the production stages A1-A3 and the use stages B1-B5 are the major contributors to the embodied carbon of buildings [c, h]. For the production stage, they consider the structure to be the highest contributor [k, l]. For the use stage, building components that need frequent replacement, maintenance or refurbishment contribute more [b]. Figure 6.2 illustrates which life cycle stages the interviewees include in their assessments. The production stage is always included and most interviewees account for transport and construction. However, poor availability of material quantities and EPDs, assumptions on transportation modes and distances as well as a lack of data on construction emissions lead to a high level of uncertainty [b, c, i]. Use stages B1-B5 and end-of-life stages C1-C4 are often omitted due to a lack of data and time, uncertainty over the future of the building after construction, and potentially a lack of understanding of the impact. This confirms findings in academic literature (Pomponi and Moncaster, 2016). The benefits and loads beyond the life cycle stages are rarely calculated (module D).

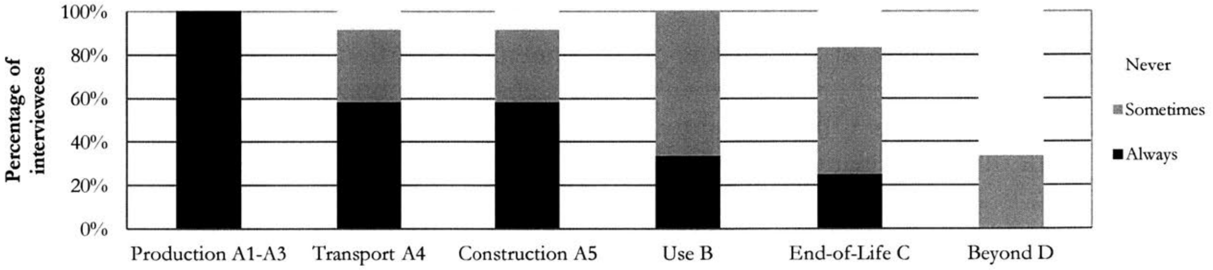


Figure 6.2: Interview results on included life cycle stages, following EN 15978

To expand from building structures to whole buildings, other life cycle stages beyond the cradle-to-gate boundaries need to be considered. Indeed, building layers such as finishes and partitions are replaced more often than the structure, leading to higher contributions of the other life cycle stages to the Life Cycle Embodied Carbon (LCEC).

6.1.4. Remaining uncertainties: life span and normalization

The design life of a building is often taken by structural engineers as 50 years, based on the structural design codes of the American Concrete Institute (ACI, 2016), the AISC (2016), the Eurocodes (2016), and the Australian/New Zealand Standard (AU/NZS, 2016). However, the common lifetime for an LCA is taken at 60 years, as this leaves enough time for most building layers except the structure to be replaced. In reality, demolition permits in the United States of America give a 45-year average lifespan (EPA, 2003). Ultimately, the assessors' scenario predictions for the life span of buildings depends on the typology of the building and the nature of the study. The life span given by interviewees was mainly 50 or 60 years by default [b, c, f, g, h, i], though some interviewees emphasized how life span is determined by occupancy type, client's view (30 – 60 years [b, j]), lease length (15 – 30 years [b, d]), rating schemes (20 – 60 years [g]) and sensitivity analysis (30 – 120 years [i]).

Table 6.3 illustrates the interviewees' responses on the different normalization strategies. Most cases normalize by floor area, but the definition of floor area varies from Net Internal Area (NIA) to Gross Internal Area (GIA) and Heated Floor Area (HFA). Practitioners would also normalize per year in order to compare embodied to operational impacts. Normalizing per occupant or based on financial cost are alternatives to area and years. Due to the variations from one case study to another and the lack of normalization conventions, practitioners compare the analyzed proposed building project to an alternative baseline design in order to measure how they can lower the embodied carbon [f, g, l]. Others mentioned normalizing per occupant or based on financial cost.

	[a]	[b]	[c]	[d]	[e]	[f]	[g]	[h]	[i]	[j]	[k]	[l]
NIA	■	▨										
GIA		▨	■			▨		■			■	
HFA					■	▨						
Per Year	■			▨	■					■		
Compare Designs						■	■					■
Per Occupant								▨				
Monetization									■	■		

***Table 6.3: Interview results on normalization strategies** (always – sometimes – never) – Interviewees are indicated by letters in Table 1.4*

Grid decarbonization and the evaluation of operational carbon are also sensitive to the assessors' choices. Based on the interview results, grid decarbonization is occasionally taken into account in practice. Often, the future scenarios for energy mixes are taken as they are at the moment of the calculation.

6.2. Low carbon pathways identified in exemplary projects

As the backbone of the building, the structure represents the longest serving component. The results of whole building carbon assessments in Section 6.1 showed that structure and cradle-to-gate impacts have a major role to play to reduce embodied carbon emissions in the next decade. In this section, case studies from the lower bound of deQo are analyzed, leading to the identification of low carbon pathways.

6.2.1. Exemplary case studies

Huberman et al. (2015) showed that structural design of the roof can optimize the life-cycle energy efficiency thanks to the use of vaulted roofs compared to a conventional flat slab. Especially the embodied carbon related to slab reinforcing steel can be avoided, due to compression-only vaults (Figure 6.3).

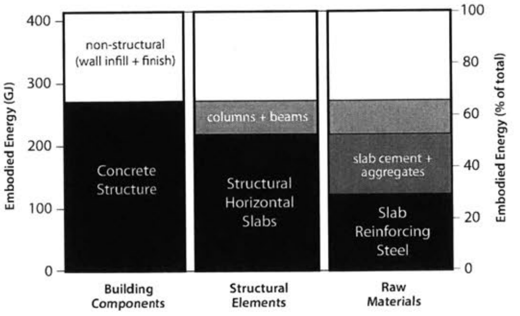


Figure 6.3: Breakdown of embodied impacts in low-rise buildings after (Huberman and Pearlmutter, 2008)

Therefore, this section describes three case studies of vaulted masonry structures, to identify more efficient ways to span roofs: the Pines Calyx in Dover, United Kingdom (Helionix Designs, 2017), the Crossway house in Kent, United Kingdom (Hawkes, 2017), and the Mapungubwe Interpretation Centre in Limpopo, South Africa (Rich, 2017). Indeed, vaulted structures are more efficient than typical beam and floor slab design due to the use of axial forces instead of bending forces. The tile-vaulting system creates thin layers so that material savings occur compared to ordinary floor slabs. As illustrated in Figure 6.4, Spanish architect Rafael Guastavino, Sr. (1842-1908) built tile vaults in the United States and patented the Guastavino tile arch system (Ochsendorf, 2010).

Figure 6.4: Guastavino Rib and Dome System (ca. 1902, New York; Guastavino/Collins Collection, 1902)

Vaulted roofs or floors use arched forms to span spaces, so that it has axial loads only. Case studies in this section are recent examples of unreinforced tile vaults, also called Catalan, timbrel or Guastavino vaults, traditional in the Mediterranean and formerly used by architects Gaudi and Guastavino (Ochsendorf, 2011). The whole life embodied carbon of different case studies of vaulted masonry is calculated and compared with the environmental impact of conventional concrete floor slabs. The material quantities of all buildings are obtained from BoQs measured and compared against the 3D models or personal conversations with the structural engineers. The ECCs of all tiles were calculated in collaboration with Craig Jones, founder of the ICE database (Hammond and Jones, 2010), on a case by case basis for the projects.

The Pines Calyx (Figure 6.5) is an event venue designed by Helionix Designs in collaboration with Cameron Taylor and Conker Conservation as an example of a low-carbon building (Helionix Designs, 2017). Rammed chalk walls, sourced from foundation excavation, and tile vaulted roofs with fired clay bricks largely replace traditional masonry and reinforced concrete. The vaulted roof is composed of tiles and concrete for the compression ring. The floor slab is composed of reinforced concrete (Table 6.4). The ECC of the fired clay bricks is 0.48 kg_{CO2e}/kg as calculated by Craig Jones (Hammond and Jones, 2010).

Figure 6.5: Case study 1 – Pines Calyx in Dover, United Kingdom (Samantha Jones Photography, 2016)

Material Quantities	kg/m^2
Fired Clay Tiles	133
Reinforced Concrete	308
Total	441

Table 6.4: SMQ of the Pines Calyx, from BoQ and BIM

The Crossway house in Figure 6.6 is designed by architect Richard Hawkes and structural engineers Michael Ramage and Phil Cooper as a zero-carbon house (Hawkes, 2017). It has an arched roof that illustrates the tile vaulting technique as an extremely thin and efficient structure. The tiles are overlapping in three layers using fast-setting mortar. The vaulting enables high thermal mass without the use of carbon-intensive reinforced concrete. The structural material quantities in the roof and floor are given in Table 6.5. The tiles are handmade from clay within 6 km of the site resulting in a low ECC of 0.08 $kg_{CO2e}kg$.

Figure 6.6: Case study 2 - Crossway in Kent, United Kingdom (Hawkes Architecture, 2016)

Material Quantities	kg/m^2
Handmade Clay Tiles	149
Plaster	4
Mortar	74
Concrete	96
Total	324

Table 6.5: SMQ of the Crossway house, from BoQ and conversations with engineer

The Mapungubwe Interpretation Centre (Figure 6.7) in Limpopo, South Africa, was designed in 2006-2007 by Peter Rich Architects and completed in 2009 (Ramage et al., 2010; Block et al., 2010). With a total area of 2,750 m^2, the center is shaped by vaults of different sizes, constructed with earth bricks covered with sandstone. The structural members include a concrete structure and slabs, sandstone walls, stabilized earth bricks and diverse recycled materials (metal, poles, etc.). The building won several awards including 2009 world building of the year at the World Architecture Festival. The material weights of the Centre are given in Table 6.6. The ECC of cement-stabilized compressed earth bricks is 0.1 kg_{CO2e}/kg.

Figure 6.7: Case Study 3 – Mapungubwe Interpretation Centre in Limpopo, South Africa (Iwan Baan Photography, 2016)

Material Quantities	kg/m^2
Stabilized Earth Tiles	99
Stone	24
Concrete	96
Steel	16
Total	234

Table 6.6: SMQ of the Mapungubwe Interpretation Centre, from BoQ, conversations with engineers, and reports

Figure 6.8 summarizes the weight breakdown by material for the three masonry vaulted case studies. They used a similar quantity of tiles per m^2, as Guastavino vaulting was used in all projects.

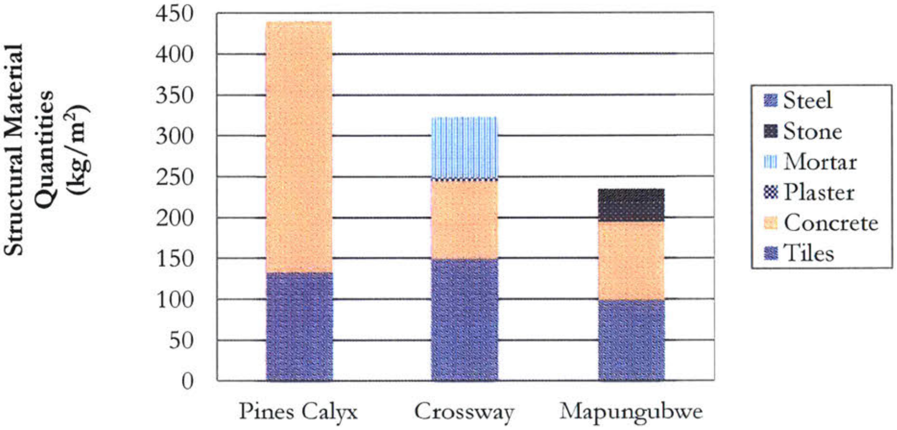


Figure 6.8: SMQ in the case studies

A Whole Life Embodied Carbon calculation was performed on the material quantities of the vaulted masonry case studies (Figure 6.9). In the United Kingdom, the ICE database can be used. Though the energy mix in South Africa relies more on coal than in the United Kingdom (Department of Energy Republic of South Africa, 2016; Department of Energy & Climate Change, 2016), the ICE values were also used for the Mapungubwe project for the sake of comparison. Also, there is no reliable ECC data available for South Africa. For the transport and construction factors, numbers from the Department for Environment, Food & Rural Affairs (DEFRA, 2016) in the United Kingdom have been used. Most materials used in the Crossway house and Mapungubwe project were local, leading to little transportation emissions.

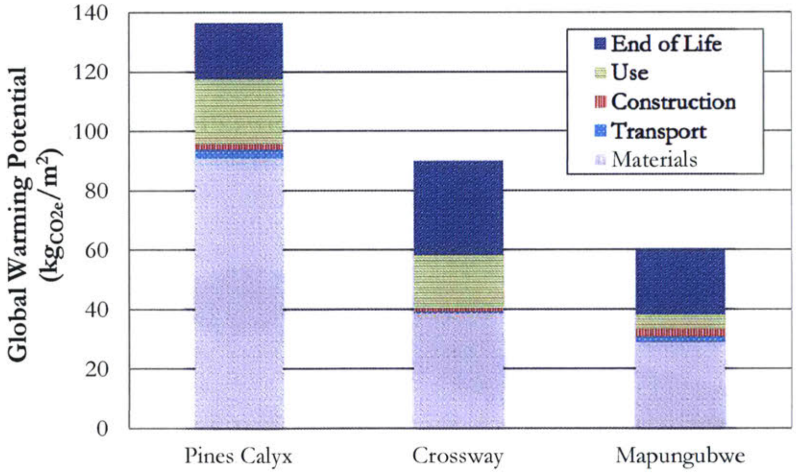


Figure 6.9: GWP of the tile vaulted masonry case studies

The results for these low carbon case studies can be compared to the other existing buildings in deQo. The average of over 600 existing buildings that were collected in deQo ranges around 353 kg$_{CO2e}$/m^2 for cradle-to-gate only, to which an average of 97 kg$_{CO2e}$/m^2 for use and end-of-life stages was added to obtain the cradle-to-grave results of 450 kg$_{CO2e}$/m^2.

These results for typical existing concrete and steel structures are four to ten times higher than the vaulted masonry projects (Figure 6.10).

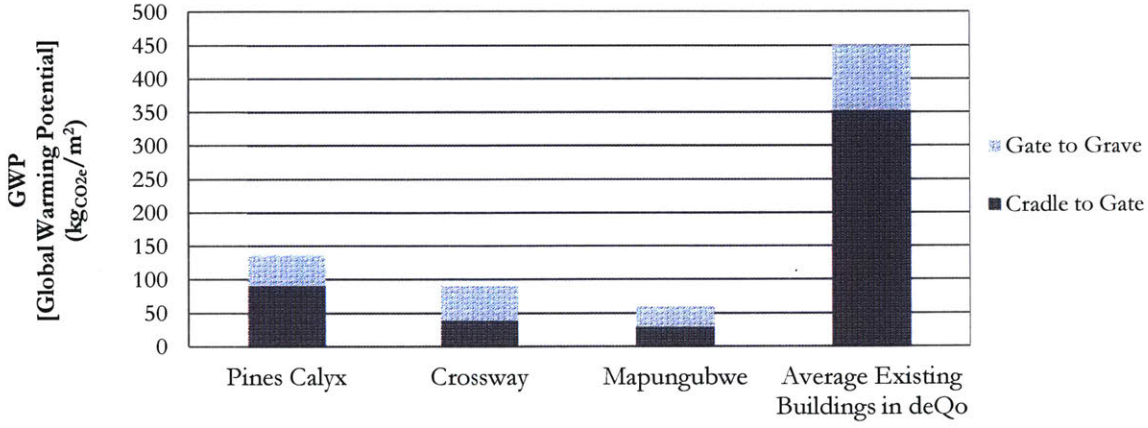


Figure 6.10: GWP of the case studies, compared to existing building structures

Compared to the results of over 600 existing building projects, the vaulted floor and roof systems offer radically lower GWP results. The exemplary buildings are mostly one to two stories, but the database buildings are more common multi-story buildings. However, the average GWP of all buildings in deQo below 3 stories is still 332 $\text{kg}_{\text{CO2e}}/\text{m}^2$. The cradle-to-gate results were 98 $\text{kg}_{\text{CO2e}}/\text{m}^2$ for the Pines Calyx, 52 $\text{kg}_{\text{CO2e}}/\text{m}^2$ for the Crossway house, and 30 $\text{kg}_{\text{CO2e}}/\text{m}^2$ for the Mapungubwe Interpretation Centre. Especially when the use of concrete is replaced with natural earth masonry materials, the embodied carbon can be reduced up to ten times.

Another strategy for reducing the embodied carbon of floor and roof systems is to optimize the material quantities needed for structurally sound and stable floors and roofs. For example, the Block research group has developed a rib-stiffened funicular floor system (Figure 6.11) that significantly reduces material quantities in floors compared to conventional concrete slabs (Davis et al., 2012). Agusti-Juan and Habert (2016) showed that the floor system saved 75% of the self-weight and 50% of the GHG emissions compared to a conventional 22 cm bidirectional concrete slab floor.

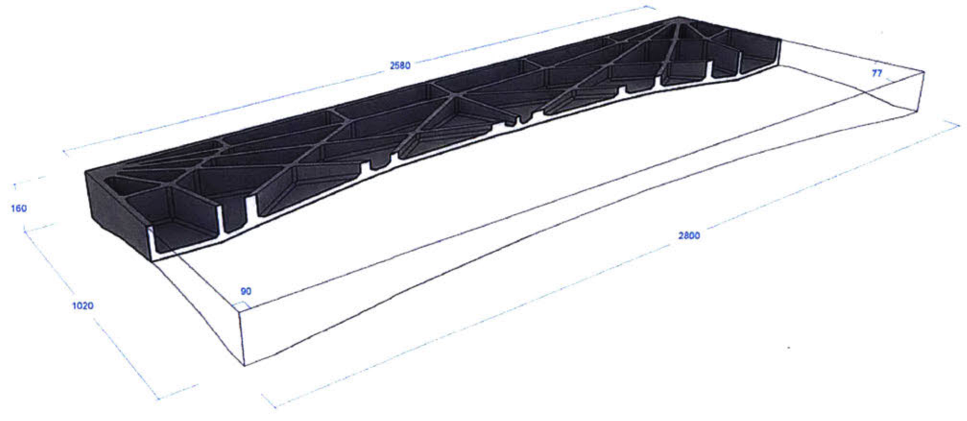


Figure 6.11: Rib-stiffened funicular floor system (Block Research Group, 2017)

Results show that the Whole Life Embodied Carbon can lower from 450 kg_{CO2e}/m^2 for existing building structures to a GWP as low as 60 kg_{CO2e}/m^2 by using vaulted tile masonry structures. The main contributions to the whole life embodied carbon are the cradle-to-gate impacts for structures. We can therefore use two key variables: the SMQs (kg/m^2) and the ECCs (kg_{CO2e}/kg). Multiplying both key variables gives the cradle-to-gate GWP (kg_{CO2e}/m^2).

The pathways illustrated in this chapter are applied specifically to tile vaulting systems, but the principles of better design for efficiency and low-carbon material choices can be extended to other types of structures. The results show how masonry vaults can illustrate the pathways for reducing embodied carbon of spanning systems.

6.2.2. Pathways for low carbon structural design

The exemplary projects in this chapter illustrated the two main pathways to reduce the embodied carbon in structural design: reducing the amount of materials needed for the structure and substituting current construction materials with alternative materials that have a lower environmental impact. The International Energy Agency's Energy in Buildings and Communities Program (IEA-EBC) identified various guidelines that can be divided into these two pathways (Lupisek et al., 2015). O'Connor and Bowick (2016) also recommend design choices that can be attributed to either pathway. Interviews with practitioners [a-l] helped to understand additional guidelines for low carbon structural design. Table 6.7 summarizes the design pathways related to low material quantities and low carbon material choices, based on the literature, interviews, and the exemplary case studies.

Low SMQ	Low ECC
Optimization of layout plan	Reuse of building parts and elements
Optimization of structural system	Recycled or recyclable materials
Low-maintenance design	Bio-based and raw materials
Flexible and adaptable design	Materials with lower environmental impacts
Component's service life optimization	Design for deconstruction
High durability	Local materials
Waste minimization	Material manufacturing changes
Building preservation rather than building new	Reuse of waste

Table 6.7: Design pathways for reduction of embodied carbon based on interviews, low carbon projects in deQo and recommendations from (Lupisek et al., 2015) and (O'Connor and Bowick, 2016)

In conclusion, two pathways can be followed to lower the embodied carbon of buildings:

- Material efficiency: lowering the amount of materials in the floor slabs is crucial;
- Low-carbon material choices: the choice of materials with lower ECCs can reduce the embodied carbon of structures drastically.

6.3. Industry strategies for low carbon structural engineering

This section discusses the strategies that can be used for lowering the embodied carbon of structural design industry-wide. First, rating schemes such as LEED can incentivize low carbon structural design (USGBC, 2017). Next, industry initiatives such as the Architecture

2030 Challenge and the Structural Engineering 2050 Commitment help practitioners to contribute towards a vision of zero carbon by 2050. Governmental initiatives and policies can also play a role in carbon reduction. Another key element is education: it is important to train future designers and clients to have the knowledge and awareness to design low carbon structures. Furthermore, engineers need to be involved with architects in early design stages, where decisions can still be made to lower the material quantities and embodied carbon of buildings. Moreover, industry should invest in research and development (R&D) to allocate some time for carbon accounting. Integrating embodied carbon assessment and direct feedback in design tools can also help engineers in this task. Finally, clients should set the targets for the design team to prioritize lowering the environmental impact of buildings.

6.3.1. Whole Building LCA credit in rating schemes

The data collection for deQo also describes the rating schemes obtained for different projects. Figure 6.12 and Figure 6.13 show the material quantities and embodied carbon of buildings collected in deQo that have no LEED certification compared to buildings that received various LEED certifications. LEED is a global environmental building certification program with four rating levels from "Certified" to "Silver," "Gold," and "Platinum" (USGBC, 2016).

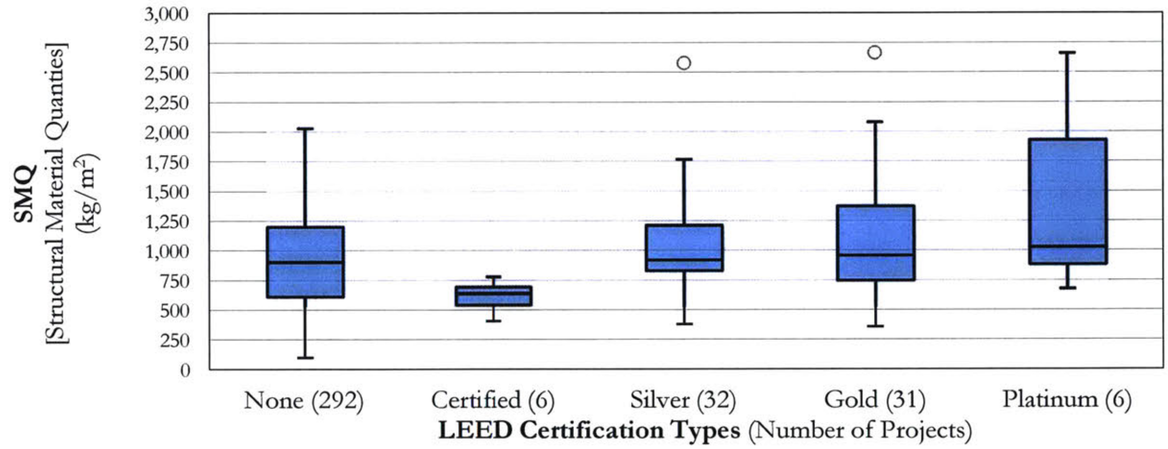


Figure 6.12: SMQ per LEED certification type

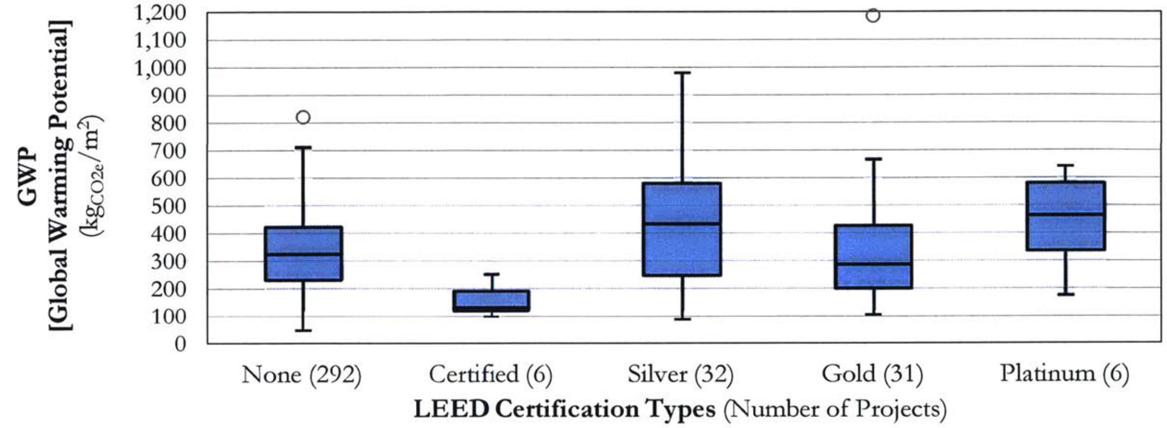


Figure 6.13: GWP per LEED certification type

The results show that platinum buildings are doing worse than non-LEED buildings in terms of embodied carbon. Though the sample size of this study is not big enough to draw conclusions, preliminary results show that Platinum LEED certification buildings have higher material usage and environmental impacts whereas the normal LEED certified buildings have the lowest impacts. Note that the limited number of collected buildings with Platinum LEED certification presents a small sample size. It is to be expected that buildings with a higher energy efficiency have a higher embodied carbon due to added insulation or thermal mass. There can be a tradeoff between embodied and operational carbon. LEED buildings may intentionally favor operational over embodied carbon savings. However, high SMQs are most likely due to the extravagancy of the types of projects that pursue the Platinum certification.

Rating schemes have not taken into account the embodied carbon emissions of buildings yet and the higher embodied impacts for the Gold and Platinum buildings show potential flaws in the LEED ranking method up to 2014, due to a lack of benchmarks of embodied carbon. The data analysis presented in this dissertation will help to create these benchmarks.

The data collected on LEED certification only contains buildings built before or in 2014. However, more recently, LEED is including credits to help lower the embodied carbon of buildings. LEED's main categories are Location & Transportation (LT), Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), and Indoor Environmental Quality (EQ). The MR section includes a credit for building product disclosure and optimization through the use of EPDs. This has motivated the development of EPDs for building products in North America (O'Connor and Bowick, 2016).

The embodied carbon is mostly included within the MR category with the Whole Building LCA credit (WBLCA). Three points are allocated to "Option 4: Whole-Building LCA". The credit can be applied to new constructions, including new additions to an existing building (USGBC, 2017) and requires a cradle-to-grave LCA of the building. The system boundary must account for all life cycle stages as defined in ISO 21930. Potentially, this new credit could incentivize design teams to calculate and lower the embodied carbon of their structures.

A lack of benchmarks and uniform methodology has presented a challenge in the implementation of the credit. To award the credit, LEED therefore requires an improvement in the proposed design compared to a yet undefined baseline building. Unifying existing methodologies is crucial to compare embodied carbon of a baseline building and a proposed design as apples-to-apples. In this chapter, the term 'proposed building' refers to the building design that is applying for the credit in their LEED certification submission, and the term 'baseline building' refers to the reference building against which the potential improvements are measured. This baseline building must have the same size (gross floor area), location, programmatic function, service life, orientation, and operational energy. An energy model is not necessary to estimate the operational energy for this credit, but it must comply with the prerequisite minimum energy performance defined by the other LEED category EA by adhering to the requirements of ASHRAE 90.1-

2010. The same data sets, compliant with ISO 14044, must be used for both proposed and baseline buildings.

The comparison between the baseline and proposed building evaluates the environmental consequences of building footprint and shape, structural system, products and assemblies, and the optimization of structural design. An example of comparing different structural system types is load-bearing walls versus columns. The documentation to be submitted needs to include the description of these LCA assumptions, the scope, and the analysis process for both buildings, as well as an LCIA summary showing the outputs of the proposed building with a percentage change from the baseline building for all impact indicators.

Five steps are defined to obtain the WBLCA credit (LEED, 2016):

1. Define LCA scope;
2. Select appropriate tools and data sets for LCA;
3. Create and model baseline buildings;
4. Select relevant impact measurement systems;
5. Use LCA to make design decisions that reduce environmental impacts.

The scope of the LCA must be clearly defined in terms of products. The minimum required scope has been limited to structure and enclosure materials due to the current databases of LCI data only including these materials. The material components of footings and foundations should be included. The structural wall assembly comprises everything from cladding to interior finishes, while structural floors and ceilings exclude finishes. Roof assemblies are also included. Parking structures are included, while parking lots are excluded. Table 6.8 gives a comprehensive overview of the building products that must be included or excluded in the LCA.

		Included	**Excluded**
Envelope	Complete envelope	✓	
Structure	Footings and foundations	✓	
	Structural wall assembly	Cladding to finishes	
	Structural floors and ceilings	✓	Finishes
	Roof assemblies	✓	
	Parking structures	✓	Parking lots
External Works	Excavation and other site development		✓
Equipment	Electrical / mechanical equipment and controls		✓
	Plumbing fixtures		✓
	Fire detection and alarm system fixtures		✓
	Elevators		✓
	Conveying systems		✓
Other	Interior nonstructural walls of finishes, etc.	May be included, earns no additional credit	

Table 6.8: Product scope in WBLCA credit

The service life of the LCA study is 60 years or more, but this has often been a complex choice (ISO, 2017). This lifespan has been selected to encompass enough replacement cycles for roof systems, curtain walls, and other envelope materials, while not replacing the structure.

The selection of the LCA tool determines whether an LCA expert is required, as different kinds of tools require changing levels of data control. On the one hand, design team LCA tools are streamlined and simplified so that non-LCA experts can use it without customizing the data, as the calculation factors are specific to the region in which the building is designed.

For North America, an example is Athena's Impact Estimator (Athena, 2009). On the other hand, LCA practitioner tools require experts to choose the suitable data sets and calculation factors for the region in which the building is designed, based on methodological decisions on a product-by-product basis. Globally, examples are GaBi (2006) and SimaPro (2012). A dataset commonly used in North America is the United States Environmental Protection Agency's Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI, 2017) system. Internationally, the Institute of Environmental Sciences CML (2017) system or ReCiPe (2017) system are used.

Six impact categories are considered. The proposed building design must have a 10% reduction compared with the baseline building for the GWP, i.e. its embodied carbon, and at least two other impact categories listed in Table 6.9. None of the other impact categories may increase by more than 5%. These categories have been selected as they are the most used, quantifiable, and understood environmental impacts evaluated by LCA tools. Less readily measurable with LCA tools, other environmental impacts such as human health, ecological, and land-use challenges are addressed under other MR credits. The appropriate output units need to be selected for each LCA impact indicator. Examples are given for TRACI 2.1, CML 2002, and ReCiPe in Table 6.9.

Impact category	**TRACI 2.1**	**CML 2002**	**ReCiPe**
GWP	CO_2 equivalent	CO_2 equivalent	CO_2 equivalent
Ozone* depletion potential	CFC-11 equivalent	CFC-11 equivalent	CFC-11 equivalent
Acidification potential (land)	SO_2 equivalent	SO_2 equivalent	SO_2 equivalent
Eutrophication potential (fresh water)	N equivalent	PO_4^3 equivalent	P equivalent
Formation of tropospheric ozone**	NO_x equivalent	C_2H_4 equivalent	kg NMVOC***
Depletion of non-renewable energy resources	MJ	kg or m^3 of raw material	kg of oil equivalent
**Stratospheric ozone layer;* ***Photochemical oxidant formation*			****Non-methane volatile organic compound*

Table 6.9: Impact categories considered in WBLCA credit

Having to compare the proposed building to the baseline has the disadvantage of being time-consuming. Indeed, two designs and two LCAs need to be developed by the applicant for the WBLCA credit. However, this is the best available method to evaluate the embodied carbon of a proposed design as no benchmarks are yet defined. Therefore, the work on embodied carbon benchmarking in structures (deQo) and buildings (ECB database; Simonen et al., 2017b) is vital to give structural engineers and architects in North America an idea of how their projects perform within the range of typical existing buildings.

From interviews with practitioners who applied for the WBLCA credit [k, l], it appeared the credit did not change the structure of the buildings extensively, as the credit comes at a time where the design is already in place (O'Connor and Bowick, 2016). However, it incentivizes better practice such as reuse of existing foundation, replacement of materials with low carbon alternatives, and enforcing different specifications for concrete to include fly ash replacement for example. Smaller changes rather than structural changes are achieved through rating schemes. The best option among alternative designs is chosen to comply with the LEED requirements.

Table 6.10 gives an overview of the most known building rating schemes, after O'Conner and Bowick (2016), with the number of points related to embodied carbon next to the maximum number of points users can achieve. In the United States, Green Globes is a competing rating scheme that also asks to compare the proposed design against a baseline building, in terms of materials performance (Green Globes, 2017). The Living Building Challenge only has mandatory measures, among which the carbon portion of a whole building LCA (Living Future, 2017).

BREEAM is the most used rating scheme in the United Kingdom and in Europe and contains a credit "Mat 01 Life cycle impacts" to recognize and encourage the use of construction materials with a low environmental impact. The credit does not require a comparison with a baseline building. Instead, the credit is achieved by performing the WBLCA and submitting the BIM file to build up a database, so that a database for benchmarking can be created in the future.

In Australia, Green Star also requires a WBLCA compared to a reference building. The LCA must comply with EN 15978, be peer-reviewed, and done by an LCA practitioner. The reference building must be a conventional alternate design or a comparable existing building. In France, HQE incentivizes a WBLCA performed with the INIES database, compliant to EN 15978 or ISO 21931. The results will later also be used to define benchmarks. In Germany, but also adopted in Austria, Switzerland, Denmark, and Bulgaria, the DGNB developed a certification system that requires the comparison of the WBLCA of the proposed building to theoretical archetypes as benchmarks. In Japan, CASBEE also requires a WBLCA compared to a reference case.

Country	Building rating scheme	Points / Maximum
International	Living Building Challenge	Mandatory
United States	LEED or Green Globes	3 / 110 or extra points
United Kingdom	BREEAM	6 / 132, 3 innovation credits
Australia	Green Star	7 / 110
France	HQE	1 / 14
Germany	DGNB	7 / 45
Japan	CASBEE	Mandatory

Table 6.10: Alternative building rating schemes

6.3.2. Structural Engineers 2050 (SE 2050) Commitment

Targets to keep the global temperatures from rising above 2°C and avoid irreversible climate change were set in the Paris Climate Agreement (UNFCCC, 2015). The IPCC (2014) reports that the building sector should be "zero carbon" by 2050 to meet these targets. While sustainability in design has customarily been the realm of architects, structural engineers have a major role to play in reducing carbon emissions. To achieve a zero-carbon built environment by 2050 will not only require architectural improvements in energy performance of buildings during their use, but also structural optimization of embodied carbon. Indeed, at least 40% of the embodied carbon of buildings comes from structural materials (Kaethner and Burridge, 2012). The significant contribution of structural materials to the environmental impact of buildings is demonstrated in this dissertation. Structural design teams consequently have a major influence on global climate change.

Therefore, a committee of the Carbon Leadership Forum and the author of this dissertation initiated the SE 2050 (2017) Commitment, which aims to inspire structural engineers to contribute towards the global vision of zero carbon buildings by 2050. To do so, they will provide measurement of progress towards this vision by adding data on material quantities and embodied carbon to deQo in an effort to refine benchmarks. The SE 2050 Commitment will challenge structural engineers to meet these increasingly higher embodied carbon reduction targets in a race towards the most efficient building as we advance towards the year 2050, similar to the AIA 2030 Commitment challenging architects to reduce the operational energy in their buildings.

To achieve the embodied carbon reduction needed by 2050, SE 2050 aims to continue the data collection of structural material quantities in buildings through deQo. This interactive, on-going data collection will enable the field to refine the embodied carbon benchmarks used in industry. DeQo has been developed to enable a user-friendly and straightforward, yet robust collection of SMQs in existing buildings. Moreover, the database calculates the embodied carbon of projects based on the entered SMQs, parameters, and material specifications. Structural engineers are rewarded for contributing data by having direct feedback on the total SMQ and GWP of their projects and the comparison with other existing buildings with the same structural system, program use, height, size, typical span, etc. This information on the material efficiency and environmental impact of buildings will help structural engineers evaluate where their projects are compared to other buildings.

The requirements for structural engineering companies that commit to SE 2050 is to provide SMQs and key project information for at least 20 projects, or 20% of their projects, in the first year, with an increasing percentage of their projects contributed per year. Eventually, this will lead to including all projects in design or completed. DeQo can work as a centralized repository to anonymize and aggregate information to keep the project information confidential unless the user wishes to make the data public.

6.3.3. National policies and EPD databases

Most "zero-carbon" policies typically focus on operational energy, which could in some cases lead to counterproductive and burden-shifting measures. In their International Policy Review (O'Connor and Bowick, 2016), the Athena Sustainable Materials Institute recognized the need for embodied carbon policies and the creation of benchmarks. They recommend any jurisdiction to build a framework for benchmarking to create embodied carbon policies:

> *"Our over-arching recommendation is to first require embodied carbon reporting for new construction and then eventually to set required performance targets. [...] A key piece of work will be creation of a "benchmark" system and approach, in other words, the infrastructure for embodied carbon performance targets, which we believe is the most critical component for measurable success."*
> –O'Connor and Bowick (2016)

European countries are increasingly unifying the EPD databases in the building sector (Passer et al., 2015). In the past decade, LCA has become a tool to quantify and report environmental impacts in the form of construction material EPDs. The European standards EN 15804 describe EPD programs. The Product Environmental Footprint (PEF) has different LCIA impact categories and recycling methodologies and is also used in Europe. Countries such as the Netherlands, Germany, France, Switzerland, the United Kingdom, Belgium, Austria, Sweden, but also non-European countries such as Japan, and certain jurisdictions of North America have started implementing policies or policy recommendation to include embodied carbon. Two elements are addressed: the collection and use of EPDs and the use of LCA in building design.

In the Netherlands, it is mandatory to report GHG emissions to get a building permit for all residential buildings and office buildings with a gross floor area higher than 100 m^2. The Stichting Bouwkwaliteit (SBK) unified all existing EPD programs into the Nationale Milieudatabase (NMD) according to the method described in the Assessment Method Environmental Performance Construction and Civil Engineering Works (GWW). SBK also offers unified LCA tools such as GPR Gebouw, the Dutch Green Building Council (DGBC) Materialen tool, and the Milieurelevante Productinformatie MilieuPrestatie Gebouwen (MRPI-MPG) software (milieudatabase.nl, 2016).

In Germany, new federal buildings must achieve the silver level of the Assessment System for Sustainable Building (Bewertungssystem Nachhaltiges Bauen, or BNB). There is also a voluntary DGNB certification system (DGNB, 2017). The Ministry for the Environment, Nature Conservation, Building and Nuclear Safety provides a national materials database (oekobaudat.de, 2016) and a free LCA software tool for buildings, eLCA (Brockmann et al., 2014).

In France, the law requires manufacturers to add EPDs to a national database, INIES owned by the HQE association, if they are claiming their product to be environmental in any way (INIES, 2016). France is also working on harmonizing European EPD programs through the ECO-EPD program.

In Belgium, a similar law has passed to mandate the submission of an EPD if manufacturers want to make claims about the environmental nature of their products in the Belgium EPD Program or B-EPD (BBRI, 2016). Milieugerelateerde materiaalprestatie van gebouwelementen (MMG) is available to perform an LCA of a whole building, using this national database (OVAM, 2012).

In Switzerland, the 2000-Watt Society calls for reducing the GHG emissions per capita with an embodied carbon component, applied in Zurich, Basel, and Geneva (Bretschger et al., 2010). The policy is implemented mainly in Zurich to limit the GHGs and energy consumption per capita through a municipal building code, in compliance with the Minergie standard. The LCIA database of EcoInvent (2016) is available for most construction products in Switzerland.

In the United Kingdom, policies are in development, but industry has published white papers and recommendations for embodied carbon calculations (Embodied Carbon Industry

Task Force, 2014). The Embodied Carbon Week 2014 was organized to get researchers, industry, and policy makers together. The goals of this dissertation were also discussed during this conference. The Government of the United Kingdom is targeting to reduce its GHG emissions from the built environment by 80% from 1990 to 2050. To achieve this, industry is taking a proactive leading role. UKGBC also developed the BRE Green Guide to Specifications to rank building elements based on their LCA results. BREEAM recognizes the need to benchmark LCA for buildings so that a credit can be developed, similar to the WRAP database (WRAP, 2017). The ICE database (Hammond and Jones, 2010) is widely used in industry.

In Austria, an official EPD program was founded by a group of experts from the Austrian Sustainable Building Platform (ASBP) to develop PCRs (Passer et al., 2015). The Austrian Bau-EPD GmbH is also a member of the ECO-EPD platform. Austrian EPDs are entered in the Austrian baubook and the German oekobau.dat. EcoInvent and/or GaBi are also authorized for WBLCAs.

In Sweden, the Swedish Transportation Administration ruling guideline TDOK 2015:0007 addresses the embodied carbon in roadway construction. A software tool Klimatkalkyl helps to calculate the climate impacts of transportation infrastructure.

In Japan, local governments include the green building rating scheme Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in their building policy, so that building owners are required to report the rating achieved to obtain a building permit (CASBEE, 2017).

In North America, local governments, for example in the state of Washington, are exploring the potential for policies on integrating LCA methods, data, and standards into the building code (Simonen et al., 2012). Green building rating programs such as LEED are frequently made mandatory in various jurisdictions. The International Green Construction Code (IgCC, 2012) and the California Green Building Standards Code (CALGreen, 2011) are including optional WBLCA components in building codes in the United States, as a voluntary alternative to prescriptive material requirements.

In Australia, the Australian National Life Cycle Inventory Database (AusLCI, 2017) and the Building Product Life Cycle Inventory database (BPLCI, 2016) include data from major trade associations for construction materials. The standards applied to embodied carbon in Australia and New Zealand is AS/NZS 1170. A widely used Australian based LCA tool is called eTool (2017).

Table 6.11 illustrates the national policies, EPD databases, WBLCA tools, and standards used in the countries discussed in this dissertation. This is not an exhaustive list and will continue to evolve when policies are updated.

Country	EPD database	WBLCA tool	Mandatory?	Standard	Rating Scheme
Australia	AusLCI BPLCI	eTool	No policies yet	AS/NZS 1170	Green Star
Austria	Austrian baubook Oekobau.dat	ASBP guidelines	Requires EPD makers and verifiers to register	EN 15804 ISO 14025	Living Building
Belgium	B-EPD	National tool MMG	Requires EPDs for products claiming to be environmental	EN 15804 EN 15978	MMG
France	INIES	ELODIE	Requires EPDs for products claiming to be environmental	EN 15978	HQE
Germany	Oekobau.dat	eLCA	New federal buildings have BNB Silver level	EN 15804 EN 15978	DGNB
Japan	JEMAI, 3EID	CASBEE	Building owners are required to report CASBEE rating	ISO 14025	CASBEE
Netherlands	NMD database with GWW method	DGBC-tool MRPI MPG	All residential and office with GIA > 100 m^2 buildings report GHG emissions to get building permit	EN 15804 EN 15978	GPR Gebouw
Sweden	TDOK	Klimatkalkyl	Recognizes importance of embodied carbon in transport infrastructure	TDOK 0007	Living Building
Switzerland	EcoInvent	Lesosai	Municipal construction projects in Zurich	2000-Watt Society	Minergie
United Kingdom	ICE	BRE's Impact	No policies yet	EN 15978	BREEAM Living Building
United States			Local governments turn LEED into policy instruments	IgCC CALGreen ISO 14025	LEED Living Building Green Globes

Table 6.11: Overview of national policies, EPD databases, WBLCA tools, standards, and rating schemes

Other incentives for industry to lower the embodied carbon of buildings include education and training of future engineers and architects, early design involvement of structural engineers, investing in R&D in academia, government, and industry, the implementation of tools and plug-ins in computer aided design tools to give direct feedback on the embodied carbon results for the design, and the demand from clients and the general public. Dissemination of the knowledge on embodied carbon assessment and low carbon design is also crucial. This dissertation aims to contribute to this dissemination.

6.4. Summary

The methodology to assess all building layers and stages has been addressed on the building scale. The remaining uncertainties in assessing WBLCA in industry have been identified through interviews and a comparative analysis of four representative case studies: an office building, a residential building, a retail building, and an infrastructure project.

Design strategies to lower the environmental impact of buildings have been discovered by examining the low carbon case studies in deQo. They can be divided in two categories: lowering the material quantities and lowering the ECCs. Structural design optimization, low-maintenance, flexible, adaptable, and durable design, as well as waste minimization can help lower the SMQs. The reuse of building parts and waste, the use of recycled, bio-based, local materials and specifications of concrete mixes with cement replacement are strategies to lower the ECCs. This has been applied to three case studies: the Pines Calyx, the Crossway house, and the Mapungubwe Interpretation Centre resulting in embodied carbon emissions between 30 and 100 kg_{CO2e}/m^2.

Next, this chapter studies how certification systems or rating schemes can help lower the embodied carbon of building structures. The deQo results show that higher levels of LEED certification (Gold and Platinum) do not correlate with a lower embodied impact of building structures, which illustrates how LEED did not reward lower embodied impacts of buildings until version 4 was implemented. LEED Platinum buildings have the highest amount of materials used and the highest environmental impact, LEED certified buildings have the lowest material usage and impact. The requirements of LEED's WBLCA credit are discussed, as well as other rating schemes in the world. The main challenge is the lack of benchmarks. This illustrates the crucial role played by this dissertation's benchmarking effort.

Other industry-wide incentives are also discussed, such as the SE 2050 Commitment, national policies, mandatory EPD databases, WBLCA software tools, education, early design involvement of structural engineers, R&D investments, direct feedback tools, dissemination of knowledge, and client targets.

7. Conclusions

This chapter first summarizes the contributions of this dissertation to draw conclusions on the life cycle impacts of building structures. Then recommendations are formulated for low carbon structural design on the material, structural, and urban scale.

7.1. Contributions

This dissertation offers a new, quantitative, standardized way of assessing the embodied carbon of building structures. By normalizing the embodied impacts of buildings by floor area, the author proposes a new metric, the Global Warming Potential (GWP), for embodied carbon, similar to the Energy Use Intensity (EUI) for operational energy. This embodied carbon metric for building structures can be calculated thanks to the collection of Structural Material Quantities (SMQ) and the transparent definition of Embodied Carbon Coefficients (ECC) with Equation 7.1.

$$GWP = \sum_{i=1}^{N} SMQ_i \times ECC_i \qquad \text{Equation 7.1}$$

where:

i	a particular component or material in the building structure $i = 1, 2, 3$, etc., N
GWP	Global Warming Potential (kg_{CO2e}/m^2)
SMQ_i	Structural Material Quantities (kg_m/m^2)
ECC_i	Embodied Carbon Coefficients (kg_{CO2e}/kg)

Both low material amounts and low carbon material choices are key pathways that can be used for low carbon design in the building industry. Standardizing and normalizing the embodied carbon of building structures is the key contribution of the database of embodied Quantity outputs (deQo), developed for this dissertation. When the ECCs change over time and location, the collected SMQs can be used to update the embodied carbon results. This benchmarking effort and data collection is therefore the first agreed upon methodology that the industry can get behind by reporting material quantities normalized by floor area through the Structural Engineers 2050 Commitment, for example. Developing the first database where both materials and carbon are key instead of only collecting the final embodied carbon results gives a greater degree of confidence. Both lower ECCs and lower SMQs are clear pathways for a low carbon construction industry.

Towards this goal, this dissertation makes four main contributions: 1) regional, recent and transparent ECC ranges for the main structural materials concrete, steel, and timber; 2) uniform benchmarks for SMQs and embodied carbon of building structures; 3) a global methodology for simulating the embodied carbon of neighborhoods; and 4) new pathways to lower the life cycle impacts of the building sector as much as possible. These new low carbon pathways for structural design will ultimately lead to the decrease of greenhouse gas (GHG) emissions, a key element in the fight against climate change and its social inequality, health and environmental consequences.

To enable true innovation in building structures within the architectural context, it is critical to consider how pioneering structures can be designed and constructed. The results of this dissertation demonstrated that design teams can make drastic reductions in GHG emissions through efficient structural design.

7.1.1. Benchmarking

This dissertation identified benchmarks for embodied carbon of building structures on three different scales: the material scale, the structural scale, and the urban scale. This answered the first fundamental question for this research:

"How are benchmarks established to determine the embodied carbon of structures?"

This dissertation addresses this question by creating a methodology and technology to calculate these embodied carbon benchmarks.

Multiplying the two key variables ECC (expressed in kg_{CO2e}/kg) and SMQ (expressed in kg/m^2) gives the GWP (expressed in kg_{CO2e}/m^2) of building structures, to benchmark the life cycle impacts of the built environment. More specifically, three key questions were identified:

- *Material scale*: How can we define reliable ECCs?
- *Structural scale*: What are the SMQs and embodied carbon of building structures and infrastructures?
- *Urban scale*: Can we simulate the GWP embodied in cities?

To answer the first question on the material scale, this dissertation reviewed available databases and tools to analyze the life cycle impacts of building materials. Based on industry statistics and on a transparent methodology, regional ECCs were defined for concrete, steel, and timber as the main structural materials. The embodied carbon of concrete varies depending on strength, cement production emissions in various regions, cement replacement, and reinforcement content. The embodied carbon of steel varies depending on the production process, the recycled content and the energy mix in various regions. The embodied carbon of timber varies depending on forest management, the sustainable forest certification, the energy mix, the transport distance and mode, and the end-of-life treatment in various regions.

To answer the second question on the structural scale, this dissertation developed an interactive, worldwide, transparent database, called deQo. As structural designers need to know the embodied carbon of structures, appropriate benchmarks are necessary. The ranges of material quantities and embodied carbon published in this dissertation can be used for policy making and referencing in rating schemes such as LEED or BREEAM. The data collection of more than 600 existing buildings worldwide enabled the establishment of these benchmarks. Typical building structures have an embodied carbon between 200 and 550 kg_{CO2e}/m^2. The average of the first 600 buildings added to deQo is 353 kg_{CO2e}/m^2. The standard deviation is 194 kg_{CO2e}/m^2.

To answer the third question on the urban scale, this dissertation applied the key variables on various buildings in the Al-Qādisiyyah neighborhood in Kuwait. This case study showed that it is possible to simulate both embodied and operational carbon through urban modeling to understand how to lower the life cycle impacts of the built environment. Governments can mandate the assessment and reduction of embodied carbon compared to the benchmarks defined in this dissertation. This research illustrates the GHG emission savings possible on a neighborhood scale for different design options, compared to the current state of the art. In spite of the fact that envelope upgrades minimally increase embodied emissions, choosing low-carbon materials can considerably decrease the carbon emissions compared to current embodied emissions.

7.1.2. Low carbon pathways

This dissertation also addressed how to expand from building structures to the whole building. The non-structural layers of a building often require more frequent maintenance and replacement, leading to an increased contribution of gate-to-grave life cycle stages. A comparative analysis of an office building, a residential building, a retail building, and an infrastructure project showed that the structure accounts for approximately 70% of the GHG emissions over a building's entire life cycle.

The integrative assessment approach discussed in Section 7.1.1 helps to define low carbon pathways for structural design: lowering the material quantities (low SMQ) and choosing low carbon materials (low ECC). To define low carbon pathways for structural design, a second fundamental key question can be answered:

"How low can we go?"

With the data collected in deQo, design pathways have been identified by looking at the lower bound of the projects. Two main pathways lead to a reduced environmental impact: lowering the SMQs and lowering the ECCs. Based on case studies such as the Pines Calyx, the Crossway house, and the Mapungubwe Interpretation Centre, this dissertation found it is possible to be more than one order of magnitude lower than the average of embodied carbon in existing buildings by applying the following strategies.

- *Low Carbon Pathway 1*: How can we lower the SMQs?
- *Low Carbon Pathway 2*: How can we lower the ECCs?

To lower the SMQs, designers can optimize the layout plan; optimize the structural system; design a low-maintenance building; design a flexible and adaptable building; optimize the components' service life; increase the durability of building components; minimize waste; and preserve existing buildings rather than building new ones.

To reduce the ECC of materials used in their projects, designers can reuse building parts and elements; use recycled or recyclable materials; use bio-based materials; use low carbon materials; design for deconstruction; use local materials; change the way materials are manufactured; and reuse waste.

Much like the Hannover Principles (2000) for designing buildings, these low carbon structural design pathways are key principles to design structures with a lower embodied carbon.

Industry initiatives and policies can help implement a new low carbon built environment. Such industry strategies include: certification systems or rating schemes; the SE 2050 Commitment; national policies; mandatory EPD databases; direct feedback WBLCA software tools; the training of structural engineers; R&D investments in companies; demands coming from the clients; and the early involvement of structural engineers in the concept design stage. A review of LEED's WBLCA credit and other existing rating schemes illustrated the recently growing awareness of embodied carbon in the building sector and in environmental assessment programs.

7.2. Recommendations for low carbon structural design

7.2.1. Material scale

The literature of this dissertation illustrated the variability of ECCs available for designers to make informed material choices. Industry and material trade associations tend to have a non-analytical approach and to make assumptions that are most advantageous to a certain material. For example, concrete and cement suppliers can emphasize a single number at the lowest bound of ECCs saying waste materials were used while rebar, cement replacement with fly ash, and strength considerably widens the range of ECCs for concrete. Steel suppliers will argue that the recycled rate at the end-of-life should be taken into account, while wood organizations will emphasize carbon sequestration. The life cycle stages and assumptions when calculating the ECCs of structural materials are both controversial and complex. A lack of standardized EPDs and transparent calculations leads to environmental claims of each material industry being the "greenest" as a marketing strategy lacking credibility in scientific communities. Comparisons between the main structural materials concrete, steel, and timber are recently en vogue, to figure out which of the materials has the lowest embodied carbon. The answer to this question is: "It depends."

The contribution of this dissertation on the material scale is twofold. First, it assessed the currently available databases and tools. Second, this dissertation showed a transparent calculation methodology to compute the ECC of concrete, steel, and timber in different regions of the world, based on data that is reliable and can be updated in the future (for example if the grid decarbonizes). The numbers given for the ECC of the three main structural materials are not meant to give definite and precise end results but are rather placeholder numbers to evaluate the environmental performance of their structure until the field matures with more accurate coefficients for each construction product.

Furthermore, this dissertation showed a high regional variability. For example, North American concrete turned out to have the highest ECC compared to other regions. This can be explained by the difference in efficiency of the kilns in different countries (Fernández, 2006; WBCSD, 2015). For example, while the United States previously invested in wet kilns to make cement, Europe and emerging economies now use dry kilns, which are more efficient than wet kilns, due to regulation and modernization.

Conversely, the opposite is true for steel: in the United States and Europe, more scrap steel is available, leading to a higher recycled content – in contrast to emerging economies such as China. In other words, when there is more available scrap steel, the ECCs are lower.

Timber also varies from one region to another, depending on the managment of forestry. For example, only 26% of global timber supply comes from sustainable certified forests (ITTO, 2011). The remaining timber therefore contributes to deforestation rather than carbon sequestration.

This dissertation therefore offers regional, transparent ECC calculations for concrete, steel, and timber so that structural designers can write the material specifications that will best lower the environmental impact of their design project. Recommendations are made to replace cement in concrete with lower emitting materials such as waste materials. Pulverized fuel ash (PFA), such as fly ash, can be used to lower the embodied carbon of concrete. High recycled content lowers the embodied carbon of steel. Timber from certified sustainable forests and sawn lumber have a lower embodied carbon than conventional engineered timber. The ranges published in this dissertation illustrate that using just one number for the ECC of a material worldwide is an oversimplification. Many factors need to be taken into account leading to wide ranges depending on regional energy mixes, material ingredients, strength, production methods, recycled content, and origin of the product.

The cradle-to-gate ECCs of concrete vary between 0.09 and 0.18 kg_{CO2e}/kg (without reinforcement), those of steel between 0.41 and 4.84 kg_{CO2e}/kg, and those of timber between negative values and 0.62 kg_{CO2e}/kg. Concrete, steel, and timber have different strength, stiffness, and density properties, so these numbers are no indication of the materials' environmental performance. Rather, they can be used as a guideline for calculating the environmental impact, more specifically the GWP, of a building structure.

7.2.2. *Structural scale*

To benchmark the embodied carbon of building structures, many companies have started collecting the quantities and the embodied carbon of their building structures in in-house databases. To offer a transparent, reliable, and accessible database to be used across companies, this dissertation developed deQo. The database collected material quantities of more than 600 projects worldwide and calculated the embodied carbon of all projects in order to define a baseline for benchmarking.

The results of the SMQs, normalized by floor area, range on average between 650 and 1350 kg/m^2. The results of the embodied carbon, also normalized by floor area, range on average between 200 and 550 kg_{CO2e}/m^2. Ranges of SMQ and GWP were given by program type, structural system, size, height, typical span, longest span, and LEED certification. Industrial buildings have the highest impacts. The timber and masonry structural systems have the lowest impacts. The material quantities increase with size, height, and span, with the strongest correlation between the typical span and the GWP.

Thus, this dissertation contributes to a unified and transparent data collection that will help define benchmarks for assessing the embodied carbon of structural design. Ranges and specific, normalized numbers are defined for material quantities and embodied carbon. To encourage architects and structural engineers to practice sustainable design, it is important to know the embodied carbon of entire structures for different typologies: within a certain building type, structural system, size or height, they can now compare their efforts to baselines for similar types in the existing building stock.

Figure 7.1 shows an example of the ranges plotted on the online interface of deQo. These graphical data visualizations were shown in Chapter 4 and further discussed in Chapter 6 to define low carbon buildings. The benchmarks are listed more explicitly in Table 4.4 in Chapter 4. For example, commercial buildings can go as low as 30 kg_{CO2e}/m^2.

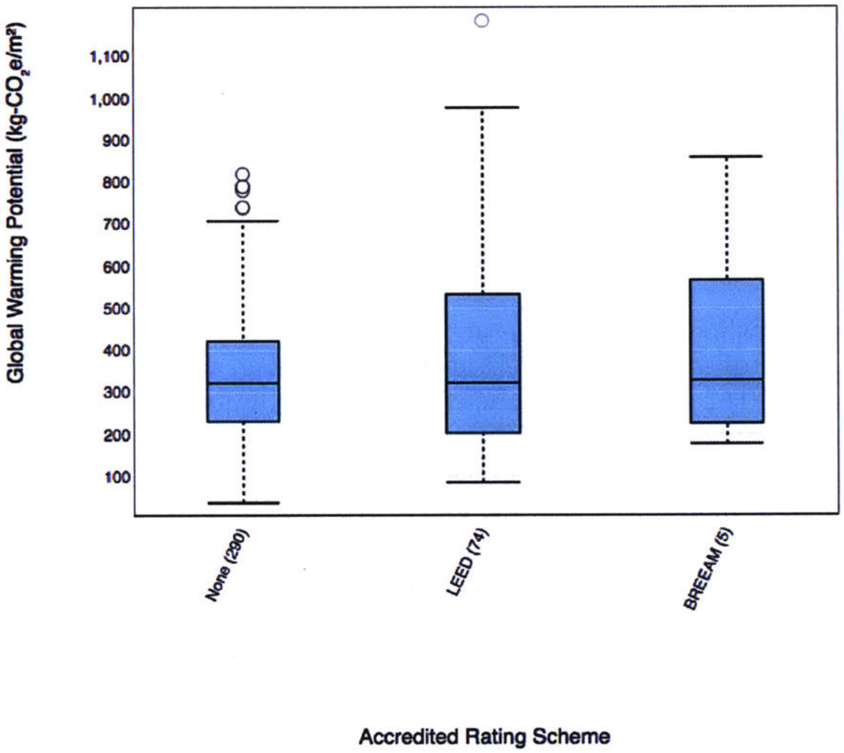


Figure 7.1: Boxplots from the online interface of deQo

Moreover, distinguishing the results for material quantities and embodied carbon allows a critical review of life cycle impacts of buildings. For structural designers, the key to improving a sustainable structure is to increase the material efficiency on the one hand and to reduce the embodied carbon of their material choices on the other hand. When this research field expands the available data from cradle-to-gate ECCs to cradle-to-grave ECCs, the results for material quantities can still be used to calculate the complete life cycle impacts of the various building structure types.

Ideally, the results of this research will also influence policy makers and rating schemes. Indeed, the embodied carbon of cultural, educational, and sports buildings can be lowered significantly by lowering the material quantities or by changing the material choices. These design decisions can be imposed or encouraged by municipalities, institutions and nations in order to approach the lower part of the GWP range for their building stock. For example, the London Olympic Stadium's embodied carbon is more than ten times lower than the Beijing Olympic Stadium, simply by their setting different targets at the concept design stage. This low carbon goal can now be regulated based on the obtained preliminary benchmarks, serving as a baseline for rating schemes.

Ultimately, this dissertation has proven that many fields can contribute to lowering the environmental impact of buildings. This research offers three new insights: first, it gives normalized numbers for the embodied carbon on the structural scale for different building types, structural systems, sizes, and heights in order to complete the literature that focused only on the material scale; second, it shows the urgent need to redirect policies and rating schemes; third, it demonstrates the impact of designers on the environmental impact of buildings. This research is an innovative step towards more environmentally responsible design in practice. Visualizing and comparing results of the database will build literacy about how various building typologies affect the climate. This analysis of material quantities and embodied carbon will hopefully direct architects and engineers towards low-impact design.

7.2.3. Urban scale

Evaluating the environmental impacts of buildings and how to reduce them on the urban scale is crucial, as urban policies have the potential to mandate the reduction of embodied carbon of buildings. To obtain a building permit, city governments could change the requirements and building codes to include embodied carbon of structures. Therefore, urban modeling can be used to evaluate both embodied and operational carbon of neighborhoods and how to reduce their impacts. Current tools only allow the simulation of operational energy and carbon of neighborhoods. Several studies have investigated the life cycle impacts of buildings on a city level, but a lack of consensus on the methodology and boundary conditions obstructs a comparative analysis.

This dissertation illustrated how urban modeling can inform on both operational and embodied carbon reductions that can occur on an urban scale. A newly developed methodology was applied to a case study of a Middle Eastern residential neighborhood. Various scenarios were measured against each other to evaluate the tradeoffs and influences of envelope upgrades and the use of PV panels on the whole life cycle energy and carbon of the neighborhood. The choice of low carbon materials and structural optimization were applied to the residential buildings, in order to make recommendations for new policies and building codes.

Current building codes only focus on operational energy and carbon savings. Often, the building codes of the United States or Europe may be "copied" in countries that have different construction demands related to their climate and resources. Many countries set goals to reduce carbon by 2030, including Kuwait, where the case study was analyzed. It is therefore essential to include embodied carbon simulations in urban models. Tradeoffs between embodied and operational impacts showed that adding insulation and PV panels in built environments such as in Kuwait can be beneficial for the whole life cycle emissions of the neighborhood, while only slightly increasing the embodied impacts. Choosing more traditional materials such as rammed earth can drastically lower these embodied impacts.

The results of this dissertation showed that urban modeling of embodied and operational carbon is needed. The distribution of building results illustrated the importance of working with the diversity of real, existing buildings. Policies can achieve reductions by setting the goals according to the potential GHG emission savings.

This research on the urban scale included results from the material and structural scales. The Al-Qādisiyyah neighborhood was used as a case study to evaluate the embodied carbon of hundreds of buildings at a time. Scenarios of design improvements showed that embodied carbon could be lowered by 200 kg_{CO2e}/m^2 or by 51%, compared to current construction techniques. The tradeoff between embodied and operational impacts led to recommendations for Middle Eastern governments to improve the sustainability of their new cities.

7.3. Future work

To fully enable an industry-wide reduction of GHG emissions of the built environment, the work presented in this dissertation should be deepened on different scales. On the material scale, a collective effort is needed to calculate ECCs worldwide. New low carbon materials could be designed. On the structural scale, detailed structural types should be compared and redesigned with embodied carbon amongst the design parameters. On the urban scale, the CO_2e emissions need to be linked with population growth and include climate change predictions. Three areas for future work are required towards a vision of carbon free buildings by 2050: industry participation, LCA expertise development, and holistic design taking operational and financial costs into account.

It is essential to look at future design and research advancements but also at what historic structures can teach us if we are to evolve toward a carbon free built environment by 2050. This dissertation showed examples of structures that could drastically lower the embodied carbon.

7.3.1. Industry participation

Industry participation is essential at multiple levels: the collection of Environmental Product Declarations (EPDs) by the manufacturing industry, the collection of SMQs by the structural engineering industry, and the integration of embodied carbon in current design tools.

- Collection of EPDs

Construction material manufacturers need to refine reliable ECCs industry-wide and globally. The collection of data on the embodied carbon of materials in different regions can be required with mandatory national EPD databases. This dissertation has shown that this is already the case in various countries for products that want to achieve an environmental rating.

- Refining the benchmarks offered by deQo

Design companies can help refine the data already collected in deQo by adding projects to the database. Gathering more data and refining the accuracy of the data can only be achieved in close collaboration with industry. Structural design firms can then measure their results against the continuously refined benchmarks.

With thousands of data points, uncertainty and sensitivity analyses can then be performed more thoroughly. Initiatives such as the SE 2050 Commitment can encourage structural engineering offices to contribute data and to reduce their embodied carbon results by a certain percentage each year to achieve zero carbon buildings by 2050. A peer review system can add an extra layer of data quality assessment.

- Direct feedback design tools

Multi-objective optimization and embodied carbon assessment can be integrated in Building Information Models (BIM) to give designers direct feedback on their designs. Data imported in deQo can be inputted automatically based on spreadsheets extracted from BIM. The next step will be to link the database and the benchmarking directly to the design space of the structural engineer or architect.

Design tools that can truly be implemented in current practice should be developed, such as Revit plug-ins, with a clear transparency on data and methodology. Currently, many commercial and non-commercial stand-alone calculation tools exist, but these are not the answer to the challenges of embodied carbon assessment (Ariyaratne and Moncaster, 2014). These in-house tools lack transparency, flexibility, and efficiency at early design stages. However, including embodied carbon assessment in Building Information Modeling software would integrate life cycle thinking in the design process of architects and engineers and needs to be explored further.

7.3.2. LCA expertise development

Two aspects of LCA need to be developed further: including other impact factors and improving knowledge on all life cycle stages. Moreover, the LCA of building structures is the first step in the assessment of the environmental impacts of whole buildings and cities. Finally, LCA of a single building takes a different approach compared to looking at entire cities.

- Impact factors

This dissertation has focused on the GWP or carbon dioxide equivalent (converting all GHGs to their equivalent in CO_2 emissions), but the environmental impact of buildings also includes other factors according to the ISO norms, such as abiotic depletion, acidification, eutrophication, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, and photochemical oxidation or smog.

Including all impact factors gives an agreed upon overview of measurable environmental impacts of building structures. Other factors are more difficult to evaluate quantitatively, such as the visual impact for example, which is prone to subjective qualitative measurements.

Furthermore, strategies for reducing GHG emissions often have co-benefits for reducing health-damaging air pollutants such as particulate matter, nitrogen oxides, and sulfur dioxide (Nemet et al., 2010; Zhang et al., 2015). Especially in emerging and developing countries (Figure 7.2), cement production is often localized and reducing particulate matter can have beneficial economic and health implications (Bagayev and Lochard, 2017).

Figure 7.2: Beijing air pollution. Image from South China Morning Post (2017)

- Whole life cycle

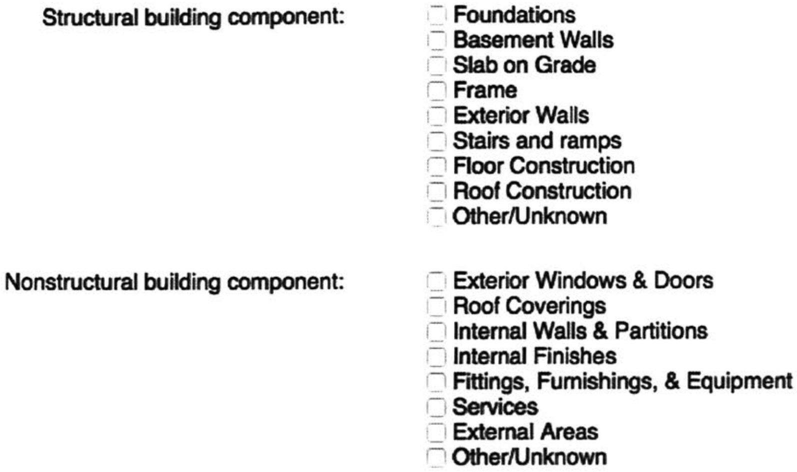
When expanding from the structural to the building scale, all life cycle stages need to be included. Indeed, structural components mainly emit GHGs at the cradle-to-gate stages A1 to A3, as they need little maintenance and replacement over a building's lifetime. However, this dissertation has shown that façade components such as curtain walling also emit a considerable amount of GHGs for their maintenance and replacement during the rest of a building's lifecycle.

The TC 350 Committee gave a clear definition of what should be included in the lifecycle of buildings according to the European norms EN 15978, which are starting to get adopted worldwide, but industry still lacks the knowledge and tools to calculate the emissions related to scenario predictions beyond the initial life cycle stages.

- Whole building

Collecting material quantities on a building scale requires a clear distinction between the building components. Athena Sustainable Materials Institute is working on developing a methodology for a WBLCA database that includes all impact factors for all life cycle stages for all building components.

Starting from deQo to expand to non-structural components, the material quantities could be associated to the different parts of the building. This option is readily available in the deQo "Create" form to input a whole building rather than only the structure (Figure 7.3).



Structural building component:

☐ Foundations
☐ Basement Walls
☐ Slab on Grade
☐ Frame
☐ Exterior Walls
☐ Stairs and ramps
☐ Floor Construction
☐ Roof Construction
☐ Other/Unknown

Nonstructural building component:

☐ Exterior Windows & Doors
☐ Roof Coverings
☐ Internal Walls & Partitions
☐ Internal Finishes
☐ Fittings, Furnishings, & Equipment
☐ Services
☐ External Areas
☐ Other/Unknown

Figure 7.3: Structural and non-structural building components associated with material quantities in deQo

LCA started in the 70s, when it was called Resource and Environmental Profile Analysis (REPA), Energy Analysis, or Product Ecobalance (Guinée, 2002). Multiple organizations such as the Society of Environmental Toxicology and Chemistry (SETAC), ISO, and United Nations Environmental Programme (UNEP) participated in the last decades towards more uniform methodologies. The field of LCA on the building scale is relatively new (Bowick, 2017). Therefore, the maturity and new research in WBLCA will enhance the accuracy of the results. New data will be available in the coming years. The development of international and European norms to standardize LCA is a sign that the field is maturing towards a consensus for measuring the environmental impact of the building sector.

- Embodied carbon of cities

This dissertation focused on the definition of embodied carbon in building structures, even on the urban scale, in contrast to studying the carbon emissions of entire cities. Looking at the temporal aspects of urban metabolism can give a different perspective on the materials to be used in buildings. A unit of carbon emitted today does not have the same impact as a unit of carbon emitted 75 years later. For example, the recyclability of steel can be exploited on a city scale and the potential decarbonization of many cities' energy mixes changes the results for the ECCs offered in this dissertation.

7.3.3. Holistic design

- Including operational carbon and financial cost

Finally, only looking at embodied carbon or other LCA impact factors applied to material manufacturing, transport, construction, maintenance, and demolition is short-sighted. Although operational impacts have decreased tremendously with recent energy efficiency measures and norms, it is still important to look at the tradeoff between both embodied and operational carbon, as was done for the case study of a Middle Eastern neighborhood in this dissertation. Looking at the potential decarbonization of the grid is also part of including operational carbon in holistic design.

Industry incentives for reducing embodied carbon will not be as effective as financial cost reduction. LCA should therefore include both operational and embodied impacts and be combined with Life Cycle Cost Analysis (LCCA). Aligning the collection material quantities with LCCA has the potential to reduce the time allocated to carbon accounting in structural engineering, architecture, and contractor firms.

- Multi-objective optimization

Multi-objective optimization (Brown and Mueller, 2016) looking at embodied carbon, operational carbon and financial cost could advance the knowledge on how to design a better built environment. Other aspects next to operational carbon and financial costs can also be included in multi-objective optimization. Many design firms are already using optimization tools to compare other building performance factors, for example daylighting autonomy. Figure 7.4 illustrates an example of an in-house tool that could include embodied carbon as one of the factors designers can look at through multi-objective optimization, called Design Explorer, developed by the CORE studio (2016) of Thornton Tomasetti.

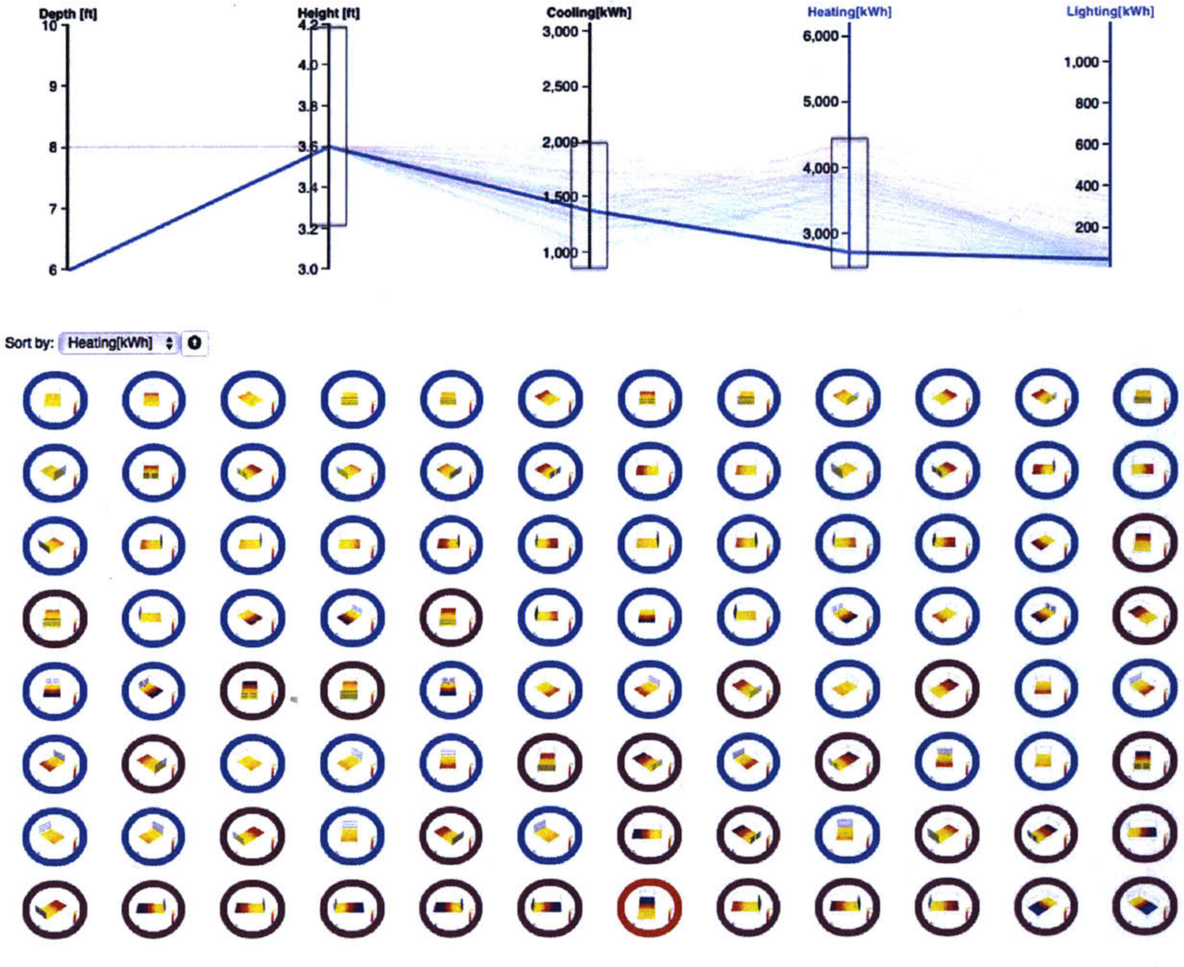


Figure 7.4: Example of multi-objective optimization tools used in industry (CORE studio, 2016)

- SE 2050 and deQo

This dissertation presented an integrated assessment approach to compare embodied life cycle impacts of building structures and recommended new pathways for low carbon structural design, vital for the development of a low carbon building industry. The database developed for this dissertation, deQo, as well as the SE 2050 Commitment Initiative aim to contribute to a low carbon future.

7.4. Concluding remarks

This dissertation answered the fundamental questions on how benchmarks are established to determine the embodied carbon of structures and how low we can go. Equation 7.1 is at the heart of the answers from the material to the urban scales. By normalizing the embodied impacts of buildings by floor area, a new metric is proposed for embodied carbon, the GWP, similar to the EUI for operational energy.

On the material scale, reliable, recent, and regional ECCs are defined. For example, 50 MPA concrete in North America has an ECC around 0.17 kg_{CO2e}/kg and structural steel in North America has an ECC around 1.37 kg_{CO2e}/kg. On the structural scale, an interactive, worldwide, transparent database, called deQo, has collected over 600 existing buildings to establish benchmarks with an average of 353 kg_{CO2e}/m^2. On the urban scale, the GWP of the Al-Qādisiyyah neighborhood in Kuwait was simulated to show that significant savings are possible with a low carbon design. Lowering both ECC and SMQ can lower the GWP of the built environment, as shown in the case study of the Mapungubwe Interpretation Center with a value as low as 30 kg_{CO2e}/m^2.

To summarize, this doctoral research made four key contributions. On the material scale, regional, recent, and transparent ECCs are developed for structural materials such as concrete, steel, and timber in a fast evolving, geography-dependent field. On the structural scale, benchmarks are established by collecting SMQs and calculating the GWPs of building structures. On the urban scale, the embodied carbon of an entire neighborhood can now be calculated. Finally, recommendations are developed for low carbon pathways in structural design.

To conclude, at the start of this work, the field of measuring embodied carbon was still in its infancy with a false sense of precision. Through this doctoral research, the embodied carbon of building structures was standardized and normalized through deQo so that when ECCs change over time and location, the collected SMQs can be used to update the embodied carbon results. This data collection and benchmarking effort is the first agreed upon methodology that the industry can get behind through the SE 2050 Commitment. Both lower ECCs and lower SMQs are clear pathways to a new carbon-centric design method initiated by the results of this dissertation.

This work aims to inspire engineers and architects to follow in the footsteps of low carbon case studies such as the Mapungubwe Interpretation Centre, in order to avoid disruptive climate catastrophes. Structural engineers and architects can now work hand in hand to lower the carbon footprint of the buildings needed to respond to rising global housing needs while reducing GHG emissions. Indeed, it is vital to reduce the embodied carbon of building structures, which can be achieved through the innovative low carbon pathways presented in this dissertation.

PART IV • APPENDICES

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C. Whole life cycle calculations

Starting at the level of the production and construction process, the calculations can be divided into three parts: the embodied carbon of the materials themselves (IEC), the carbon emissions due to the transportation to the site and the carbon emitted during the building erection. The production stage (cradle-to-gate) is often the main contribution to the embodied carbon of structures (Vukotic et al., 2010). Equation C.1 gives the IEC of a building structure. In all following equations, the subscripts "b" stand for "building structure" and "m" for "material". The ECC refer to cradle-to-gate coefficients. A waste percentage can also be taken into account.

$$IEC_b = \sum_{m=1}^{M} \left[ECC_m \times \left(1 + \frac{w_m}{100}\right) SMQ_m\right] \qquad \text{Equation C.1}$$

where:

IEC_b	Building Initial Embodied Carbon (kg_{CO2e}/m^2)
ECC_m	Embodied Carbon Coefficient (kg_{CO2e}/kg)
w_m	Waste (%)
SMQ_m	Structural Material Quantity (kg_m/m^2)

The transportation emissions are illustrated in Equation C.2, where for each material the number of truckloads is multiplied by twice the distance traveled from manufacturer to the site and with the fuel consumption in liter per kilometer as well as the fuel combustion emissions in kilograms of CO_2e per liter.

$$TEC_b = \sum_{m=1}^{M} TEC_m = \sum_{m=1}^{M} [SMQ_m \times 2d_m \times fc_m \times fCO_{2m}] \qquad \text{Equation C.2}$$

where:

TEC_b	Building structure Transport Embodied Carbon (kg_{CO2e}/m^2)
TEC_m	Material Transport Embodied Carbon (kg_{CO2e}/m^2)
SMQ_m	Structural Material Quantity (kg_m/m^2)
d_m	Distance traveled from manufacturer to site (km)
fc_m	Fuel consumption (l/km)
fCO_{2m}	Fuel combustion CO_2e emissions (kg_{CO2e}/l)

The third part looks at the carbon emitted during building erection (Equation C.3). The CO_2e emissions during construction and demolition of the building are obtained by summing over all materials the product of the equipment days on site, the fuel consumption per day and the fuel combustion CO_2e emissions per liter of fuel consumed.

$$CEC_b = \sum_{m=1}^{M} CEC_m = \sum_{m=1}^{M} \left[\frac{ed_i \times fc_m \times fCO_{2m}}{A}\right] \qquad \text{Equation C.3}$$

where:

CEC_b	Building structure Construction Embodied Carbon (kg_{CO2e}/m^2)
TEC_m	Material Transport Embodied Carbon (kg_{CO2e}/m^2)
CEC_m	Material Construction Embodied Carbon (kg_{CO2e}/m^2)
ed_m	Equipment days on site
fc_m	Fuel consumption per day (l/day)
fCO_{2m}	Fuel combustion CO_2 emissions (kg_{CO2e}/l)
A	Floor area (m^2)

Equation C.4 gives the REC of a building structure. The transport and construction emissions of the replaced products should also be added.

$$\mathrm{REC_b} = \sum_{y=1}^{\mathrm{life\ span}} \sum_{m=1}^{M} [\mathrm{ECC_m} \times \mathrm{SMQ_m} + \mathrm{TEC_m} + \mathrm{CEC_m}] \qquad \text{Equation C.4}$$

where:

$\mathrm{REC_b}$	Building structure Recurrent Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$) (only use phase, starts at year 1)
$\mathrm{CEC_m}$	Material Construction Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{ECC_m}$	Embodied Carbon Coefficient ($\mathrm{kg_{CO2e}/kg}$)
$\mathrm{SMQ_m}$	Structural Material Quantity ($\mathrm{kg_m/m^2}$)

Equation C.5 gives the EoLEC of a building structure. This definition of end-of-life carbon includes both the emissions of the end-of-life stages (C1-C4) and the emissions beyond the life cycle stages (D). If life cycle stage D is not included, the benefits are excluded the calculations.

$$\mathrm{EoLEC_b} = \sum_{m=1}^{M} [\mathrm{L_m} \times \mathrm{SMQ_m} - \mathrm{B_m} \times \mathrm{SMQ_m}] \qquad \text{Equation C.5}$$

where:

$\mathrm{EoLEC_b}$	Building structure End of Life Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{L_m}$	Loads (deconstruction, demolishing, transport, waste processing, disposal)
$\mathrm{B_m}$	Benefits (reuse, recovery, recycling)

Finally, the total embodied carbon is calculated by summing all the previous definitions of embodied carbon and is called LCEC (Equation C.6).

$$\mathrm{LCEC_b} = \mathrm{IEC_b} + \mathrm{TEC_b} + \mathrm{CEC_b} + \mathrm{REC_b} + \mathrm{EoLEC_b} \qquad \text{Equation C.6}$$

where:

$\mathrm{LCEC_b}$	Building structure End of Life Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{IEC_b}$	Building Initial Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{TEC_b}$	Building structure Transport Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{CEC_b}$	Building structure Construction Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{REC_b}$	Building structure Recurrent Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{EoLEC_b}$	Building structure End of Life Embodied Carbon ($\mathrm{kg_{CO2e}/m^2}$)

The IEC corresponds to cradle-to-gate embodied carbon. Adding TEC to the IEC gives the cradle-to-site embodied carbon. The LCEC gives the cradle-to-grave or cradle-to-cradle (depending on whether or not the benefits are included) embodied carbon.

When comparing the embodied carbon of different structures, the IEC is studied, as the TEC and the CEC depend on the location of the construction site, the REC is small for the structural part, which often remains until the end-of-life of a building, and the EoLEC requires predicting unknown scenarios.

D. Description and specifications of deQo

This research proposes 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. In 2017, the University of Washington also launched a database collecting embodied carbon end results for buildings in the Embodied Carbon Benchmark Study (Simonen et al., 2017a; Simonen et al., 2017b; Simonen et al., 2017c). The purpose was to start benchmarking embodied carbon in buildings and the study recommended working on collecting material quantities and on establishing an LCA practice guide. The results of the database developed for this dissertation were included in this initial embodied carbon data visualization.

Therefore, this dissertation proposes a framework for a complete database including material quantities together with the embodied carbon of building structures: the database of embodied Quantity outputs (deQo). The input and output parameters is compatible with other databases such as WRAP, Project Embodied Carbon Database (PECD), the Embodied Carbon Benchmark (ECB) database, etc. and use existing, international listings, classes and standards. The database contains a significant amount of data (over 600 buildings) entered with comparable assumptions.

On one side, 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. The user can access this part online and can make different queries. On the other side, a relational database, inaccessible to the user, stores the project data. DJANGO is currently processing the data back and forth from the website to the SQLite database.

The Global Warming Potential (GWP) is the final embodied carbon result for the building as illustrated in the following equation.

$$\mathrm{GWP} = \sum_{i=1}^{N} \mathrm{SMQ}_i \times \mathrm{ECC}_i \qquad \text{Equation D.1}$$

where:

i	a particular component or material in the building structure $i = 1, 2, 3$, etc., N
GWP	Global Warming Potential ($\mathrm{kg_{CO2e}/m^2}$)
$\mathrm{SMQ_i}$	Structural Material Quantities ($\mathrm{kg_m/m^2}$)
$\mathrm{ECC_i}$	Embodied Carbon Coefficients ($\mathrm{kg_{CO2e}/kg}$)

This section explains the general framework of the database and expands on the features and options that the database includes in order to be useful for the industry. The in- and output parameters of the database are discussed. The collected information is divided into different groups (Table D.1): general and structural information. A future integration of operational energy, maintenance and financial cost is possible.

1.	**General Information** Credits, references, photo	
2.	**Building Location** Region, country, detailed location	
3.	**Building Status** Year, project phase	
4.	**Building Type** Program, number of occupants/seats/units	
5.	**Building Unit System** Metric (SI) or imperial units	
6.	**Building Geometry** Floor area, height, number of floors, span	
7.	**Accreditation** Rating scheme	
8.	**Building Surroundings** Hazard zone, soil, climate	
9.	**Building Components** Main structural system material, vertical/horizontal/lateral structural system	
10.	**Used Materials** Material quantities and specifications, sources	
11.	**Expected Building Life**	
	Embodied Carbon Coefficients	*Default or entered by user*
	Results Material Quantities or GWP ranges	Comparative charts

Table D.1: Framework for a database

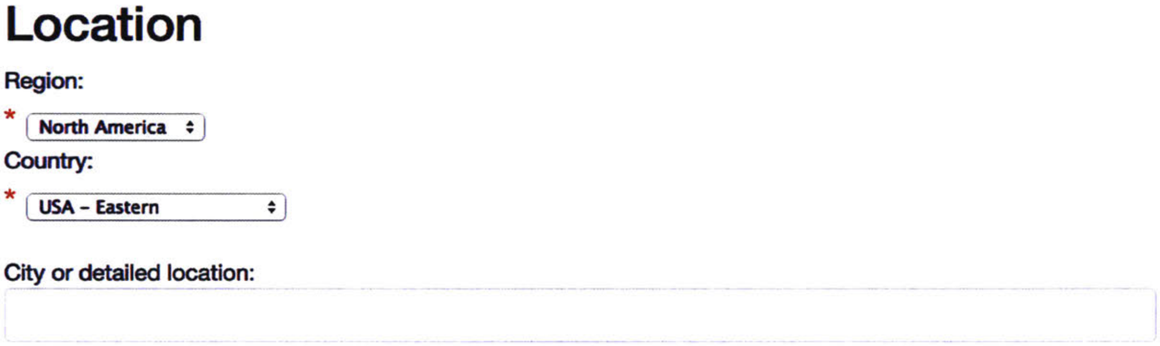
The database contains the following input parameters (the * indicates mandatory fields). The units (m, ft, m^2, ft^2) are showing next to the user's entry in the metric system they selected for "Units" (metric or imperial). General information is illustrated in Table D.2.

	General Information	
*	Project name	Text
	Should this building be publicly viewable?	☑ ☐
	Is this a Structural Engineers 2050 (SE2050) submission?	☑ ☐
	References and sources for this information	Text
	Publication journal	Text
	Architect	Text
	Engineer	Text
	Contractor	Text
	Client	Text
	Upload photo	Choose File no file selected
	Image source, as URL, if applicable:	

Table D.2: General Information

Building Location is illustrated in Table D.3.

	Building Location	
*	Region	Multiple choice: Africa, Asia, Australia, Europe, Middle East, North America, South America
*	Country	Multiple choice that offers all countries available in the region that the user selected above
*	City or detailed location	Text



Location

Region:

* North America

Country:

* USA - Eastern

City or detailed location:

Table D.3: Building Location

Building Status is illustrated in Table D.4.

	Building Status	
*	Construction completion year	Year
*	Current project phase category	☐ Theoretical Design ☐ Existing Building
*	Current project phase	If Theoretical Building: ☐ Theoretical Design If Existing Building: ☐ Concept Design ☐ Developed Design ☐ Technical Design ☐ Fabrication Design ☐ Construction ☐ In Use

Table D.4: Building Status

Building Program Type is illustrated in Table D.5.

	Building Program Type	
*	Program type category	Multiple choice: ☐ Residential ☐ Commercial ☐ Industrial ☐ Infrastructure ☐ Other Non-Residential ☐ Mixed Use
*	Program type	Multiple choice: If Residential

	☐ Single-family ☐ Multi-family – Low Rise (< 5 storeys) ☐ Multi-family – Medium Rise (5 – 15 storeys) ☐ Multi-family – High Rise (>15 storeys) If Commercial ☐ Retail ☐ Warehouses ☐ Office ☐ Air, Rail or Road Transport Terminals ☐ Parking Garages or Gas Stations If Industrial ☐ Factories and Plants ☐ Agricultural If Infrastructure ☐ Sports or recreation installations (stadium/hall) ☐ Bridge If Other Non-Residential ☐ Public Entertainment ☐ Hotel/Motel/Hostel ☐ Restaurant ☐ Educational ☐ Healthcare ☐ Conference Center ☐ Cultural or Institutional ☐ Prison ☐ Civic Building ☐ Other If Mixed Use ☐ Residential/Office/Retail ☐ Other
Number of full time occupants	Number
Number of seats	Number (stadium only)
Number of units	Number (residential only)

Table D.5: Building Program Type

Building Geometry is illustrated in Table D.6.

	Building Geometry	
*	Total gross floor area (m^2)	Number
	Total useable floor area (m^2)	Number
	Height (m)	Number
*	Number of total stories	Number
	Number of stories aboveground	Number
	Number of stories belowground	Number
	Average story height (m)	Number
	Longest clear span (m)	Number
	Average clear span (m)	Number

Table D.6: Building Geometry

Accreditation is illustrated in Table D.7.

Accreditations	
Accredited rating scheme	Multiple choice, with possibility to enter text if "Other" is selected: ☐ None ☐ LEED ☐ BREEAM ☐ Green Star ☐ HQE ☐ DGNB ☐ CASBEE ☐ CEEQUAL ☐ Minergie Other: ....
Accredited rating	Multiple choice: If LEED ☐ Certified ☐ Silver ☐ Gold ☐ Platinum If BREEAM ☐ Pass ☐ Good ☐ Very Good ☐ Excellent ☐ Outstanding

Table D.7: Accreditations

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, 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 an important mandatory entry: the total useable net floor area (m^2 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 (kg_{CO2e} or kg_{CO2e}) in structures. However, another functional unit could be used if more appropriate, for example the number of seats in stadia or the number of fulltime occupants for schools. The net floor area is asked along the gross floor area.

The second set of input parameters contains the structural information 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 and soil conditions are taken into account. Alongside this information, factors such as the climate zone are entered.

Information on building surroundings is illustrated in Table D.8.

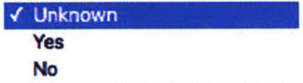
Building Surroundings	
Located in a natural hazard zone?	
Soil Condition	Multiple choice: ☐ A Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface. ☐ B Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth. ☐ C Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters. ☐ D Deposits of loose-to-medium cohesion less soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil. ☐ E 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 > 800 m/s. ☐ S1 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 S2 Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S 1
Climate Zone	Multiple choice: Polar, Temperate, Arid, Tropical, Mediterranean, Mountains (Tundra)

Table D.8: Building Surroundings

Information on building components is illustrated in Table D.9.

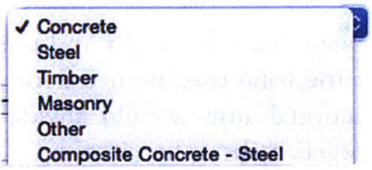
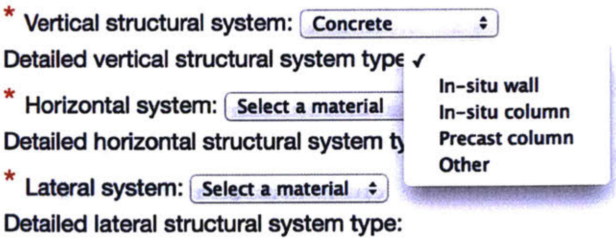
Building Components	
* Main structural system material	Multiple Choice: 
• Vertical Structural System: main material + detailed system • Horizontal Structural System: main material + detailed system • Lateral Structural System: main material + detailed system	* Vertical structural system: Concrete Detailed vertical structural system type ✓ * Horizontal system: Select a material Detailed horizontal structural system ty * Lateral system: Select a material Detailed lateral structural system type: See Table D.10
Material quantity structure included	☑ Substructure only ☐ Superstructure only ☐ Combined sub- and superstructure

Table D.9: Building Surroundings

A main material is selected for vertical, horizontal and lateral loads before specifying the structural system. Table D.10 illustrates the available structural systems the user can pick.

	Structural System		
Material	**Vertical**	**Horizontal**	**Lateral**
Concrete	In-situ wall	In-situ 1-way spanning	Shear wall
	In-situ column	In-situ 2-way spanning	Rigid frame
	Precast column	In-situ flat slab	Infill wall
	Other	Ribbed and waffle slab	Other
		Post-tensioned band beams (long span)	
		Post-tensioned flat slab	
		Precast hollow core (composite)	
		Precast hollow core (non-composite)	
		Precast long span (composite)	
		Other	
Steel	Studs & panel wall	Composite metal decking	Bracing
	Steel column	Non-composite metal decking	Diagrid
	Diagrid	Beam & decking	Other
		Truss & decking	
		Diagrid	
		Other	
Timber	Studs & panel wall	Solid timber slab	Shear wall
	Solid column	Timber joists & decking	Bracing
	Glue laminated column	Solid beams & girders	Other
	Solid stacked wall	Glue laminated beams & girders	
	Other	Timber truss & girders	
		Other	
Masonry	Brick Wall	Vaults	Shear wall
	Concrete Block Wall	Other	Other
	Other		
Other			

Table D.10: Main Materials and corresponding Structural Systems

Information on used materials is illustrated in Table D.11. The user enters all materials used, with the quantities they were used in. The user can click "add another" to include another material, and click "delete" to remove a material. Entering Custom Used Materials with carefully calculated ECC* improves the accuracy of the GWP, if project-specific data is available. Entering the corresponding rebar quantities improves the accuracy of the GWP. Typical rebar percentages range between 2 and 3%.

Used Materials	
Input	☑ Relative Material Quantities ☐ Absolute Material Quantities
Building components included in the material quantity (N.B. Non-structural building components are added in order to make the database expandable to non-structural material quantities in the future.)	☐ **Structural Components**: ☐ Foundations ☐ Basement Walls ☐ Slab on Grade ☐ Frame ☐ Exterior Walls ☐ Stairs and ramps ☐ Floor Construction ☐ Roof Construction ☐ **Non-Structural Components**: ☐ Exterior Windows & Doors ☐ Roof Coverings

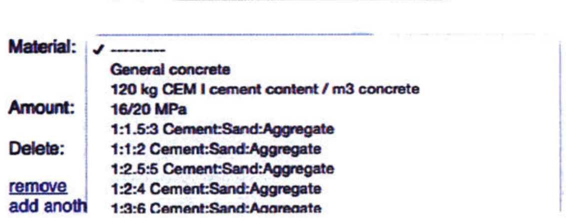
	☐ Internal Walls & Partitions ☐ Internal Finishes ☐ Fittings, Furnishings & Equipment ☐ Services ☐ External Areas
What is the source of material quantities?	Multiple Choice: BIM, Bill of Quantities, Drawings, Other
* *Add a material*	
Select main material:	Multiple Choice: Concrete, Steel, Timber, Masonry, Other
Select material specification:	For each main material chosen for the list above, a multiple choice shows up for the material specification:  Material category: Concrete Material: ✓ --------- General concrete 120 kg CEM I cement content / m3 concrete 16/20 MPa 1:1.5:3 Cement:Sand:Aggregate 1:1:2 Cement:Sand:Aggregate 1:2.5:5 Cement:Sand:Aggregate 1:2:4 Cement:Sand:Aggregate 1:3:6 Cement:Sand:Aggregate Amount: Delete: remove add anoth
Select weight or volume: Quantity (kg or lb if user chose weight, m^3 or ft^3 if user chose volume)	 ● Weight ○ Volume Quantity: : in kg or lb remove add another
Add custom material	
If a material wasn't in the list above, Select main material:	Multiple Choice: Concrete, Steel, Timber, Masonry, Other
Enter material specification:	Text
Select weight or volume:	 ● Weight ○ Volume
Enter ECC (kg_{CO2e}/kg):	Number
Source ECC:	Multiple Choice, with possibility to enter text if "Other" is selected: Athena, GaBi, EcoInvent, ICE, SimaPro, Quartz, National EPD Database, Other
Select what is accounted for in ECC:	Multiple Choice: Carbon Sequestration, Recycling, Cradle-to-Gate, Cradle-to-Site, Cradle-to-Grave
Quantity (kg or lb if user chose weight, m^3 or ft^3 if user chose volume)	 Quantity: : in kg or lb remove add another
Rebar	The quantity can be entered as % or as kg/m^3 (or lbs/ft^3 in case imperial units were chosen by the user) and the database will automatically calculate how much kg of steel rebar that is compared to the quantity of concrete that was entered in the previously added material.
Modification factor for reinforced concrete	For steel rebar (bar & rod steel), the user needs to be able to enter a % rebar in percentage of the concrete by weight or by volume. This means the rebar needs to be connected to the concrete quantity it applies to. For reinforcement add 0.077 kg_{CO2e}/kg to the appropriate concrete coefficient for each 100 kg of rebar per m3 of concrete. For example, for 150 kg steel / m^3 of concrete, 1.5 * 0.077 kg_{CO2e}/kg is added to the ECC for that concrete.
Modification factor precast (prefabricated) concrete	For precast concrete 0.029 kg_{CO2e}/kg is added to the appropriate concrete mix.

Table D.11: Used Materials

For the material quantities are entered, the source of these data is specified (dwgs, BIM, bill of quantities, etc.). Materials are classified in "main material" categories: concrete, steel, timber, masonry, and other. For each of these main materials, a "material specification" has to be defined. Material quantities can either be entered in absolute values (in kg if weight was selected or in m^3 if volume was selected) or relative values (kg or m^3 per appropriate functional unit, usually m^2). If only the absolute value is given, this value is normalized (by dividing by the functional unit). In most cases, the functional unit will be the gross floor area, given in the general information section. The relative material quantities are consequently expressed in kilograms per square meter (if metric was chosen by the user).

The user can choose from a list of predefined materials with ECCs or enter his/her own ECC calculations when citing the source clearly. 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 web-interface is aiming at clarity and transparency. The user is given a url https://deqo.mit.edu which brings them to the homepage of the deQo interface. This gives the logo of deqo, the name "database of embodied Quantity outputs (deQo)" and general information of the project and research group at MIT, as well as the logos of the companies who contributed data to the database. It has three tabs: Home, Register, Login (Figure D.1). The Home tab links to the homepage. The Register tab links to the registration page. The Login tab links to the login page. Once the user is logged in, four tabs are available: Add Building, Search Results, My Buildings, Account, Logout (Figure D.2).

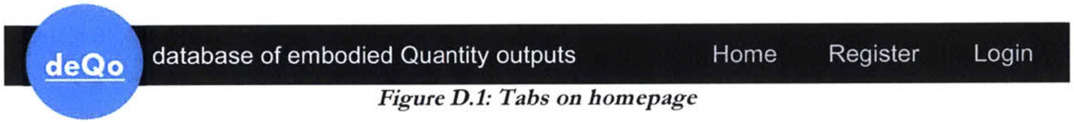


Figure D.1: Tabs on homepage

Figure D.2: Tabs on page once user logged in

When the user is logged in, the default page is the 'Add Building' page. When the user clicks on 'Search Results', the graphical output page of the database results appear.

When the user clicks on 'My Buildings', a list of the buildings from this specific user show up, with the information as illustrated in Figure D.3. The Structural Material Quantities gives the sum of all the normalized material quantities entered by the users and the units (for example kg/m^2). The Global Warming Potential gives the sum of all the normalized embodied carbon results obtained by the database for this building and the units (for example kg$_{CO2e}$/m^2). When the user clicks on 'Update', the user is able to correct information it in the 'Add Building' entry format.

Building Name:	St Mary Axe
Target Construction Completion Date:	2001
Current Project Phase:	In Use
Location:	London, United Kingdom
Structural Material Quantities	1200 kg/m^2
Global Warming Potential	400 kg$_{CO2e}$/m^2

Figure D.3: My Buildings example building

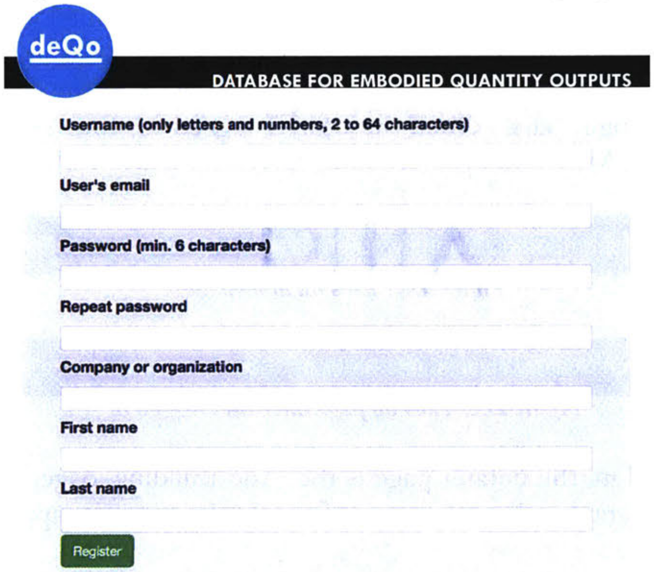
When the user clicks on 'Account', the page shows the user's username, email address, first name, last name, and company or organization. It also allows the user to edit his/her details or change his/her password, as shown in Figure D.4. The 'Logout' tab logs out the user.

Username:	cdewolf
Email Address:	cdewolf@mit.edu
First Name:	Catherine
Last Name:	De Wolf
Company or Organization:	MIT

Edit details
Change password

Figure D.4: Account tab

The access to the database through the web-interface is granted after a (free) 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 D.5. All projects have to be individually approved by an administrator to be added to the ranges plotted.



deQo
DATABASE FOR EMBODIED QUANTITY OUTPUTS

Username (only letters and numbers, 2 to 64 characters)

User's email

Password (min. 6 characters)

Repeat password

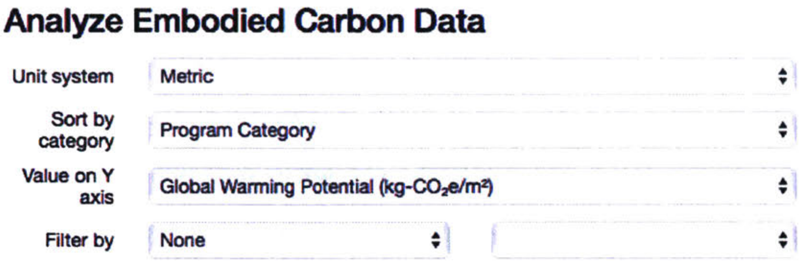
Company or organization

First name

Last name

Figure D.5: Register for deQo

In the interactive web-interface, the user can click on the 'Search' button to illustrate the ranges of results already entered in the database. On the y-axis of the search tool, either "Material Quantities" or "Global Warming Potential" can be shown (Figure D.6). The results can be sorted by Building Program Type, by Height, by Rating Scheme Accreditation, by Region, etc. The user can choose to show the graphics in metric or imperial units. The user can also show to filter by Building Program Type, by Height, by Rating Scheme Accreditation, by Region to only show one part of the data. Figure D.7 illustrates the results when you select 'Material amount' and 'Global Warming Potential' for value on y-axis for 'Structural Type' as a category, in 'Metric' units with no filter and click on "Search".



Analyze Embodied Carbon Data

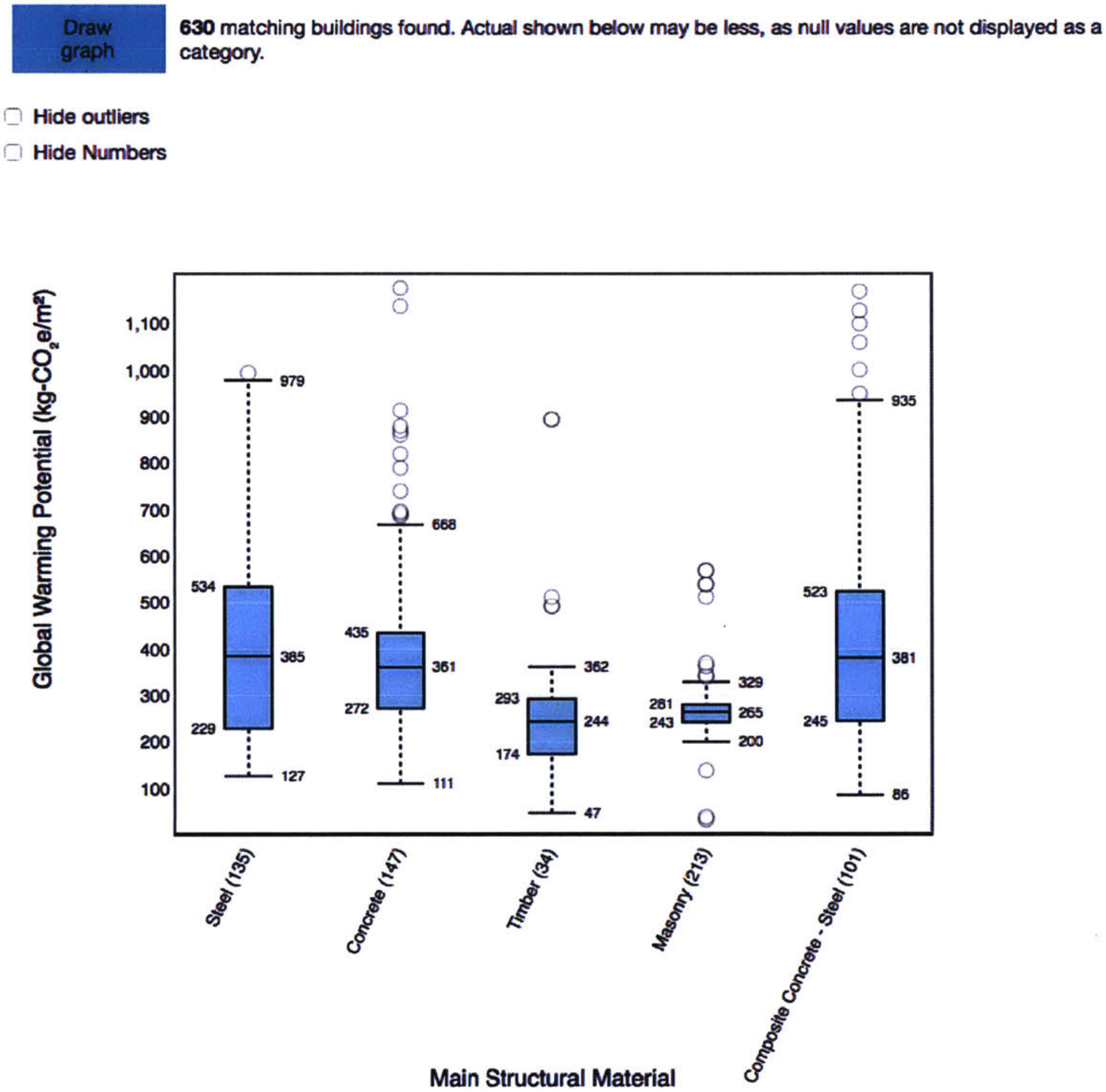
Unit system: Metric

Sort by category: Program Category

Value on Y axis: Global Warming Potential (kg-CO$_2$e/m^2)

Filter by: None

Figure D.6: Options for the graphical output



630 matching buildings found. Actual shown below may be less, as null values are not displayed as a category.

☐ Hide outliers

☐ Hide Numbers

Figure D.7: Example 2 of the graphical results

E. Detailed results from deQo

This section includes more detailed boxplots including all outliers and numbers next to the minimum, lower quartile, medial, upper quartile, and maximum. Figure E.1 gives the SMQ and Figure E.2 gives the GWP for different main structural materials. Figure E.3 gives the SMQ and Figure E.4 gives the GWP for different number of stories. Figure E.5 gives the SMQ and Figure E.6 gives the GWP for different sizes by floor area. Figure E.7 gives the SMQ and Figure E.8 gives the GWP for different average spans.

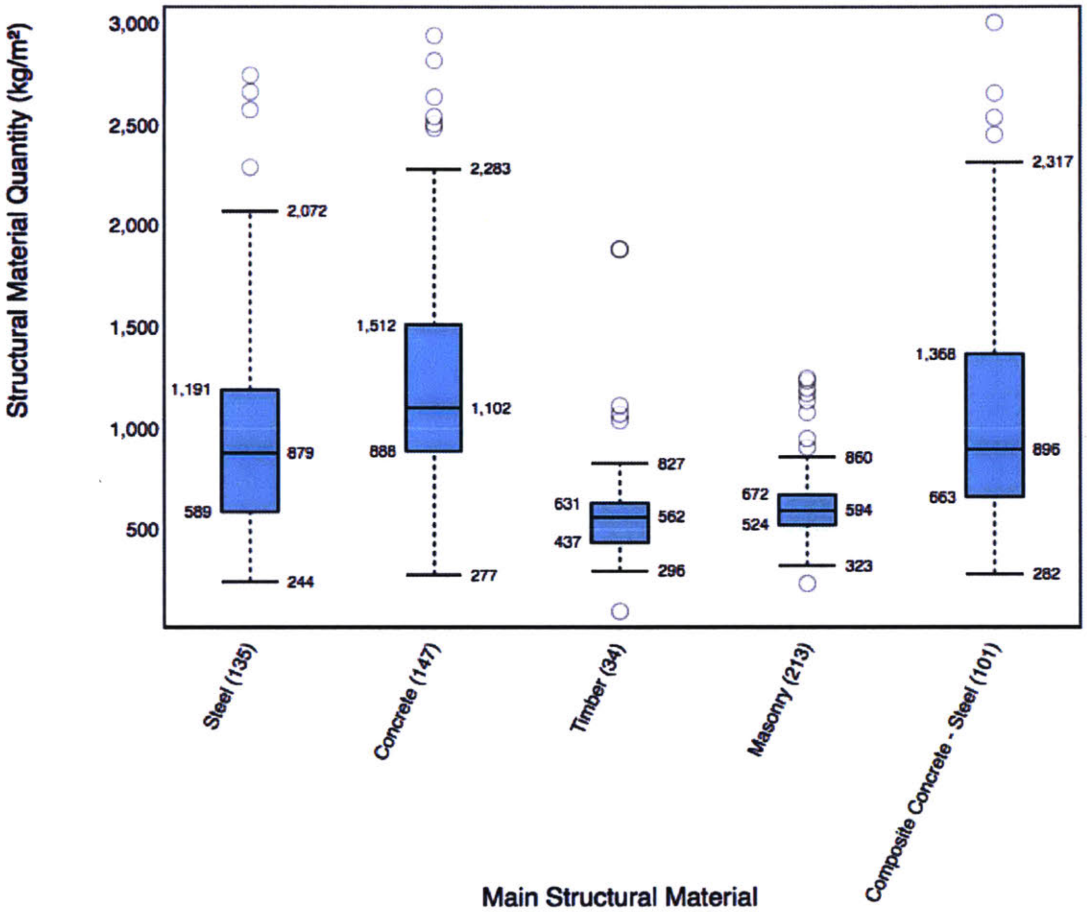


Figure E.1: SMQ for for main structural material

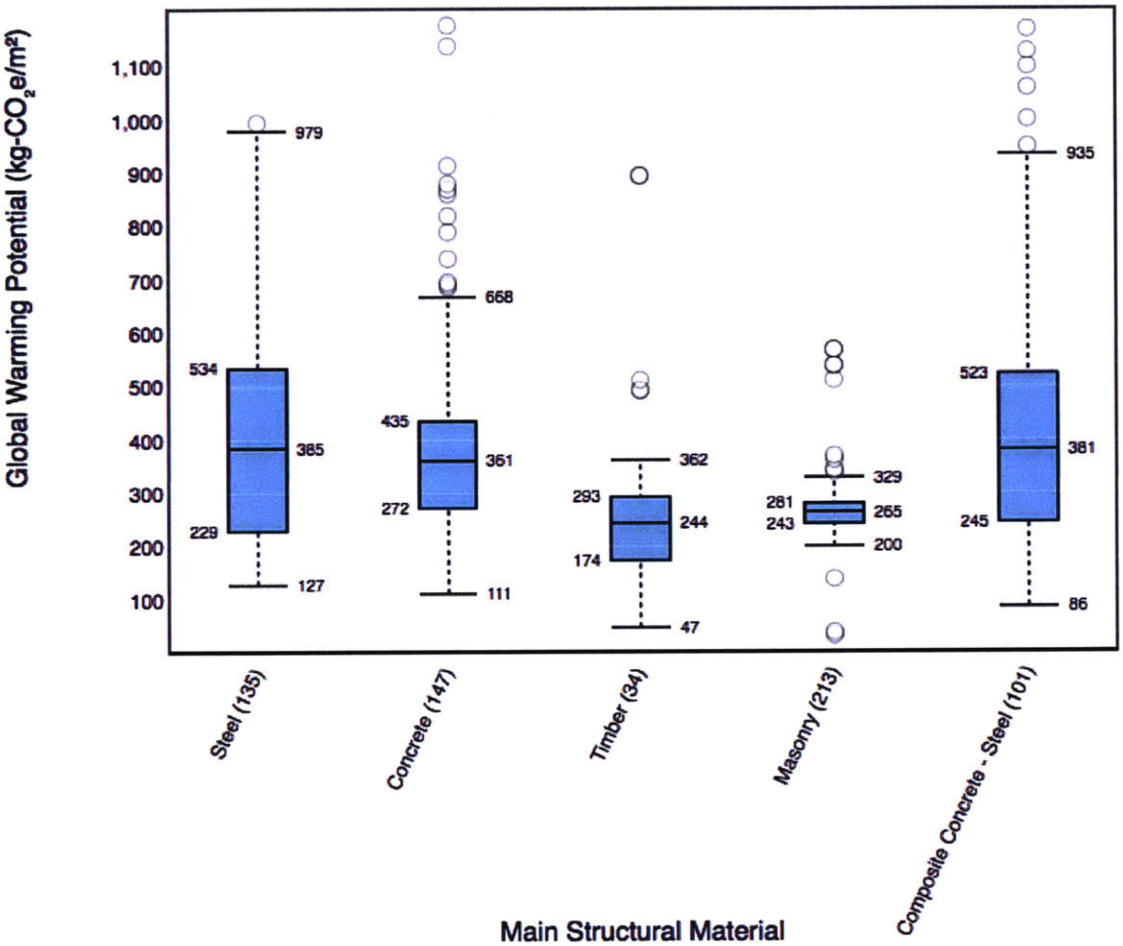


Figure E.2: GWP for main structural material

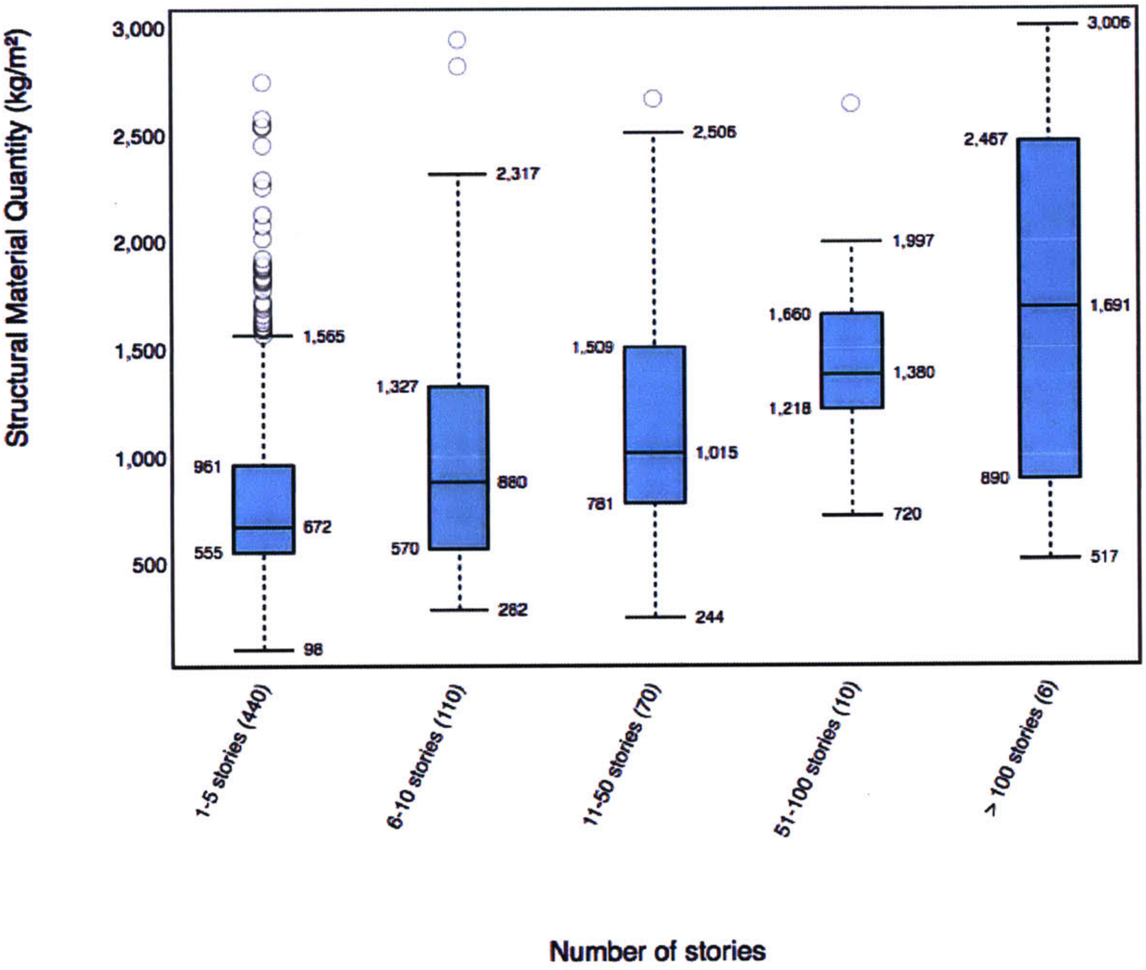


Figure E.3: SMQ for number of stories

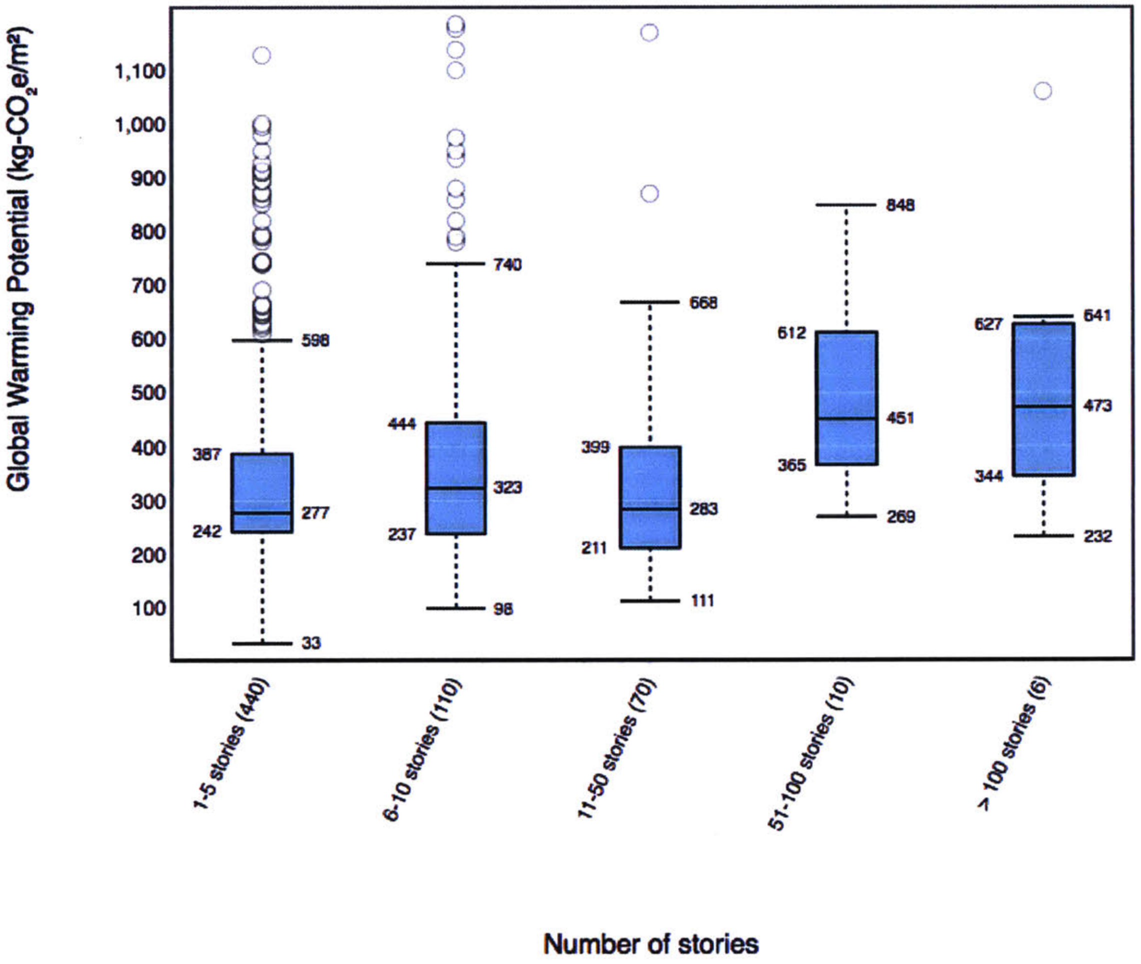


Figure E.4: GWP for number of stories

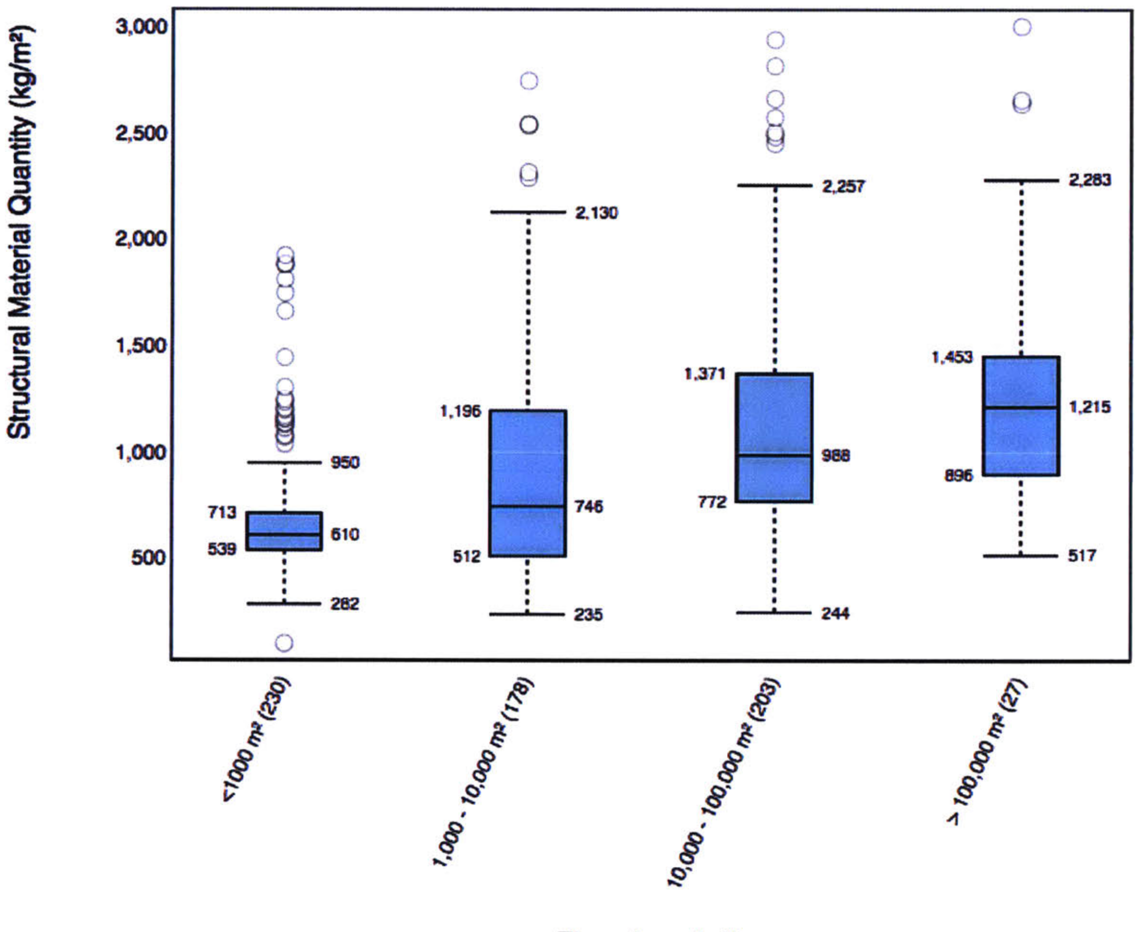


Figure E.5: SMQ for floor area

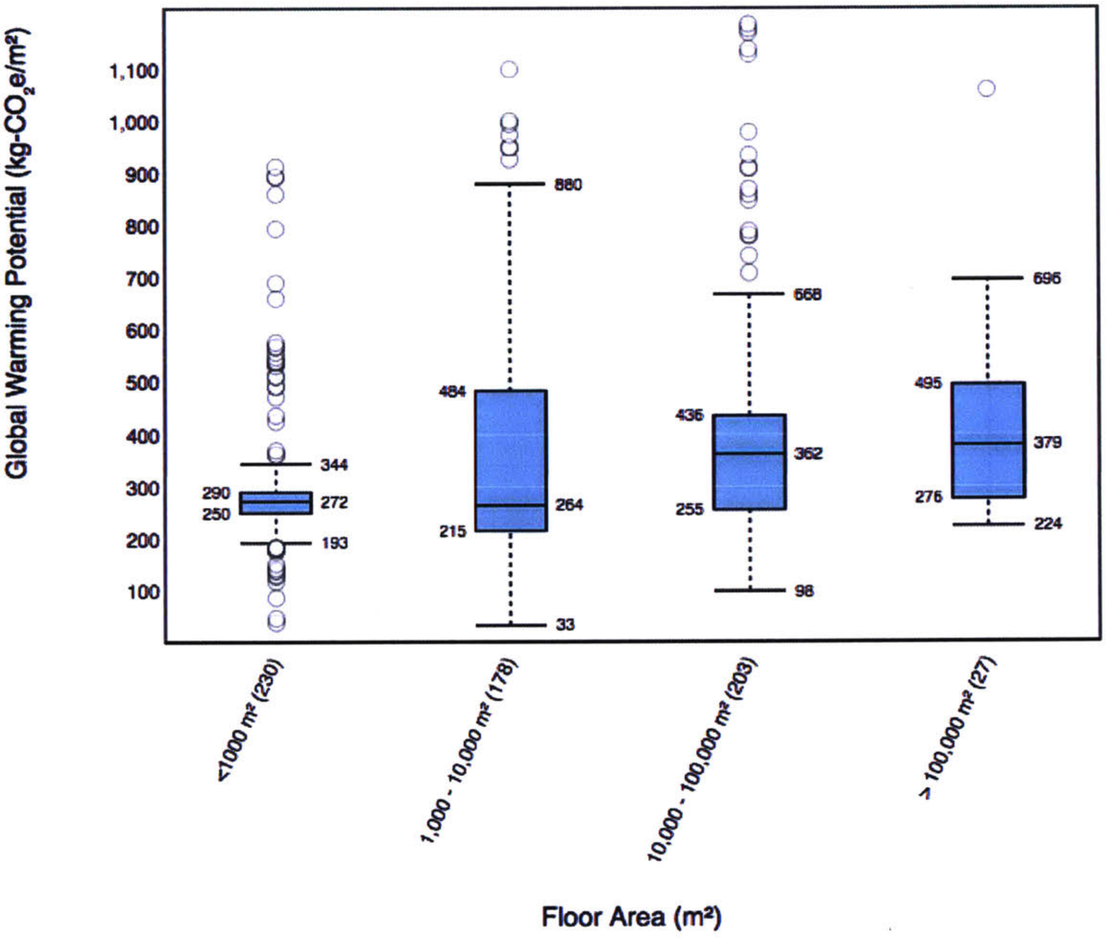


Figure E.6: GWP for floor area

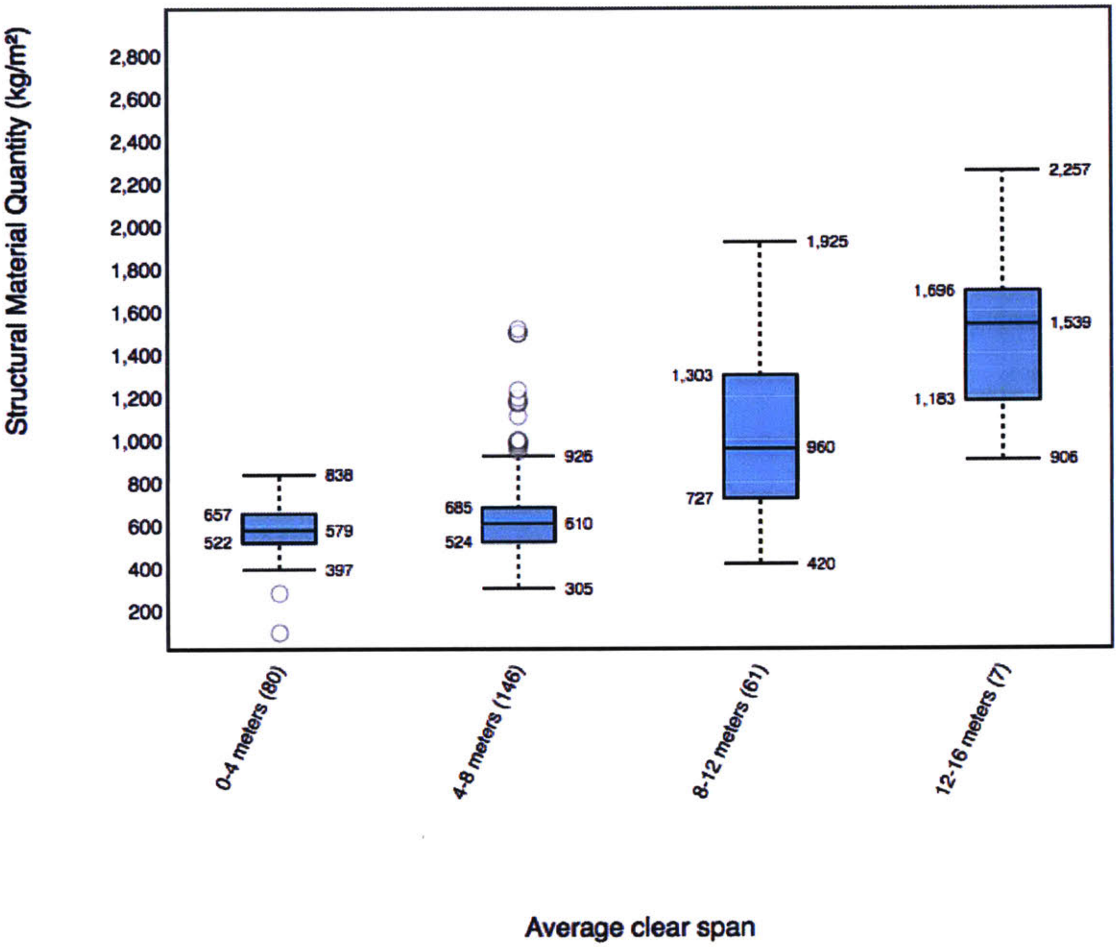


Figure E.7: SMQ for average clear span

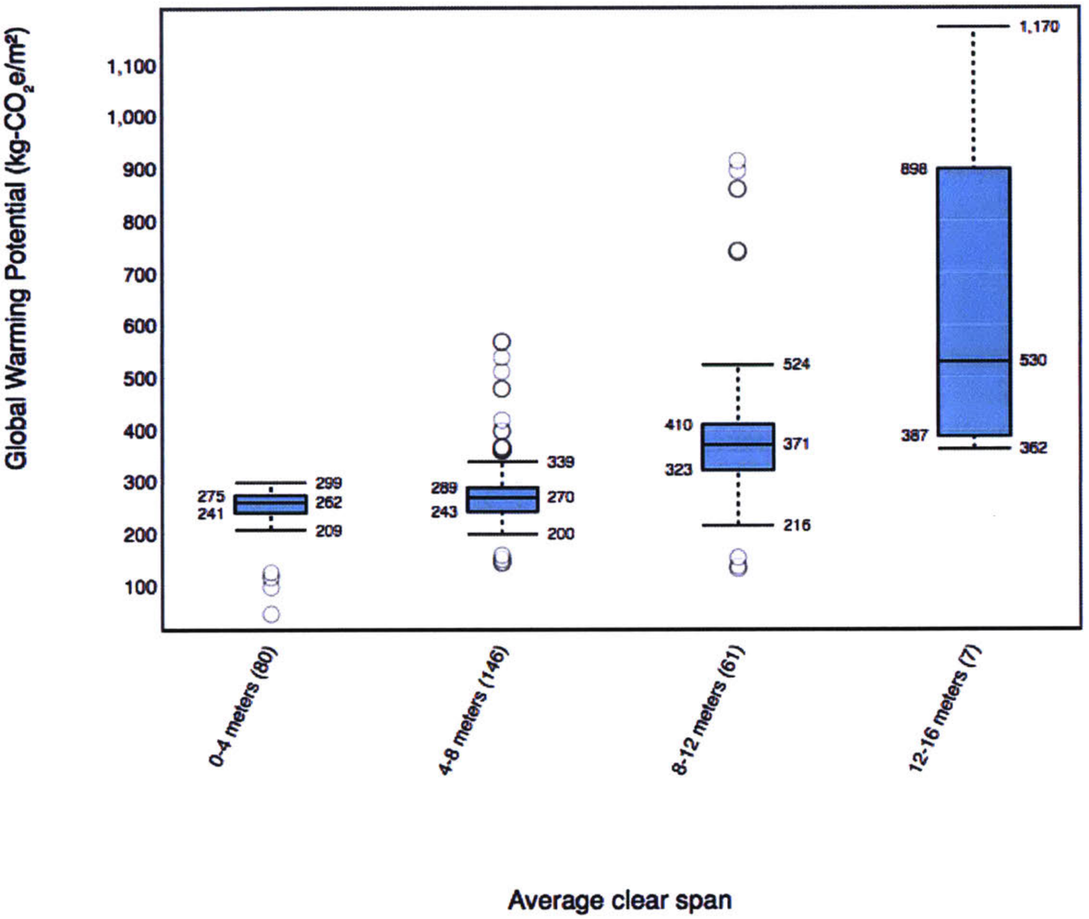


Figure E.8: GWP for average clear span

F. Data points quality matrix

Table F.1 gives the scores for the pedigree data quality matrix for each data entry in deQo.

Building ID	Reliability	Completeness	Temporal	Geographical	Technological	SMQ	GWP	Distribution
1	1	1	1	2	1	1,227	405	1
2	1	1	1	2	1	856	346	1
3	1	1	1	2	1	601	231	1
4	1	1	1	2	1	999	240	1
5	1	1	1	2	1	509	268	1
6	1	1	1	2	1	296	131	1
7	1	1	1	2	1	504	265	2
8	1	1	1	2	1	668	278	1
9	1	1	1	2	1	580	223	1
10	1	1	1	2	1	535	282	1
11	1	1	1	2	1	712	274	2
12	1	1	1	2	1	694	645	2
13	1	1	1	2	1	852	286	2
14	1	1	1	2	1	1,445	795	1
15	1	1	1	2	1	1,696	848	1
16	1	1	1	2	1	2,486	870	1
17	1	1	1	2	1	692	318	1
18	1	1	1	2	1	1,228	356	1
19	1	1	1	2	1	579	276	1
20	1	1	1	2	1	1,028	329	2
21	1	1	1	2	1	770	285	1
22	1	1	1	2	1	678	542	1
23	1	1	1	2	1	765	273	1
24	1	1	1	2	1	1,634	780	1
25	1	1	1	2	1	515	211	3
26	1	1	1	2	1	799	274	1
27	1	1	1	2	1	856	231	1
28	1	1	1	2	1	1,038	493	1
29	1	1	1	2	1	2,001	950	2
30	1	1	1	2	1	1,120	392	2
31	1	1	1	2	1	448	323	1
32	1	1	1	2	1	531	244	1
33	1	1	1	2	1	683	273	1
34	1	1	1	2	1	305	145	1
35	1	1	1	2	1	582	128	1
36	1	1	1	2	1	331	157	1
37	1	1	1	2	1	756	291	1
38	1	1	1	2	1	462	257	3
39	1	1	1	2	1	534	223	1

40	1	1	1	2	1	479	345	1
41	1	1	1	2	1	1,282	309	1
42	1	1	1	2	1	525	262	1
43	1	1	1	2	1	1,298	340	1
44	1	1	1	2	1	590	280	3
45	1	1	1	2	1	1,157	995	2
46	1	1	1	2	1	1,131	648	1
47	1	1	1	2	1	594	258	1
48	1	1	1	2	1	551	253	1
49	1	1	1	2	1	1,035	413	2
50	1	1	1	2	1	748	247	1
51	1	1	1	2	1	1,647	1,186	1
52	1	1	1	2	1	737	284	3
53	1	1	1	2	1	282	127	1
54	1	1	1	2	1	794	389	1
55	1	1	1	2	1	514	245	1
56	1	1	1	2	1	777	288	1
57	1	1	1	2	1	1,263	202	1
58	1	1	1	2	1	703	211	1
59	1	1	1	2	1	561	129	1
60	1	1	1	2	1	629	233	1
61	1	1	1	2	1	754	279	1
62	1	1	1	2	1	1,764	491	1
63	1	1	1	2	1	1,497	509	1
64	1	1	1	2	1	2,819	1,138	1
65	1	1	1	2	1	2,018	444	1
66	1	1	1	2	1	770	208	3
67	1	1	1	2	1	846	401	1
68	1	1	1	2	1	984	362	1
69	1	1	1	2	1	1,005	477	1
70	1	1	1	2	1	851	621	1
71	1	1	1	2	1	582	277	1
72	1	1	1	2	1	479	252	1
73	1	1	1	2	1	464	232	1
74	1	1	1	2	1	1,269	406	1
75	1	1	1	2	1	1,172	539	1
76	1	1	1	2	1	489	272	2
77	1	1	1	2	1	675	293	1
78	1	1	1	2	1	1,033	413	1
79	1	1	1	2	1	672	292	1
80	1	1	1	2	1	1,303	524	1
81	1	1	1	2	1	538	86	1
82	1	1	1	2	1	603	302	1
83	1	1	1	2	1	521	208	3
84	1	1	1	2	1	412	229	1
85	1	1	1	2	1	244	188	1
86	1	1	1	2	1	663	255	1
87	1	1	1	2	1	546	251	1
88	1	1	1	2	1	384	177	1

89	1	1	1	2	1	896	242	1
90	1	1	1	2	1	539	284	1
91	1	1	1	2	1	592	282	1
92	1	1	1	2	1	463	111	1
93	1	1	1	2	1	557	265	1
94	1	1	1	2	1	1,163	651	1
95	1	1	1	2	1	2,576	979	1
96	1	1	1	2	1	640	278	1
97	1	1	1	2	1	492	226	1
98	1	1	1	2	1	512	256	1
99	1	1	1	2	1	631	299	1
100	1	1	1	2	1	2,200	594	1
101	1	1	1	2	1	677	176	1
102	1	1	1	2	1	1,305	691	1
103	1	1	1	2	1	838	402	1
104	1	1	1	2	1	2,665	533	2
105	1	1	1	2	1	430	239	2
106	1	1	1	2	1	676	282	1
107	1	1	1	2	1	1,873	543	1
108	1	1	1	2	1	459	255	1
109	1	1	1	2	1	517	272	1
110	1	1	1	2	1	800	176	1
111	1	1	1	2	1	454	216	1
112	1	1	1	2	1	480	346	1
113	1	1	1	2	1	725	399	1
114	1	1	1	2	1	1,997	639	1
115	1	1	1	2	1	677	264	2
116	1	1	1	2	1	710	273	1
117	1	1	1	2	1	1,332	859	2
118	1	1	1	2	1	578	275	1
119	1	1	1	2	1	327	136	1
120	1	1	1	2	1	988	336	1
121	1	1	1	2	1	665	153	1
122	1	1	1	2	1	1,179	479	1
123	1	1	1	2	1	926	213	1
124	1	1	1	2	1	389	216	1
125	1	1	1	2	1	547	238	1
126	1	1	1	2	1	1,882	894	2
127	1	1	1	2	1	1,288	335	1
128	1	1	1	2	1	594	258	1
129	1	1	1	2	1	1,427	742	1
130	1	1	1	2	1	755	270	1
131	1	1	1	2	1	1,170	316	3
132	1	1	1	2	1	453	178	1
133	1	1	1	2	1	997	392	1
134	1	1	1	2	1	621	230	1
135	1	1	1	2	1	609	290	1
136	1	1	1	2	1	703	281	1
137	1	1	1	2	1	475	226	2

138	1	1	1	2	1	659	244	1
139	1	1	1	2	1	453	145	1
140	1	1	1	2	1	919	285	1
141	1	1	1	2	1	644	239	1
142	1	1	1	2	1	1,267	950	1
143	1	1	1	2	1	1,321	317	1
144	1	1	1	2	1	499	263	1
145	1	1	1	2	1	827	416	1
146	1	1	1	2	1	452	215	1
147	1	1	1	2	1	1,083	260	1
148	1	1	1	2	1	768	315	1
149	1	1	1	2	1	283	134	1
150	1	1	1	2	1	584	269	1
151	1	1	1	2	1	701	280	1
152	1	1	1	2	1	622	249	1
153	1	1	1	2	1	1,614	597	1
154	1	1	1	2	1	950	339	1
155	1	1	1	2	1	888	180	1
156	1	1	1	2	1	447	235	1
157	1	1	1	2	1	1,415	283	1
158	1	1	1	2	1	566	269	1
159	1	1	1	2	1	1,983	528	2
160	1	1	1	2	1	548	274	1
161	1	1	1	2	1	601	261	1
162	1	1	1	2	1	815	322	1
163	1	1	1	2	1	1,778	480	1
164	1	1	1	2	1	553	254	1
165	1	1	1	2	1	762	259	1
166	1	1	1	2	1	892	535	1
167	1	1	1	2	1	657	243	1
168	1	1	1	2	1	718	237	1
169	1	1	1	2	1	599	820	1
170	1	1	1	2	1	983	177	1
171	1	1	1	2	1	962	384	3
172	1	1	1	2	1	866	339	1
173	1	1	1	2	1	1,217	438	1
174	1	1	1	2	1	534	243	1
175	1	1	1	2	1	1,211	575	1
176	1	1	1	2	1	610	472	1
177	1	1	1	2	1	905	361	1
178	1	1	1	2	1	393	177	1
179	1	1	1	2	1	407	98	1
180	1	1	1	2	1	1,104	309	1
181	1	1	1	2	1	2,538	533	2
182	1	1	1	2	1	884	168	1
183	1	1	1	2	1	1,136	539	1
184	1	1	1	2	1	648	270	1
185	1	1	1	2	1	524	291	1
186	1	1	1	2	1	665	289	1

187	1	1	1	2	1	681	184	1
188	1	1	1	2	1	553	398	1
189	1	1	1	2	1	601	273	1
190	1	1	1	2	1	1,094	197	1
191	1	1	1	2	1	752	268	1
192	1	1	1	2	1	589	112	1
193	1	1	1	2	1	453	158	1
194	1	1	1	2	1	416	219	1
195	1	1	1	2	1	689	232	1
196	1	1	1	2	1	2,543	485	1
197	1	1	1	2	1	1,005	477	1
198	1	1	1	2	1	425	236	1
199	1	1	1	2	1	616	228	1
200	1	1	1	2	1	472	255	1
201	1	1	1	2	1	865	533	1
202	1	1	1	2	1	1,721	384	1
203	1	1	1	2	1	633	275	1
204	1	1	1	2	1	434	228	1
205	1	1	1	2	1	1,312	328	2
206	1	1	1	2	1	610	281	1
207	1	1	1	2	1	509	243	1
208	1	1	1	2	1	679	283	1
209	1	1	1	2	1	655	243	1
210	1	1	1	2	1	562	159	1
211	1	1	1	2	1	654	262	1
212	1	1	1	2	1	1,594	384	1
213	1	1	1	2	1	908	361	1
214	1	1	1	2	1	555	252	1
215	1	1	1	2	1	1,595	740	1
216	1	1	1	2	1	560	252	1
217	1	1	1	2	1	616	228	1
218	1	1	1	2	1	693	257	1
219	1	1	1	2	1	617	237	1
220	1	1	1	2	1	320	152	1
221	1	1	1	2	1	713	155	1
222	1	1	1	2	1	1,626	392	1
223	1	1	1	2	1	1,380	207	1
224	1	1	1	2	1	692	318	1
225	1	1	1	2	1	441	200	1
226	1	1	1	2	1	819	262	1
227	1	1	1	2	1	753	290	2
228	1	1	1	2	1	1,363	647	1
229	1	1	1	2	1	575	213	1
230	1	1	1	2	1	1,663	532	1
231	1	1	1	2	1	1,540	433	1
232	1	1	1	2	1	567	270	1
233	1	1	1	2	1	556	200	1
234	1	1	2	2	2	614	134	1
235	1	1	2	2	2	419	221	3

236	1	1	2	2	2	610	226	1
237	1	1	2	2	2	1,368	342	1
238	1	1	2	2	2	700	252	1
239	1	1	2	2	2	1,765	459	1
240	1	1	2	2	2	677	176	1
241	1	1	2	2	2	319	151	1
242	1	1	2	2	2	652	242	1
243	1	1	2	2	2	585	293	1
244	1	1	2	2	2	1,336	935	1
245	1	1	2	2	2	591	281	2
246	1	1	2	2	2	423	343	1
247	1	1	2	2	2	1,016	254	1
248	1	1	2	2	2	866	316	1
249	1	1	2	2	2	1,278	294	1
250	1	1	2	2	2	870	261	1
251	1	1	2	2	2	880	138	1
252	1	1	2	2	2	1,626	392	2
253	1	1	2	2	2	765	199	1
254	1	1	2	2	2	1,491	359	1
255	1	1	2	2	2	1,069	171	1
256	1	1	2	2	2	1,032	227	1
257	1	1	2	2	2	595	259	1
258	1	1	2	2	2	562	173	1
259	1	1	2	2	2	304	144	1
260	1	1	2	2	2	819	254	1
261	1	1	2	2	2	1,827	402	1
262	1	1	2	2	2	1,692	220	1
263	1	1	2	2	2	380	323	2
264	1	1	2	2	2	2,506	401	1
265	1	1	2	2	2	468	246	3
266	1	1	2	2	2	1,559	421	1
267	1	1	2	2	2	496	248	1
268	1	1	2	2	2	627	117	1
269	1	1	2	2	2	1,500	362	1
270	1	1	2	2	2	594	297	1
271	1	1	2	2	2	512	270	4
272	1	1	2	2	2	2,130	1,001	1
273	1	1	2	2	2	594	313	2
274	1	1	2	2	2	1,224	355	1
275	1	1	2	2	2	1,306	620	1
276	1	1	2	2	2	782	290	1
277	1	1	2	2	2	323	38	1
278	1	1	2	2	2	512	244	1
279	1	1	2	2	2	1,215	328	1
280	1	1	2	2	2	723	289	1
281	1	1	2	2	2	1,854	880	1
282	1	1	2	2	2	1,560	655	1
283	1	1	2	2	2	394	181	2
284	1	1	2	2	2	611	226	1

285	1	1	2	2	2	1,732	381	1
286	1	1	2	2	2	1,170	381	1
287	1	1	2	2	2	847	314	1
288	1	1	2	2	2	942	292	1
289	1	1	2	2	2	459	330	1
290	1	1	2	2	2	826	133	1
291	1	1	2	2	2	497	276	1
292	1	1	2	2	2	779	289	1
293	1	1	2	2	2	1,513	350	1
294	1	1	2	2	2	654	273	1
295	1	1	2	2	2	1,511	408	1
296	1	1	2	2	2	571	260	1
297	1	1	2	2	2	1,050	419	1
298	1	1	2	2	2	988	257	1
299	1	1	2	2	2	558	243	1
300	1	1	2	2	2	1,203	445	1
301	1	1	2	2	2	723	344	2
302	1	1	2	2	2	711	192	1
303	1	1	2	2	2	1,521	367	1
304	1	1	2	2	2	683	273	1
305	1	1	2	2	2	397	209	1
306	1	1	2	2	2	1,058	529	1
307	1	1	2	2	2	1,561	741	1
308	1	1	2	2	2	850	304	1
309	1	1	2	2	2	552	276	1
310	1	1	2	2	2	960	480	1
311	1	1	2	2	2	549	261	1
312	1	1	2	2	2	422	222	1
313	1	1	2	2	2	2,747	563	2
314	1	1	2	2	2	568	155	1
315	1	1	2	2	2	822	329	1
316	1	1	2	2	2	1,102	313	1
317	1	1	2	2	2	571	194	1
318	1	1	2	2	2	946	435	1
319	1	1	2	2	2	1,249	138	2
320	1	1	2	2	2	477	227	1
321	1	1	2	2	2	1,094	279	1
322	1	1	2	2	2	575	230	1
323	1	1	2	2	2	355	168	1
324	1	1	2	2	2	1,373	453	1
325	1	1	2	2	2	399	200	1
326	1	1	2	2	2	1,311	316	3
327	1	1	2	2	2	558	106	3
328	1	1	2	2	2	1,595	384	1
329	1	1	2	2	2	599	272	1
330	1	1	2	2	2	499	263	1
331	1	1	2	2	2	616	293	1
332	1	1	2	2	2	3,006	1,060	2
333	1	1	2	2	2	2,943	1,177	1

334	1	1	2	2	2	419	193	1
335	1	1	2	2	2	1,071	493	3
336	1	1	2	2	2	663	126	1
337	1	1	1	2	2	495	228	1
338	1	1	1	2	2	565	269	2
339	1	1	1	2	2	609	184	1
340	1	1	1	2	2	1,925	914	1
341	1	1	1	2	2	1,838	478	1
342	1	1	1	2	2	686	316	1
343	1	1	1	2	2	1,772	820	2
344	1	1	1	2	2	490	272	1
345	1	1	1	2	2	581	215	1
346	1	1	1	2	2	530	244	1
347	1	1	1	2	2	1,132	538	1
348	1	1	1	2	2	1,178	460	1
349	1	1	1	2	2	879	791	1
350	1	1	1	2	2	594	258	1
351	1	1	1	2	2	1,323	344	1
352	1	1	1	2	2	669	257	2
353	2	1	1	1	1	1,175	423	1
354	2	1	1	1	1	1,128	535	1
355	2	1	1	1	1	581	267	2
356	2	1	1	1	1	725	203	1
357	2	1	1	1	1	420	221	1
358	2	1	1	1	1	1,439	446	2
359	2	1	1	1	1	535	385	3
360	2	1	1	1	1	1,664	790	1
361	2	1	1	1	1	1,217	292	1
362	2	1	1	1	1	645	269	1
363	2	1	1	1	1	1,615	436	1
364	2	1	1	1	1	2,031	709	1
365	2	1	1	1	1	661	245	1
366	2	1	1	1	1	766	306	1
367	2	1	1	1	1	763	362	1
368	1	2	4	1	2	513	118	1
369	1	2	4	1	2	2,257	1,129	2
370	1	2	4	1	2	1,310	524	1
371	1	2	4	1	2	548	249	1
372	1	2	4	1	2	927	371	1
373	1	2	4	1	2	383	182	2
374	1	2	4	1	2	1,650	561	1
375	1	2	4	1	2	755	280	1
376	1	2	4	1	2	1,539	371	1
377	1	2	4	1	2	1,688	422	1
378	1	2	4	1	2	1,381	442	1
379	1	2	3	1	3	1,331	652	1
380	1	2	3	1	3	612	255	1
381	1	2	3	1	3	282	135	1
382	1	2	3	1	3	572	229	1

383	1	2	3	1	3	531	253	1
384	1	2	3	1	3	2,639	686	1
385	1	2	3	1	3	1,565	743	1
386	1	2	3	1	3	455	216	1
387	1	2	3	1	3	431	168	1
388	2	1	1	4	2	773	201	1
389	2	1	1	4	2	813	252	1
390	2	1	1	4	2	594	258	1
391	2	1	1	4	2	672	289	1
392	2	1	1	4	2	1,370	330	2
393	2	1	1	4	2	1,605	594	1
394	2	1	1	4	2	602	626	1
395	2	1	1	4	2	1,228	567	1
396	2	1	1	4	2	296	127	1
397	2	1	1	4	2	906	362	1
398	2	1	1	4	2	520	237	1
399	2	1	1	4	2	1,270	381	1
400	2	1	1	4	2	1,171	562	1
401	2	1	1	4	2	1,368	424	1
402	2	1	1	4	2	906	362	1
403	2	1	1	4	2	399	184	1
404	2	1	1	4	2	1,068	598	1
405	2	1	1	4	2	826	256	1
406	2	1	1	4	2	864	410	2
407	2	1	1	4	2	667	278	1
408	2	1	1	4	2	636	255	1
409	2	1	1	4	2	862	330	2
410	2	1	1	4	2	681	143	1
411	2	1	1	4	2	1,054	253	1
412	2	1	1	4	2	1,070	610	1
413	1	2	2	2	3	1,813	861	1
414	1	2	2	2	3	1,870	374	2
415	1	2	2	2	3	424	223	1
416	1	2	2	2	3	629	286	3
417	1	2	2	2	3	472	321	1
418	1	2	2	2	3	563	256	1
419	1	2	2	2	3	637	290	1
420	1	2	2	2	3	1,406	661	2
421	1	2	2	2	3	1,557	739	1
422	1	2	2	2	3	952	276	2
423	1	2	2	2	3	686	245	1
424	1	2	2	2	3	2,317	1,100	1
425	1	2	2	2	3	575	265	1
426	1	2	2	2	3	305	145	1
427	1	2	2	2	3	886	248	1
428	1	2	2	2	3	954	782	1
429	1	2	2	2	3	895	425	1
430	1	2	2	2	3	480	253	2
431	1	2	2	2	3	512	266	1

432	1	2	2	2	3	967	577	1
433	1	2	2	2	3	883	256	1
434	1	2	2	2	3	574	109	1
435	1	2	2	2	3	286	389	1
436	1	2	2	2	3	2,078	570	1
437	1	2	2	2	3	1,643	630	1
438	1	2	2	2	3	547	228	1
439	1	2	2	2	3	796	308	1
440	1	2	2	2	3	554	399	1
441	1	2	2	2	3	932	317	1
442	1	2	2	2	3	1,891	586	1
443	1	2	2	2	3	520	226	1
444	1	2	2	2	3	981	206	3
445	1	2	2	2	3	1,011	910	1
446	1	1	2	3	2	555	278	1
447	1	1	2	3	2	846	401	1
448	1	1	2	3	2	1,056	380	1
449	1	1	2	3	2	916	384	1
450	1	1	2	3	2	1,625	1,170	1
451	1	1	2	3	2	582	419	3
452	1	1	2	3	2	727	280	1
453	1	1	2	3	2	1,648	379	1
454	1	1	2	3	2	677	149	1
455	1	1	2	3	2	926	367	2
456	1	1	2	3	2	1,041	229	1
457	1	1	2	3	2	743	223	1
458	1	1	2	3	2	1,280	576	1
459	1	1	2	3	2	870	409	1
460	1	1	2	3	2	750	278	1
461	1	1	2	3	2	1,094	194	1
462	1	1	2	3	2	532	296	1
463	1	1	2	3	2	1,380	530	1
464	1	1	2	3	2	663	288	1
465	1	1	2	3	2	1,015	487	1
466	1	1	2	3	2	1,157	549	1
467	1	1	2	3	2	2,453	910	1
468	1	1	2	3	2	327	131	3
469	1	1	2	3	2	662	245	2
470	1	1	2	3	2	1,235	383	1
471	1	1	2	3	2	678	261	1
472	1	1	2	3	2	727	523	1
473	1	1	2	3	2	448	323	1
474	1	1	2	3	2	399	205	1
475	1	1	2	3	2	609	226	1
476	1	1	2	3	2	923	286	1
477	1	1	2	3	2	816	232	1
478	1	1	2	3	2	525	262	1
479	1	1	2	3	2	632	263	1
480	1	1	2	3	2	936	385	1

481	1	1	2	3	2	1,777	391	1
482	1	1	2	3	2	942	245	1
483	1	1	2	3	2	869	344	3
484	1	1	2	3	2	607	289	2
485	1	1	2	3	2	866	927	1
486	3	1	1	1	4	1,898	873	1
487	3	1	1	1	4	480	346	1
488	3	1	1	1	4	509	231	1
489	3	1	1	1	4	1,600	352	2
490	3	1	1	1	4	525	292	1
491	3	1	1	1	4	827	130	1
492	3	1	1	1	4	664	266	4
493	3	1	1	1	4	664	315	1
494	3	1	1	1	4	971	367	1
495	3	1	1	1	4	235	33	1
496	3	1	1	1	4	614	292	1
497	3	1	1	1	4	337	160	1
498	3	1	1	1	4	979	399	1
499	3	1	1	1	4	859	644	1
500	3	1	1	1	4	524	377	1
501	3	1	1	1	4	997	392	1
502	3	1	1	1	4	663	232	1
503	3	1	1	1	4	1,748	437	1
504	3	1	1	1	4	580	277	1
505	3	1	1	1	4	508	231	3
506	3	1	1	1	4	643	225	1
507	3	1	1	1	4	905	181	1
508	3	1	1	1	4	2,072	974	1
509	3	1	1	1	4	631	285	3
510	3	1	1	1	4	1,170	386	1
511	3	1	1	1	4	513	270	1
512	3	1	1	1	4	779	257	1
513	3	1	1	1	4	1,766	668	1
514	3	1	1	1	4	712	285	1
515	3	1	1	1	4	720	269	4
516	3	1	1	1	4	98	47	1
517	3	1	1	1	4	860	319	1
518	3	1	1	1	4	749	288	1
519	3	1	1	1	4	823	255	1
520	3	1	1	1	4	1,158	558	1
521	2	2	1	1	3	561	266	1
522	2	2	1	1	3	1,570	424	1
523	2	2	1	1	3	1,141	662	1
524	2	2	1	1	3	748	277	1
525	2	2	1	1	3	965	251	1
526	2	2	1	1	3	333	158	2
527	2	2	1	1	3	1,569	745	1
528	2	2	1	1	3	656	243	1
529	2	2	1	1	3	578	263	1

530	2	2	1	1	3	996	259	1
531	2	2	1	1	3	440	210	1
532	2	2	1	1	3	577	241	1
533	2	2	1	1	3	695	248	2
534	2	2	1	1	3	905	507	1
535	2	2	1	1	3	562	244	1
536	2	2	1	1	3	596	143	1
537	2	2	1	1	3	622	271	1
538	2	2	1	1	3	996	398	1
539	2	2	1	1	3	635	302	1
540	2	2	1	1	3	665	479	1
541	2	2	1	1	3	1,074	419	1
542	2	2	1	1	3	887	665	1
543	2	2	1	1	3	2,659	641	1
544	2	2	1	1	3	277	347	1
545	2	2	1	1	3	641	267	1
546	2	2	1	1	3	986	403	1
547	2	2	1	1	3	826	345	1
548	2	2	1	1	3	835	167	1
549	2	2	1	1	3	568	142	2
550	2	2	1	1	3	897	260	1
551	2	2	1	1	3	358	172	1
552	2	2	1	1	3	569	258	1
553	2	2	1	1	3	446	235	2
554	2	2	1	1	3	723	175	1
555	2	2	1	1	3	310	147	1
556	2	2	1	1	3	625	272	1
557	2	2	1	1	3	1,498	361	2
558	2	2	1	1	3	743	196	1
559	2	2	1	1	3	1,720	516	1
560	2	2	1	1	3	1,389	852	1
561	2	2	1	1	3	489	258	1
562	2	2	1	1	3	1,113	512	1
563	2	2	1	1	3	1,710	359	2
564	2	2	1	1	3	928	371	1
565	2	2	1	1	3	1,886	895	1
566	2	2	1	1	3	529	220	1
567	2	2	1	1	3	1,000	310	1
568	2	2	1	1	3	850	510	1
569	2	2	1	1	3	584	243	1
570	2	2	1	1	3	533	661	1
571	2	2	1	1	3	2,292	871	2
572	2	2	1	1	3	779	370	1
573	2	2	1	1	3	456	254	1
574	2	2	1	1	3	660	275	1
575	2	2	1	1	3	524	291	1
576	2	2	1	1	3	972	371	1
577	2	2	1	1	3	896	224	1
578	2	2	1	1	3	335	171	1

579	2	2	1	1	3	1,551	352	1
580	2	2	1	1	3	956	258	1
581	2	2	1	1	3	567	272	1
582	2	2	1	1	3	524	218	1
583	2	2	1	1	3	743	205	1
584	2	2	1	1	3	528	220	1
585	2	2	1	1	3	713	264	1
586	2	2	1	1	3	539	257	1
587	2	2	1	1	3	1,686	236	1
588	2	2	1	1	3	1,550	341	1
589	2	2	1	1	3	1,305	315	1
590	2	2	1	1	3	579	266	1
591	2	2	1	1	3	577	173	1
592	2	2	1	1	3	1,232	456	1
593	2	2	1	1	3	1,198	569	1
594	2	2	1	1	3	1,066	309	1
595	2	2	1	1	3	1,078	512	1
596	2	2	1	1	3	2,283	696	1
597	2	2	1	1	3	455	216	1
598	2	2	1	1	3	1,276	308	1
599	2	2	1	1	3	556	265	1
600	2	2	1	1	3	517	339	1
601	2	2	1	1	3	453	149	1
602	2	2	1	1	3	951	428	1
603	2	2	1	1	3	540	257	2
604	2	2	1	1	3	1,285	610	1
605	2	2	1	1	3	960	384	1
606	2	2	1	1	3	1,604	401	1
607	2	2	1	1	3	979	235	1
608	2	2	1	1	3	1,463	790	1
609	2	2	1	1	3	455	216	1
610	2	2	1	1	3	1,207	577	1
611	2	2	1	1	3	803	287	2
612	2	2	1	1	3	1,179	479	1
613	2	2	1	1	3	735	149	1
614	2	2	1	1	3	1,058	508	1
615	2	2	1	1	3	1,001	398	1
616	2	2	1	1	3	838	299	1
617	2	2	1	1	3	806	266	1
618	2	2	1	1	3	522	275	2
619	2	2	1	1	3	515	286	1
620	2	2	1	1	3	656	274	1
621	2	2	1	1	3	1,236	569	1
622	2	2	1	1	3	574	413	1
623	2	2	1	1	3	511	189	1
624	2	2	1	1	3	810	583	1
625	2	2	1	1	3	977	399	1
626	2	2	1	1	3	808	323	1
627	2	2	1	1	3	850	130	1

628	2	2	1	1	3	841	328	1
629	2	2	1	1	3	936	385	2
630	2	2	1	1	3	676	294	1
631	2	2	1	1	3	695	257	1
632	2	2	1	1	3	725	203	1
633	2	2	1	1	3	605	275	1
634	2	2	1	1	3	969	460	1
635	2	2	1	1	3	1,824	310	1
636	2	2	1	1	3	570	300	1
637	2	2	1	1	3	785	281	1
638	2	2	1	1	3	754	294	1
639	2	2	1	1	3	481	209	1

Table F.1: Pedigree matrix to assess the quality of data sources contributing to deQo, adapted from Table 4.1