REDUCING EMBODIED CARBON IN THE BUILT ENVIRONMENT: 
THE ROLE OF ENVIRONMENTAL PRODUCT DECLARATIONS 

SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY 

SUPERVISORS: 
Dr Alice Moncaster  
Emeritus Professor Robin Roy  
Dr Derek Jones 

The Open University  
Faculty of Science, Technology, Engineering and Mathematics  
School of Engineering and Innovation
I Abstract

The embodied carbon of construction, caused by the production, transport, installation, maintenance and disposal of construction products, accounts for 12% of global CO₂ emissions. However, concerns about the availability and variation of embodied carbon data have been cited as barriers to the widespread adoption of embodied carbon assessment and regulation.

This thesis examines these concerns through an analysis of embodied carbon data, including Environmental Product Declarations (EPD), for construction products. It describes the use and value of embodied carbon data and EPD by experienced UK embodied carbon practitioners. It addresses the availability of EPD globally, finding exponential growth in the number of EPD and considering the causes driving this growth. It provides an overview of EPD and embodied carbon data for the UK and finds similar availability as other countries when embodied carbon regulation was introduced. The increasing number of EPD has itself the potential to offer further insights. Using a quantitative meta-analysis of impacts from cement and concrete, steel, brick, and timber EPD, aleatory variability is found to explain the wide variation, and a typology of causes is proposed. The concept of EPD Landscapes is developed to visualise this variability within materials, providing a new approach to EPD analysis and an essential resource for stakeholders. The role of renewable energy in EPD is also explored, developing EPD Energy Arrays to identify products which have reduced both fossil and total primary energy demand, but raising concern of correlation between increasing the proportion of renewable energy and increased primary energy.

As the construction industry starts on its journey towards net zero, this thesis combines the previously poorly connected knowledge of EPD in industry and academia, with a major and innovative analysis, providing new knowledge of direct relevance for multiple stakeholders looking to reduce the embodied carbon of the built environment.
For many years, I have been fascinated by the growth in the numbers of Environmental Product
Declarations (EPD), and how incentives such as credits in Green Building Certification including
Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment
Environmental Assessment Method (BREEAM), and regulations such as RE2020 introduced in France
and the Buy Clean California Act have driven uptake. More recently, EPD tools, particularly in the
concrete industry, have provided the potential to supply environmental information for every concrete
mix from every concrete plant. From a situation in the 2000’s when there was hardly enough data to
enable the calculation of embodied carbon of buildings, or the procurement of products with lower
impact, we now have a situation where there is starting to be too much data, with EPD for over 80,000
separate concretes available in the US EC3 tool at the start of 2023, a very significant increase on the
number available at the end of 2022 (Building Transparency, 2022a, 2023).

The idea for this research is strongly influenced by my previous experiences and knowledge. After a
degree in Architecture, ten years’ experience in the construction industry, and then an MSc in
Advanced Energy and Environmental Systems, I started work as a researcher at BRE, where I co-
authored one of the first set of Product Category Rules (PCR) for EPD, the BRE Environmental Profiles
Methodology for construction materials (Howard, Edwards and Anderson, 1999), and three editions
Anderson, Shiers and Steele, 2009); with use of the 2009 edition mandatory for all publicly funded UK
housing projects as part of the UK Government’s Code for Sustainable Homes (DCLG, 2010). I also
worked on the development of tools to evaluate embodied impacts of buildings (Envest2 and IMPACT),
and have been heavily involved in international standards development, as the UK expert to both
Centre for European Standards (CEN) and International Standards Organisation (ISO) working groups
developing standards for EPD such as EN 15804:2012 and ISO 21930:2017, revising the European
standard for life cycle assessment of buildings (prEN 15978-1:2020) and creating a standard enabling
the digitisation of EPD to link with Building Information Modelling (BIM) (EN ISO 22057:2022).

The work on digitisation of EPD stimulated my thinking about the way that we provide EPD data
digitally, to maximise their utility and ability to influence embodied carbon reductions. As the number
of EPD has grown, what can be learnt from this increasing resource of information on product impact:
for example, does it provide the potential to generate benchmarks for different products, to provide
reasonable estimates of generic impact in the absence of collective EPD, to identify trends in embodied
impact, and to assist those producing and verifying EPD by highlighting outliers, and to offer a basis
for plausibility checks.

This research has explored the growing resource of EPD to understand if it provides this potential. I
hope that this thesis will play a part in moving the industry to net zero. The EPD Landscapes developed
in Chapter 6, 7 and 8 have already been used as the basis for further research, and overall the research
covered by the thesis has already been cited in over 60 articles or papers.
Acknowledgements

I am extremely grateful to my three supervisors, Alice Moncaster, Robin Roy, and Derek Jones for all their encouragement over these years. Their clear-headed ability to see to the nub of the issue and their insights have been thankfully received. They have consistently pushed me to achieve more, and our discussions have been both challenging and stimulating – I shall be sad when we no longer meet every month!

I would also like to thank those who have shared their time, knowledge, and experience with me, either through interviews or as part of conversations which have developed my thinking, especially Katherine Adams, Will Arnold, Paul Astle, Jake Attwood Harris, Clara Bagenal George, Kathryn Bourke, Duncan Cox, Tim den Dekker, Christian Donath, Mirko Farnetini, Orlando Gibbons, Jannik Giesekam, Julia Goerke, Oliver Kusche, Gary Newman, Francesco Pomponi, Freja Rasmussen, Anne Rønning, Eva Schmincke, Simon Sturgis, Katie Symons, Jane Thornback, Marios Tsikos, Rob Wheaton, Joe Jack Williams and Bastian Wittstock.

My particular thanks go to my children, who have been so understanding of my commitment to this PhD as they have worked on their GCSEs and A levels, especially my daughter whose knowledge of the Oxford comma, and the correct use of quotation marks was invaluable.

I am very grateful to the Open–Oxford–Cambridge Arts and Humanities Research Council (AHRC grant number AH/R012709/1) Doctoral Training Partnership for funding my PhD research from October 2019. The Whitbybird Foundation provided funding for the initial work on EPD for concrete. The Irish, Italian and Croatian Green Building Councils provided funding for collection and analysis of data for construction products other than cement and concrete as part of the Life Level(s) project (Life Level(s), 2020) funded by the European Union and I am grateful to Julia Barnard who assisted in collecting and tabulating initial data from EPD for structural products other than cement.
The following papers are based primarily on my work undertaken as part of the PhD and have been published in journals or presented at conferences during the course of my PhD studies.


Some of the findings in Chapter 4 have been included as a part of the IEA report, ‘Understanding the impact of individual, industry & political decisions on transitions towards environmental sustainability’ (Moncaster et al., 2023)

Chapter 5 has drawn on data from my earlier investigations of EPD numbers globally (Anderson and Thornback, 2012; Anderson, 2017, 2018, 2019b, 2020c, 2021c, 2022a) and in the UK undertaken as part of the research for this PhD (Anderson, 2021a)

The thesis also draws on work for industry on the themes of this PhD, undertaken largely when studying part-time or on placement:

- Alliance for Sustainable Building Products – [various briefing papers and webinars on Embodied Carbon and EPD](#)
- Construction Products Association – [briefing papers on EPD and embodied carbon](#)
- Eco Platform – articles for [newsletters](#)
- [Update of the RICS Professional Statement on Whole Life Carbon in the Built Environment](#) together with other members of the Whole Life Carbon Network (6-month part-time placement)

I have also drawn on my experiences working on the development of European and International Standards in CEN/TC 350 WG3 and ISO TC59 SC17 WG3, such as the amendment of EN 15804:2013+A2:2019, ISO 22057:2022 and the drafting of the revision of CEN/TR 15941:2010, prEN 15941 considering data quality at product and building level, and my involvement on the steering groups for the revision of PAS 2080:2016 (Carbon Management in the built environment) and the development the [UK Net Zero Carbon Building Standard](#).
V Table of Contents

I Abstract ........................................................................................................................................... i
II Foreword ........................................................................................................................................ ii
III Acknowledgements .................................................................................................................... iii
IV Previously published work ......................................................................................................... iv
V Table of Contents ........................................................................................................................ v
VI Table of Figures ........................................................................................................................ ix
VII Table of Tables .......................................................................................................................... xiii
VIII Acronyms and Abbreviations ................................................................................................... xv
IX Glossary ....................................................................................................................................... xviii

1. Introduction .................................................................................................................................... 1
   1.1. Research context and overview of thesis ................................................................................. 1
   1.2. Embodied carbon ..................................................................................................................... 2
   1.3. Environmental Product Declarations (EPD) and generic data ............................................. 3
   1.4. Assessing embodied carbon using EPD and generic data .................................................. 5
   1.5. Consideration of embodied carbon: the current state in the UK ......................................... 7

2. Embodied Carbon Data and EPD in the Literature ...................................................................... 8
   2.1. Approach to reviewing the literature ....................................................................................... 8
      2.1.1. Initial meta-review to identify the trends and gaps in the academic literature ............. 8
      2.1.2. Approach to reviewing the academic literature .............................................................. 8
      2.1.3. Approach to reviewing the grey literature ..................................................................... 10
   2.2. Findings from the meta-review ............................................................................................... 10
      2.2.1. General themes relating to building LCA and embodied carbon assessment from the meta-review ........................................................................................................... 10
      2.2.2. Data related themes from the meta-review ...................................................................... 12
      2.2.3. Main findings from the meta-review ................................................................................ 14
   2.3. Literature Review .................................................................................................................... 15
      2.3.1. The role of EPD in reducing embodied carbon .............................................................. 15
      2.3.2. Awareness of construction product EPD in the literature .......................................... 16
      2.3.3. The availability of EPD .................................................................................................. 17
      2.3.4. Drivers of growth in EPD .............................................................................................. 18
      2.3.5. UK grey literature on measurement and reduction of embodied carbon .................... 23
      2.3.6. UK construction product data ....................................................................................... 28
      2.3.7. What product level data is important globally, and in the UK? .................................. 30
      2.3.8. What the literature says about variation in product level data from EPD .................. 31
   2.4. Research questions arising from the literature review .......................................................... 40

3. Research Design .......................................................................................................................... 42
3.1. Epistemology and approach ................................................................. 42
3.2. Research methodology generally ...................................................... 42
3.3. Data collection methodologies .............................................................. 43
  3.3.1. Data on the views of embodied carbon expert practitioners ................. 43
  3.3.2. Data on the availability of Environmental Product Declarations (EPD) globally .......... 47
  3.3.3. Data on the availability of EPD by product group ................................ 48
  3.3.4. Data on the drivers for growth of EPD ........................................... 48
  3.3.5. Data on the availability of generic embodied carbon data in European national databases used for regulation .................................................. 49
  3.3.6. Data on the availability of embodied carbon data and EPD in the UK .......... 49
  3.3.7. Data on cradle-to-gate impacts from EPD (Modules A1-A3) .................. 50
  3.3.8. Data collection to consider of end of life data in EPD ........................ 54
3.4. Data analysis methodologies ............................................................... 55
  3.4.1. Thematic analysis of interviews ..................................................... 55
  3.4.2. Types of data visualisation used to aid analysis and interpretation of data .......... 55
  3.4.3. Data visualisation used to aid analysis and interpretation of renewable energy consumption and non-renewable energy consumption ......................... 57
  3.4.4. Embodied Carbon Product Datasheets developed to consider the availability of embodied carbon data in the UK ......................................................... 58
3.5. Research timeline ............................................................................ 59
4. Use of EPD in practice ........................................................................ 61
  4.1. Introduction ..................................................................................... 61
  4.2. Embodied carbon: knowledge and intuition ........................................ 61
  4.3. The complexity of using guiding principles ........................................ 63
  4.4. Assess, don’t guess: measurement versus intuition .............................. 72
  4.5. Embodied carbon: the role of data .................................................. 72
  4.6. An exploration of expert views on concrete ....................................... 74
  4.7. Discussion ...................................................................................... 77
  4.8. Conclusion ..................................................................................... 79
5. Environmental Product Declarations and Embodied Carbon Data: Growth and Needs .......... 81
  5.1. Introduction ..................................................................................... 81
  5.2. Availability of EPD for construction products: a growing resource .......... 81
  5.3. Drivers of growth in EPD numbers .................................................... 84
  5.4. The critical mass of data needed to mandate embodied carbon assessment at building level 96
  5.5. Product-level embodied carbon data in the UK .................................... 100
  5.6. Is there sufficient data for the UK to mandate embodied carbon assessment? .... 106
  5.7. Discussion and conclusion ................................................................ 108

vi
6. Explorations of Variation in EPD data ................................................................. 111
   6.1. Introduction ....................................................................................................... 111
   6.2. Typology of variability ..................................................................................... 111
   6.3. Types of technological variability ................................................................. 112
       6.3.1. Variability due to input materials .......................................................... 112
       6.3.2. Variability due to different manufacturing technology ......................... 113
       6.3.3. Variability due to energy source ............................................................ 115
       6.3.4. Variability due to product design ........................................................... 116
   6.4. Types of geographical variability ................................................................. 117
       6.4.1. Variability due to differences in electricity grids ................................. 118
       6.4.2. Variability due to differences in typical practices ................................. 118
       6.4.3. Variability due to differences in scenarios ............................................ 119
       6.4.4. Summary of findings about geographical variability ......................... 124
   6.5. Temporal variability ....................................................................................... 125
   6.6. Variability due to granularity ........................................................................ 127
   6.7. Discussion and conclusion ............................................................................. 129
7. Analysis of EPD for Cement and Concrete ...................................................... 134
   7.1. Introduction ....................................................................................................... 134
   7.2. Overview of EPD for cementitious products generally .............................. 134
   7.3. Analysis of EPD by cement class .................................................................... 138
   7.4. Overview of EPD for ready-mix Concrete ..................................................... 140
   7.5. Analysis of EPD for C30 concrete ................................................................ 144
   7.6. Proposed uses for the ‘EPD Landscapes’ ......................................................... 146
   7.7. Conclusion ....................................................................................................... 147
8. Analysis of renewable energy use in EPD ....................................................... 149
   8.1. Introduction ....................................................................................................... 149
   8.2. Renewable energy and EPD for Ordinary Portland Cement (CEM I) ............ 151
   8.3. Renewable energy and EPD for steel .............................................................. 153
   8.4. Renewable energy and EPD for brick ............................................................. 155
   8.5. Renewable energy and EPD for structural timber ........................................ 157
   8.6. Proposed uses of the ‘EPD Energy Arrays’ ..................................................... 160
   8.7. Summary and Discussion .............................................................................. 161
   8.8. Conclusion ....................................................................................................... 164
9. Conclusion ........................................................................................................... 165
   9.1. Summary .......................................................................................................... 165
   9.2. Additional commentary on UK situation .................................................... 166
   9.3. Suggestions for future research .................................................................... 168
10. References ................................................................................................................................. 170
Appendix A: Environmental Product Declarations (EPD) ............................................................. 191
Appendix B: Questionnaire for Interviews .................................................................................. 197
Appendix C: Statistical Terms ....................................................................................................... 199
Appendix D: EPD for construction products produced in the UK ............................................. 201
Appendix E: Embodied Carbon Product Datasheets ...................................................................... 204
VI Table of Figures

Figure 1: CEN/TC 350 Life cycle stages of EN 15978 and EN 15804 (CEN/TC 350, 2019a) ...........................................4
Figure 2 Diagram explaining how to undertake an embodied carbon assessment, source (RICS, 2017) ........................................................................................................................................................................6
Figure 3 Life cycle stages and modules, and the relationship between product and building level ........................................................................................................................................................................6
Figure 4 Prevalence of specified terms in Academic Literature (Scopus, 2022) over time...............9
Figure 5 Citations of Standards within the academic literature (Scopus, 2022) ..........................................................9
Figure 6 Upfront carbon impacts by material for the UK, adapted from Drewniok et al. (2022)........ 30
Figure 7 UK Embodied Carbon by Material Group ........................................................................................................ 31
Figure 8 Relation between the different types of EPD data for each building material, from (Hodková and Lasvaux, 2012) ........................................................................................................................................................................38
Figure 9 The Mixed Methods Research Approach, derived from Johnson and Onwuegbuzie (2004) ........................................................................................................................................................................42
Figure 10 Data reduction in thematic qualitative analysis, from (Irvine, 2011) based on Hinds et al. (1997) ........................................................................................................................................................................55
Figure 11 Stacked area chart example .................................................................................................................................56
Figure 12 Stacked bar chart .......................................................................................................................................................56
Figure 13 Box and Whisker Graph explained ..........................................................................................................................56
Figure 14 Examples of R and R² for samples with different linear correlations (adapted from Pierce (no date)) ........................................................................................................................................................................56
Figure 15 Example treemap chart ................................................................................................................................................57
Figure 16 Example of the data visualisation developed to consider the distribution of renewable and non-renewable energy use consistently for key construction product groups ........................................................................................................................................................................58
Figure 17 Emissions intensity ranges for low emission steel production, sourced from IEA (2022) (fig 3.7) ........................................................................................................................................................................68
Figure 18: Growth of EN 15804 EPD ...........................................................................................................................................82
Figure 19 ECO Platform EPD at the start of 2019 by product type ..........................................................................................83
Figure 20 ECO Platform EPD in September 2015 by product type ..........................................................................................83
Figure 21 EN 15804 EPD from Verified EPD tools available in 2022 (EPD not registered within an EPD programme) .........................................................................................................................................................84
Figure 22 EPD to ISO 21930 in January 2023 ........................................................................................................................................84
Figure 23 Growth of Verified EPD and Generic Data in France .................................................................................................89
Figure 24 Numbers of DED and Collective EPD within the inies database ...............................................................................90
Figure 25 Numbers of EPD in Germany ........................................................................................................................................91
Figure 26 EPD numbers in North America (note change of scale between 0-6,000 and 10,000-100,000 EPD) ................................................................. 93
Figure 27 Location of EPD for concrete (source (Building Transparency, 2023)) ...................... 94
Figure 28 UK Manufacturer and UK Trade Association EPD by product group and sub-group at the start of 2023. .................................................................................. 105
Figure 29 Typology of Causes of Variability developed from the analysis ............................. 112
Figure 30 EPD Landscape for CEM I, CEM II and CEM III EPD, showing the GWP range by type. Adapted from analysis presented in Anderson and Moncaster, 2020. ........................... 113
Figure 31 EPD Landscape for steel EPD, showing the range of GWP dependent on recycled content and process. Adapted from analysis presented in Moncaster, Anderson and Mulligan, 2021. .................................................................................. 114
Figure 32 EPD landscape for steel EPD showing the range of GWP by product type. Adapted from analysis presented in Moncaster, Anderson and Mulligan, 2021. ......................................................... 114
Figure 33: CEM I EPD: energy consumption, ECO₂ and clinker content, based on analysis previously presented in Anderson and Moncaster, 2020 ........................................................................ 115
Figure 34 Effect of renewable energy usage on GWP and Total Primary Energy from EAF steel EPD, adapted from analysis presented in Anderson and Moncaster, 2022a. ........................................... 116
Figure 35 Examples of Ziegel bricks (left) and facing bricks (right) ............................................. 116
Figure 36 EPD Landscape for Bricks showing the range GWP (A1-A3) by type ..................................... 117
Figure 37 Total energy demand per tonne and % of renewable energy used for different designs and types of brick, adapted from analysis presented in Moncaster, Anderson and Mulligan, 2021. .................................................................................................................... 117
Figure 38 Carbon intensity of Electricity for the EU27, 2021 (source (European Environment Agency (EAA), 2022) ........................................................................................................ 118
Figure 39 GWP and Total Energy Demand for EPD for reinforcing steel (100% scrap) from CARES members .................................................................................................................. 118
Figure 40 GWP of Generic Concrete EPD from national trade associations per m³ by 28-day compressive strength. Adapted from analysis presented in Anderson and Moncaster, 2020. .................................................................................................................. 119
Figure 41 EoL routes for mineral Construction and demolition waste for Europe, 2020, source Eurostat (2023); UK, 2018, source DEFRA and Government Statistical Service (2021) .... 119
Figure 42 EoL routes for all non-hazardous timber waste for Europe, 2020, source Eurostat (2018 for UK, source DEFRA) .................................................................................................................. 120
Figure 43 Carbon intensity (grams CO₂e/kWh) for EU Electricity, source (EAA, 2022) ............ 125
Figure 44: GWP from cementitious EPD by year of registration and clinker content. Analysis previously presented in Anderson and Moncaster, 2020. ......................................................... 126
Figure 45 GWP of Steel EPD by year of data collection .................................................................. 126
Figure 46 GWP for concretes by year of EPD Registration. Analysis previously presented in Anderson and Moncaster, 2020. .................................................................................................................. 127
Figure 47 EPD Landscape for Buzzi |Unicem cement EPD by site (covering all products produced) and by product type (from all production sites). Analysis previously presented in Moncaster, Anderson and Mulligan, 2021 ........................................................................................................128

Figure 48 Concrete EPD from UK manufacturers showing their impact in relation to the UK generic concrete .................................................................................................................................................................129

Figure 49 EPD Landscape for Cementitious EPD showing the range of GWP by type ..........................................................136

Figure 50 EPD Landscape for cementitious EPD showing the range of GWP by Country of Producer ........................................................................................................................................................................137

Figure 51 EPD Landscape showing GWP excluding calcination v use of fossil fuel (ADP-F) and non-renewable secondary fuel (SR-nr) ........................................................................................................................................................................137

Figure 52 EPD Landscape showing GWP and Clinker Content shown for all Cementitious EPD ............................................................138

Figure 53 EPD Landscape for CEM II EPD showing Energy, ECO₂ and clinker content ..........................................................................................................................139

Figure 54 EPD Landscape showing non-renewable energy and fuel use v GWP for CEM III, CEM IV and CEM V cements ........................................................................................................................................................................140

Figure 55 EPD Landscape for concrete EPD showing range of GWP by compressive strength ............................................................142

Figure 56 EPD Landscape for concrete EPD showing range of GWP per unit of structural performance (MPa) by compressive strength ........................................................................................................142

Figure 57 EPD Landscapes showing GWP (A1-A3) by Compressive Strength, shown for each country ........................................................................................................................................................................143

Figure 58 EPD Landscapes for concretes with a compressive strength around 30 MPa, showing the range of GWP for a variety of differentiators ........................................................................................................................................................................145

Figure 59 EPD Landscape for concretes from Holcim Australia EPD ..........................................................................................................................145

Figure 60 GWP and % Renewable Energy for CEM I cement EPD ..........................................................................................................................152

Figure 61 Total Energy Consumption and Total Non-renewable Energy consumption v GWP for CEM I cement EPD ........................................................................................................................................................................152

Figure 62 Total Energy consumption v % Renewable Energy for all CEM I EPD ..........................................................................................................................152

Figure 63 EPD Energy Array for CEM I EPD ........................................................................................................................................................................153

Figure 64 GWP v % Renewable Energy for Steel EPD by type ........................................................................................................................................................................153

Figure 65 Total Energy consumption and total non-renewable energy consumption v GWP for Steel EPD by type ........................................................................................................................................................................154

Figure 66 Total Primary Energy consumption v % Renewable Energy for Steel EPD by type ........................................................................................................................................................................154

Figure 67 EPD Energy Array for BOF and EAF Steel EPD ........................................................................................................................................................................155

Figure 68 EPD Energy Array for Structural and Reinforcing Steel EPD ..........................................................................................................................155

Figure 69 GWP v % Renewable Energy for Brick EPD by type ........................................................................................................................................................................156

Figure 70 Total Energy consumption and total non-renewable energy consumption v GWP for Brick EPD by type ........................................................................................................................................................................156

Figure 71 Total energy v % Renewable Energy for Brick by type ........................................................................................................................................................................157

Figure 72 EPD Energy Array for Facing and Ziegel Bricks ........................................................................................................................................................................157

Figure 73 GWP v % Renewable Energy for Timber EPD by type ........................................................................................................................................................................158
Figure 74 Total Primary Energy v GWP for Timber EPD ......................................................... 158
Figure 75 Total Non-renewable Primary Energy v GWP for Timber EPD ........................................ 159
Figure 76 Total Energy consumption v % Renewable Energy for Timber EPD ...................................... 159
Figure 77 EPD Energy Array for Timber EPD .................................................................................. 159
Figure 78 Illustrative EPD Energy Array ......................................................................................... 160
Figure 79 Total energy use and GWP from EPD for various product groups ......................................... 161
Figure 80 Renewable and Non-renewable Energy use from EPD for various product groups .............. 161
Figure 81 EPD Landscape showing percentage of renewable energy from EPD for various product groups ......................................................................................................................................................... 162
Figure 82 Change in GWP as Percentage of renewable energy used increases (weight of line represents the strength of correlation) ................................................................................................................. 163
Figure 83 Changes in total energy consumption as the percentage of renewable energy increases (weight of line represents the strength of correlation) .......................................................... 163
VII Table of Tables

Table 1 Analysis of embodied carbon mitigation strategies from the literature ........................................ 16
Table 2 Summary of factors from the academic literature affecting the growth of EPD (+ = growth factor, - = limiting factor) .................................................................................................................. 19
Table 3 Overview of the data and specifications within the Green Guide to Specification obtained by analysing the literature ........................................................................................................... 28
Table 4 Classification of variation in Kellenberger et al. (2004) into aleatory and epistemic uncertainty .................................................................................................................................................. 32
Table 5 Classification of causes of impact variation from the literature considering EPD to EN 15804 ............................................................................................................................................... 34
Table 6 Classification of causes of impact variation from the literature considering EPD and generic databases ...................................................................................................................................... 35
Table 7 Research methodologies used for each research question .............................................................................. 44
Table 8 Interviewees and their background ..................................................................................................................... 47
Table 9 Stakeholders contacted to review national drivers for EPD growth ................................................................. 49
Table 10 Product types and sub-types analysed .............................................................................................................. 51
Table 11 Cement classifications from EN 197-1:2011 .................................................................................................... 51
Table 12 Product Types and Sub-types and the Declared Units used for this study ..................................................... 53
Table 13 Some Mitigation Strategies from the Literature and corresponding Guiding Principles suggested by the ECEPs .................................................................................................................... 63
Table 14 Comparison of functionally equivalent steel and concrete beam for modules A-C, sourced from Arnold et al. (2021) ........................................................................................................... 64
Table 15 Comparison of embodied carbon for Brick and Portland Stone using EPD ............................................. 65
Table 16 Comparison of impact of reused and virgin bricks using EPD ........................................................................ 66
Table 17 Comparison of reused and virgin access flooring using EPD ........................................................................ 66
Table 18 ECO2 for aggregates from Swiss Collective EPD ............................................................................................. 66
Table 19 Comparison of embodied carbon for two concrete blocks using EPD ......................................................... 67
Table 20 Comparison of steel and aluminium profiled sheet roofing using generic global data ............................... 69
Table 21 Impact for transport for common construction materials .................................................................................. 71
Table 22 The use of cement replacement in the literature on mitigation strategies ..................................................... 75
Table 23 Initiatives at national and regional level linked to EPD Growth .................................................................... 86
Table 24 Quantity and types of generic and specific data in Databases used in National Regulation in Europe at the start of January 2023 .................................................................................. 98
Table 25 Summary of generic dataset availability in countries with regulation when regulation introduced and at the start of 2023 .................................................................................................. 99
Table 26 EPD Numbers over time in national EPD programmes in countries with embodied carbon regulation .............................................................................................................................. 99
Table 27: Largest manufacturing sectors associated with the construction products industry in 2021 (source: Office for National Statistics (2022))

Table 28: Largest UK imports by value of products related to the construction sector in 2021. 5 product groups with the largest net import are also included. (BEIS, 2023; United Nations, 2023)

Table 29: UK Generic Databases

Table 30: Scenario data for Polystyrene Insulation EPD. Adapted from analysis presented in Anderson, Rønning and Moncaster, 2019

Table 31: Scenario data for wood panel product EPD. Adapted from analysis presented in Anderson, Rønning and Moncaster, 2019

Table 32: Typology of variability and indicative effect on impact

Table 33: Cementitious EPD by Programme and Country

Table 34: Ready-mix concrete EPD by EPD programme and country

Table 35: Number of products (Number of EPD) covered by EPD by country, PCR standard and year of registration

Table 36: EPD for structural products considered for the analysis of the role of renewable energy

Table 37: EPD covering UK Production
### VIII Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACAN</td>
<td>Architects Climate Action Network</td>
</tr>
<tr>
<td>ACM</td>
<td>Alternative cementitious material</td>
</tr>
<tr>
<td>ADPF</td>
<td>Abiotic Depletion Potential – Fossil fuels</td>
</tr>
<tr>
<td>AEC</td>
<td>Architecture, Engineering and Construction</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>ASBP</td>
<td>Alliance for Sustainable Building Products</td>
</tr>
<tr>
<td>AUB</td>
<td>Association of Building Product Producers and Distributors (DE)</td>
</tr>
<tr>
<td>BECD</td>
<td>Built Environment Carbon Database</td>
</tr>
<tr>
<td>BEIS</td>
<td>Department of Business, Energy, Innovation and Skills</td>
</tr>
<tr>
<td>BE-ST</td>
<td>Built Environment - Smarter Transformation (formally Construction Scotland Innovation Centre)</td>
</tr>
<tr>
<td>BF/BOF</td>
<td>Blast furnace/Basic Oxygen Furnace route to make steel</td>
</tr>
<tr>
<td>BNB</td>
<td>Bewertungssystem Nachhaltiges Bauen (Evaluation System for Sustainable Building)</td>
</tr>
<tr>
<td>BIM</td>
<td>Building Information Modelling or sometimes Building Information Management</td>
</tr>
<tr>
<td>BRE</td>
<td>Building Research Establishment</td>
</tr>
<tr>
<td>BREEAM</td>
<td>Building Research Establishment Environmental Assessment Method</td>
</tr>
<tr>
<td>BREF</td>
<td>Reference Document on Best Available Techniques</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>CLF</td>
<td>Carbon Leadership Forum</td>
</tr>
<tr>
<td>CEM I</td>
<td>Portland cement with a maximum of 5% other materials, as defined in EN 197-1:2011</td>
</tr>
<tr>
<td>CEN</td>
<td>European Standards Organisation</td>
</tr>
<tr>
<td>CEN/TC 350</td>
<td>CEN Technical Committee 350</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined heat and power</td>
</tr>
<tr>
<td>CIBSE</td>
<td>Chartered Institute of Building Services Engineers</td>
</tr>
<tr>
<td>CIC</td>
<td>Construction Industry Council</td>
</tr>
<tr>
<td>CIOB</td>
<td>Chartered Institute of Building</td>
</tr>
<tr>
<td>CLC</td>
<td>Construction Leadership Council</td>
</tr>
<tr>
<td>CLT</td>
<td>Cross Laminated Timber</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CO₂e</td>
<td>Carbon Dioxide equivalent</td>
</tr>
<tr>
<td>CoV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>CPR</td>
<td>Construction Products Regulation</td>
</tr>
<tr>
<td>DCLG</td>
<td>Department of Communities and Local Government</td>
</tr>
<tr>
<td>DED</td>
<td>Données environnementales par défaut (Default Environmental Declaration)</td>
</tr>
<tr>
<td>DEFRA</td>
<td>Department for Environment, Farming and Rural Affairs</td>
</tr>
<tr>
<td>DFT</td>
<td>Department for Transport</td>
</tr>
<tr>
<td>DGNB</td>
<td>German Sustainable Building Council</td>
</tr>
<tr>
<td>DLUHC</td>
<td>Department of Levelling Up, Housing and Communities</td>
</tr>
<tr>
<td>DoP</td>
<td>Declaration of Performance</td>
</tr>
<tr>
<td>DRI/EAF</td>
<td>Direct Reduced Iron/Electric Arc Furnace route to make steel</td>
</tr>
<tr>
<td>E+C</td>
<td>Bâtiment à Énergie Positive et Reduction Carbone</td>
</tr>
<tr>
<td>EAF</td>
<td>Electric Arc Furnace route to make steel</td>
</tr>
<tr>
<td>EC</td>
<td>Embodied Carbon</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>ECEP</td>
<td>Embodied Carbon Expert Practitioner</td>
</tr>
<tr>
<td>ECO₂e</td>
<td>Embodied carbon (embodied carbon dioxide equivalent)</td>
</tr>
<tr>
<td>EDEC</td>
<td>Échanges de Données Environnementales Configurées (EPD Tool Exchange)</td>
</tr>
</tbody>
</table>
EN European Standard
EoL End of Life
EoW End of Waste
EPD Environmental Product Declaration(s)
EPS Expanded polystyrene
EU European Union
FDES Fiches de Déclaration Environnementale et Sanitaire (Environmental and Health Product Declaration)
GCB The Green Construction Board
GCCA Global Cement and Concrete Association
GGBS Ground granulated blast furnace slag
GHG Greenhouse gas
GPP Green Public Procurement
Gtonne Gigatonne (1000 million tonnes)
GWP Global Warming Potential
H\B:ERT Hawkins Brown: Emission Reduction Tool
HM Treasury Her Majesty's Treasury
IBU Institut Bau und Umwelt (DE)
ICE Institution of Civil Engineers
ICE Database Inventory of Carbon and Energy database
IDDI Industrial Deep Decarbonisation Initiative
IEA International Energy Agency
ILCD International Life Cycle Database
IPCC Intergovernmental Panel on Climate Change
ISO International Standards Organisation
IStuctE Institution of Structural Engineers
KrWG Kreislaufwirtschaftsgesetz (Circular Economy Act)
LCA Life Cycle Assessment (or Analysis)
LCI Life Cycle Inventory
LEED Leadership in Energy and Environmental Design
LETI London Energy Transition Initiative
LVL Laminated veneered timber
M350 Mandate 350 from the European Commission to CEN
MDF Medium Density Fibreboard
MEP Mechanical, electrical and plumbing
MJ Mega Joule (1 million joules)
MMC Modern Methods of Construction
MND Module not declared
MPA Mineral Products Association
MPa MegaPascal
MRIO Multi-region input-output
MS Mitigation Strategy
Mt Mega tonne (1 million tonnes)
Mt CO\textsubscript{2}e Mega tonne carbon dioxide equivalent
NBS National Building Specification
OPC Ordinary Portland Cement
OSB Oriented Strand Board
PCR Product Category Rules
PEF Product Environmental Footprinting
PENRE Non-renewable Primary Energy used as Energy
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PENRM</td>
<td>Non-renewable Primary Energy used as Material</td>
</tr>
<tr>
<td>PENRT</td>
<td>Total Non-renewable Primary Energy</td>
</tr>
<tr>
<td>PERE</td>
<td>Renewable Primary Energy used as Energy</td>
</tr>
<tr>
<td>PERM</td>
<td>Renewable Primary Energy used as Material</td>
</tr>
<tr>
<td>PERT</td>
<td>Total Renewable Primary Energy</td>
</tr>
<tr>
<td>PFA</td>
<td>Pulverised fuel ash</td>
</tr>
<tr>
<td>PUR</td>
<td>Rigid polyurethane foam</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RE2020</td>
<td>Réglementation environnementale des bâtiments neufs</td>
</tr>
<tr>
<td>RIBA</td>
<td>Royal Institute of British Architects</td>
</tr>
<tr>
<td>RICS</td>
<td>Royal Institute of Chartered Surveyors</td>
</tr>
<tr>
<td>RQ</td>
<td>Research question</td>
</tr>
<tr>
<td>SCM</td>
<td>Supplementary cementitious material</td>
</tr>
<tr>
<td>SME</td>
<td>Small and medium enterprises</td>
</tr>
<tr>
<td>T&amp;D</td>
<td>Transmission and distribution</td>
</tr>
<tr>
<td>TC</td>
<td>Technical Committee</td>
</tr>
<tr>
<td>TDUK</td>
<td>Timber Development UK</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UKGBC</td>
<td>UK Green Building Council</td>
</tr>
<tr>
<td>WBCSD</td>
<td>World Business Council for Sustainable Development</td>
</tr>
<tr>
<td>WGBC</td>
<td>World Green Building Council</td>
</tr>
<tr>
<td>WLC</td>
<td>Whole Life Carbon</td>
</tr>
<tr>
<td>WLCN</td>
<td>Whole Life Carbon Network</td>
</tr>
<tr>
<td>WRAP</td>
<td>Waste Resources Action Programme</td>
</tr>
<tr>
<td>WRI</td>
<td>World Resources Institute</td>
</tr>
<tr>
<td>WTT</td>
<td>Well to tank</td>
</tr>
<tr>
<td>XPS</td>
<td>Extruded Polystyrene</td>
</tr>
</tbody>
</table>
Arm's length bodies | a specific category of central government public bodies that is administratively classified by the Cabinet Office
Baseline carbon model | Model (normally created in the early design stage) used to benchmark improvements as the design progresses
Collective EPD | EPD produced by a group of manufacturers or industry association
Embodied carbon | Total of all the greenhouse gas emissions and removals associated with the production and life cycle of a product, excluding its operation
Embodied energy | Total of all the energy consumed in the processes associated with the production and life cycle of a product
Environmental Product Declaration (EPD) | A verified declaration to ISO 14025 providing information on the environmental impacts of a product using life cycle assessment. For construction product EPD, EN 15804 or ISO 21930 provide the core product category rules.
Generic data | Data not associated with any particular manufacturer, for example, a trade association EPD, a national default dataset or LCI data from a commercial database
Non-renewable energy | Energy taken from a source which is depleted by extraction (e.g. fossil fuels or uranium)
Primary Energy | Energy that has not been subjected to any conversion or transformation process
Product Category Rules (PCR) | Consistent set of rules used for EPD to allow comparison
R1 Status | R1 status according to the Waste Framework Directive Energy Efficiency Formula: \( \text{Energy efficiency} = \frac{(E_p - (E_f + E_i))(0.97 \times E_w + E_f))}{0.97} \) where \( E_p \) means annual energy produced as electricity multiplied by 2.6 and heat produced for commercial use multiplied by 1.1, \( E_f \) means annual energy input to the system from fuels contributing to the production of steam, \( E_w \) means annual energy contained in the treated waste calculated using the net calorific value of the waste, \( E_i \) means annual energy imported excluding \( E_w \) and \( E_f \). 0.97 is a factor accounting for energy losses due to bottom ash and radiation.
Renewable energy | Energy from renewable non-fossil sources, e.g. wind, solar, hydropower, sustainable biomass.
Secondary fuels | Fuel recovered from previous use or from waste derived from a previous product system. Renewable secondary fuels include fuels recovered from cooking oil and waste wood or landfill gas. Non-renewable secondary fuels include fuels recovered from synthetic rubber tyres or motor oils.
Technosphere | Sphere or realm of human technological activity which results in a technologically modified environment
Upfront carbon | Embodied carbon impact of A1-A5 minus the biogenic carbon sequestered in the product (as CO₂).
Whole life carbon | Embodied and operational carbon
Ziegel brick | A perforated clay block, commonly used in Europe
1. Introduction

1.1. Research context and overview of thesis

Sir David Attenborough has highlighted that in climate change, ‘we are facing a man-made disaster of global scale. Our greatest threat in thousands of years.’ (Attenborough, 2018). Meanwhile, the International Panel on Climate Change has considered how much carbon we could emit globally from 2020 (the ‘remaining carbon budget’) to limit global warming to 1.5°C with a 50% probability, and predicts that based on current global emissions, we will have nearly spent this remaining carbon budget by 2030 (IPCC Working Group III, 2021). They emphasised the need for action, stating

‘Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 °C by 2100.’

This, together with the climate strikes inspired by Greta Thunberg, and Extinction Rebellion protests, has raised concerns about climate change significantly in the general UK population (Carrington, 2019). The UK Government has responded by setting a legally binding target to reach net zero by 2050 (UK Government, 2019).

As major emitters, the construction industry and the built environment in general will need to reduce their greenhouse gas (GHG) emissions, in order to stay within the global carbon budget. In the UK, this is essential to help achieve the 2050 net zero target; however historically, most of the policy and industry focus has been on reducing operational energy use and emission – predominantly from heating in new buildings - with sporadic efforts to retrofit existing housing with basic energy efficiency measures. Until recently, in the UK and globally, there has been very little focus on embodied carbon – the carbon emissions associated with construction products and the construction process. Embodied carbon matters however, because these emissions equated to nearly 10% of UK greenhouse gas emissions in 2014 (Giesekam, 2018), and are estimated to account for 12% of global energy and process related CO₂ emissions (UN Environment Programme, 2022).

In order to assess and reduce embodied carbon in the built environment, it is necessary to understand the embodied carbon coefficients for construction products. This information is contained within Environmental Product Declarations (EPD), a standardised and verified form of environmental data which are widely used to communicate information within the architecture, engineering, and construction industry on the embodied carbon coefficients and other embodied impacts of construction products. EPD, and generic datasets which provide the typical embodied carbon coefficients for construction materials, together provide essential data for any assessment of embodied carbon, and its subsequent reduction.

However, within the UK at least, Government concerns about the availability and uncertainty of this data appear to be one of the barriers to the adoption of regulation of embodied carbon. A recent Government tender for a research project for example included a requirement for research to be carried out into “uncertainties in data” and noted the crucial need for sufficient product data to be in place for the reduction of embodied carbon, stating, ‘there are questions about whether there is the critical mass of EPDs needed’ (DLUHC, 2022).

This thesis explores EPD and their potential to support the reduction of embodied carbon, addressing in particular, these two concerns about the availability and uncertainty in existing data. As data, and approaches to embodied carbon, vary between different regions of the world, and different nations, in addition to a global review of data, there is a specific focus on the situation within the UK.
The following sections of the introduction provide an overview of embodied carbon generally, of product-level embodied carbon data including EPD and generic data, of how this data is used within embodied carbon assessment, and of the current status of embodied carbon in the UK.

Subsequent chapters focus on the literature review (Chapter 2) which ends with specific research questions, the methodology (Chapter 3), five analysis chapters each of which address a particular question and research area and end in a short conclusion, and then a final concluding chapter (Chapter 9).

1.2. Embodied carbon

Embodied carbon is defined in the International Standard, ISO 6707-3 (ISO, 2022, para. 3.9.28), which provides definitions for sustainability terms used within the built environment, as:

‘the total of all the greenhouse gases emitted or removed in the processes associated with the extraction, production, transportation to site, installation, use, refurbishment, replacement and disposal at end of life of materials and products and construction works, expressed as CO\textsubscript{2} equivalent.’

Carbon dioxide (CO\textsubscript{2}) is the most significant greenhouse gas, but other greenhouse gases such as methane, or hydrofluorocarbons which are used as refrigerants and blowing agents for insulation foams, also cause global warming (Stocker \textit{et al.}, 2013).

Whole life carbon, covering both embodied carbon and operational carbon, is synonymous with product carbon footprinting as described in ISO 14067 (ISO, 2018) and broadly with greenhouse gas accounting for products across Scope 1, 2 and 3 according to the Greenhouse Gas Protocol (WRI and WBCSD, 2011). The energy consumed to create embodied carbon is known as embodied energy, and is measured as it enters the technosphere, normally in MJ. Embodied impacts include not just embodied carbon, but other environmental impacts such as acidification, toxicity and fossil fuel depletion, and are measured using Life Cycle Assessment (LCA).

Until recently, embodied energy and embodied carbon were not considered significant, and the focus instead was on the operational impacts associated with buildings (Balouktsi and Lützkendorf, 2016). Ibn-Mohammed \textit{et al.} (2013) reported that in 1991, BRE estimated that the operational energy required to operate a 3-bed house would equate to the embodied energy in a period of 2-5 years. However, more recently, Röck \textit{et al.} (2020) reviewed over 650 building level case studies across Europe, and found that the average impact of embodied carbon for a building following current regulations for energy performance is approximately 20–25% of the total life cycle emissions (around 15 years operational energy), while for the highly energy-efficient buildings that will be required to achieve net zero, this figure rises to 45–50%, though there is a considerable range of results. They note that highly energy efficient buildings are also associated with a significant increase in embodied carbon impacts, emphasising the need to focus on their reduction.

Looked at globally, 12% of energy and process-related greenhouse gas emissions already come from the production of construction materials and construction processes associated with buildings and infrastructure according to the UN Environment Programme (2022) (fig.15). In the UK, embodied carbon was calculated to be nearly 10% of UK greenhouse gas emissions in 2014 (Giesekam, 2018). In the UK, both the Environmental Audit Committee and the Committee on Climate Change have suggested that some form of mandatory assessment and reporting is required in the UK to address embodied carbon at building level (Committee on Climate Change, 2020; Environmental Audit Committee, 2022a). Therefore it is clear that the embodied carbon of buildings and infrastructure is, in fact, significant.
Across other nations too, although many countries have regulations and building codes to address operational energy and carbon, regulation of embodied carbon is much less common, with the World Green Building Council suggesting this can be due to lack of awareness and demand, but also political aspects such as policy cycles and changing priorities (World Green Building Council, 2019). However a growing number of countries have recently introduced regulation of embodied carbon at building level, including Germany for public buildings from 2011, Netherlands for new housing and offices from 2012, a pilot regulation in France from 2018 (Le Moniteur, 2016) and more recently, full regulation in France (Ministère de la Cohésion des Territoires et des Relations avec les Collectivités Territoriales, 2020), and the introduction of regulation in Sweden, Denmark, and Finland (Bionova Ltd/One Click LCA, 2018; One Click LCA, 2022).

1.3. Environmental Product Declarations (EPD) and generic data

To allow embodied carbon of buildings to be assessed accurately, a consistent methodology and adequate data on GHG emissions from products and energy, transport and construction services is necessary; in fact, the academic literature deems it essential (e.g. Kuittinen and Häkkinen, 2020; Rasmussen, Malmqvist and Birgisdóttir, 2020). When regulating embodied carbon, other countries have adopted the building level standard, EN 15978, with the introduction of national appendices or annexes, and have also set a preference for the use of EPD to EN 15804 within their approaches (One Click LCA, 2022).

EPD are a type of environmental label which provide independently verified environmental information about a product, using life cycle assessment (LCA) based on primary data from a manufacturer.

For construction products, an EPD is a standardised way of reporting an LCA so it can be used and compared at building level. The types of information provided by EPD for construction products, and how this information can be understood, are described in Appendix A: Environmental Product Declarations (EPD).

The international standard for EPD is ISO 14025:2006, which provides the requirements for EPD programmes and for EPD for any type of product. It also defines the need for Product Category Rules to ensure that the LCA methodology used by EPD in the EPD programme is the same so that EPD can be compared.

Within Europe, the European standard EN 15804 provides the Product Category Rules for all construction products in line with ISO 14025. Two European countries, France and Belgium, require manufacturers to provide EPD to EN 15804 if they wish to make environmental claims about construction products (Ministère de l’Égalité des Territoires et du Logement, 2013; Federal Government, 2014). The original EU Construction Products Regulation (CPR) in 2011 already referenced the use of EPD for ‘the assessment of the sustainable use of resources and of the impact of construction works on the environment’ (European Parliament and Council, 2011, article 56). The current proposal to revise the CPR mentions the possibility of using ‘permalinks’ from the Declaration of Performance (DoP) covering environmental aspects to EPD (Commission, 2022). This does not reference the use of EN 15804 for the provision of environmental information, although the process is expected to be based on standardisation mandates using EN 15804 (Unit GROW H.1-Construction, 2022), but both Construction Product Europe and the European Council have requested a more explicit link to EN 15804 (Construction Products Europe, 2022; European Parliament, 2022).

EN 15804 has been developed specifically to address the particular needs of construction products, for example their long life, the fact that their main purpose is to provide functionality at building or infrastructure level, rather than as products themselves, and to allow comparison of all types of construction product at building level. To address these needs, the product life cycle has been divided
up into a framework of life cycle stages and information modules, so that environmental information can be provided separately for each module, and to ensure compatibility, these same stages and modules are also used in building and infrastructure level assessments. This framework is shown in Figure 1.

ISO 21930:2017 is the corresponding international standard to EN 15804, and the two construction product EPD standards follow each other very closely, and both use the same framework.

Figure 1: CEN/TC 350 Life cycle stages of EN 15978 and EN 15804 (CEN/TC 350, 2019a)

Modules B6 and B7 cover operational impacts or operational carbon, while the other modules (A1-A5, B1-B5 and C1-C4) cover what are known as embodied impacts or embodied carbon (ISO, 2022). However the Energy Performance in Buildings Directive (European Parliament and Council, 2010), currently only requires European member states to measure operational impacts and does not cover embodied impacts (Szalay, 2007), although the proposed recast of the Directive includes a requirement for member states to publish roadmaps introducing whole life carbon limits and targets for different building types by 2025, using a common measurement methodology developed by the European Commission.

With its publication in 2012, European national EPD programmes started to adopt EN 15804 as the basis for their product category rules (PCR), as did new programmes around the world. Through mutual recognition, it also became possible for manufacturers to use a single LCA study to provide EPD across different countries and programmes (Anderson and Thornback, 2012).

As well as individual manufacturers, construction product EPD Programmes (international, national, sectoral, or in some cases company specific) are able to develop their own product category rules using EN 15804 or ISO 21930, providing further detail about the types of approaches, data, or assumptions to use for assessments. They also appoint verifiers, and publish EPD. There are also European and International Standards being developed to provide complementary PCR (c-PCR) for specific product types, using the rules of EN 15804 or ISO 21930, and providing further specification relevant to the product type, for example, EN 16485:2013 for timber, EN 16908:2017 for cement and lime and EN 16757:2017 for concrete.

ECO Platform is an association of EPD Programmes and other interested parties, which looks to ensure mutual recognition and a high quality of EPD across its members. ECO Platform members have agreed to use EN 15804 as their core PCR and the CEN c-PCR developed as product standards within their EPD Programmes as sub-category PCR.

In terms of EPD owner, there are two types of EPD:
**Collective EPD**: EPD produced by a group of manufacturers for an average or representative product. UK trade associations such as British Precast and the Brick Development Association, European trade associations such as the European General Galvanisers Association, marketing organisations such as WoodforGood, and certification bodies such as UK CARES have all produced collective EPD.

**Manufacturer-specific EPD**: EPD produced by a single manufacturer for a single product, a representative product, or an average product, for one or more of their sites.

In LCA, there are two types of product level data, described below using the definitions from ISO 6707-3:2022 (ISO, 2022).

- **Generic data**: data that are not product, service, site, or enterprise specific
- **Specific data**: data representative of a product or product group or service, provided by one supplier.

Collective EPD are generic data. Generic data is also made available within national databases like Oekobaudat in Germany (Gantner et al., 2018), created by reviewing a selection of EPD and other datasets, e.g. (Silvestre et al., 2015; Hammond and Jones, 2019), or in databases provided by academics or consultancy firms, e.g., ecoinvent or GaBi (Lasvaux et al., 2015). Manufacturer-specific EPD are the most common source of specific data.

### 1.4. Assessing embodied carbon using EPD and generic data

European countries which have introduced regulation of embodied carbon, either for specific building types or for public buildings, such as the Netherlands, France, Germany, Finland, Denmark, and Sweden, have all based their regulations on EN 15978, the European standard for building life cycle assessment, using its framework to produce their own more detailed national assessment methodologies to ensure consistency of assessment at a national level (One Click LCA, 2022). Elsewhere, New Zealand has also used EN 15978 as the basis for its embodied carbon regulation (Symons, 2022).

Embodied carbon should ideally be assessed over the full life cycle (cradle-to-grave), although other scopes, such as cradle-to-gate (when the product is ready to leave the factory) or cradle-to-site (which includes transport to the construction site) are sometimes used, particularly at product level.

The assessment of embodied carbon for buildings or infrastructure requires:

- environmental data about products and constructions,
- the quantification of the materials and processes used,
- an assessment of the expected service lives of components,
- the development of scenarios for the transport, installation, maintenance, deconstruction and waste treatment of the asset (Rasmussen et al., 2018).

The process is described in Figure 2 below.

Typically generic data is used before a specific product or manufacturer has been chosen, when representative data is required for the assessment. Generic data is also used when there is no specific data such as an EPD available for a particular manufacturer’s product. (CEN/TC 350, 2010)
In those countries where embodied carbon assessment has been regulated, EPD are preferred as a reliable source of embodied carbon data over generic data and most countries provide a corresponding national database of generic data and EPD for use in building assessment (One Click LCA, 2022).

Using the life cycle stages and modules from the standards, Figure 3 shows how environmental data for products provided in EPD for the Product, Construction and End of life Stage modules (and the Use Stage modules if provided) can be used at building level. EPD to EN 15804:2012+A2:2019 are always required to provide impact data for the product stage (A1-A3), the end of life stage (C1-C4) and Module D1, the other modules are optional. Data for modules A4-A5, B1-B7, C1-C4 and Module D can only be used at building level however if the scenarios used in the EPD are appropriate for the building being assessed. For example, data for A4 or C3 can be used if the transport or end of life scenarios from the EPD and for building are the same, shown in Figure 3 by the lighter arrows for these modules, whereas the product stage data will always be applicable at building level. For the Use Stage of the building, for example the replacement of a window in Module B4, impacts can be modelled using data from the Product, Construction and End of life Stages of a window EPD.

*1 Energy Efficiency Formula1 A small number of construction products like cement and timber preservatives whose end of life is always determined by other products like concrete or structural timber do not need to provide the Modules C1-C4 and Module D according to EN 15804+A2.
1.5. Consideration of embodied carbon: the current state in the UK

There is no national regulation for embodied carbon assessment or reduction as yet in the UK. However, the Environmental Audit Committee in their Inquiry into the Sustainability of the Built Environment, found that ‘A broad cross-section of the construction industry is willing and able to undertake whole-life carbon assessments’ (Environmental Audit Committee, 2022a, para. 79).

A range of useful and practical guidance on embodied carbon has also been produced by various bodies (e.g. UK Green Building Council and Crown Estate, 2015; London Energy Transformation Initiative (LETI), 2020). Formal and informal groups focussing on embodied carbon have been created such as LETI (2020), Architects Climate Action Network (ACAN, 2020), and the Whole Life Carbon Network (WLCN, no date).

The Royal Institute of Chartered Surveyors (RICS) has produced a Professional Statement providing a UK methodology for embodied and whole life carbon assessment compliant with EN 15978 (RICS, 2017) which the Royal Institute for British Architects (RIBA) have said is ‘the most comprehensive and consistent approach available to UK industry.’ The RICS methodology has also been adopted by the Greater London Authority in its regulation of embodied carbon for referable schemes (Mayor of London, 2022) and to assess embodied carbon in the Scottish Government’s Net Zero Carbon Public Sector Building Standard (Scottish Government et al., 2021). The recent report of the Environmental Audit Committee Inquiry stated, ‘the RICS Professional Statement on [Whole Life Carbon (WLC)] is used as the accepted industry methodology for WLC assessments’ (Environmental Audit Committee, 2022a, para. 79). The RICS Professional Statement is currently being updated (RICS, 2023).

In terms of data, the Inventory of Carbon and Energy (Hammond and Jones, 2019) was originally developed as an academic project funded by EPSRC and the Carbon Trust to provide generic embodied energy and carbon coefficients for building materials used in UK (Hammond and Jones, 2008). The 2019 update (v3.0) has moved to use EN 15804 EPD as the main source of embodied carbon data (88% of datasets), and provides around 600 embodied carbon coefficients relevant to the UK for over 200 materials, including aggregates, sand, aluminium, bitumen, bricks, cement and mortar, concrete, glass, timber, and steel. When specific or collective EPD are not available, the ICE database would offer a reliable source of embodied carbon data, and is ‘currently accepted as the most consistent database for carbon factors in the UK’ (Mohebbi et al., 2021).
2. Embodied Carbon Data and EPD in the Literature

2.1. Approach to reviewing the literature

2.1.1. Initial meta-review to identify the trends and gaps in the academic literature

As a first approach to the literature review, a meta review of recent systematic reviews of building LCA and embodied carbon was undertaken\(^2\), to identify the key themes in the academic literature. These themes are summarised in section 2.2, first into the general themes that were identified, and secondly, addressing themes related to product level embodied carbon data and EPD. A concluding section provides a critical evaluation and discussion and considers how this could shape the research.

The initial meta-review suggested that grey literature is often ignored in academic studies, but is clearly influential to practice in the UK construction industry. Therefore the literature review will cover both academic literature and grey literature provided by professional bodies, trade associations and other organisations relevant to industry.

The meta review also noted one of problems of product data was that databases were not regionally representative, so the literature review will therefore have a focus primarily on UK practice with regard to use EPD and materials data in building level assessment. However it will be important to consider what is happening overseas, particularly for policy, for example where the meta review shows several European countries have already adopted regulation of embodied carbon assessment or provision of EPD.

As the field is rapidly growing and practice is likely to change as a result, the focus should also be on more recent literature.

In the next section, the approach to the review of both academic and grey literature is explained.

2.1.2. Approach to reviewing the academic literature

The literature review is provided in section 2.3, and is based on the following themes suggested by the initial meta-review:

- How EPD and other material data are being used in practice, particularly in the UK.
- Whether the growing number of EPD are helping to address the problems of scarcity of data identified in the systematic reviews.
- What is the nature of variation in product level data in EPD, and whether it is aleatory (inherent variation) or epistemic (caused by differences in methodology) in nature.
- Whether the ‘flawless exchange’ of data between EPD and BIM has been achieved, or what progress has been made.

The literature search was undertaken in Google Scholar, Web of Science, Scopus, and Science Direct for the terms ‘Environmental Product Declaration’ and ‘building’ or ‘construction,’ as ‘Environmental Product Declaration’ alone brought up papers covering their use in other sectors such as food or chemicals. Searches for the EPD standards ‘EN 15804’ and ‘ISO 21930’ were also undertaken.

---

\(^2\) The systematic reviews were identified through a literature search using Google Scholar, Web of Science, Scopus, and Science Direct for ‘systematic review’ and the terms ‘embodied carbon,’ ‘embodied energy’ or ‘building LCA’ or ‘building life cycle assessment’ in title, abstract or keywords, for the years 2017-2023. Reviews which did not address the use of product level environmental data were not included.
General Findings

Figure 4 shows the prevalence of terms such as “EPD”, “embodied carbon” or “building LCA” within a topic search (title, abstract or keywords) of the academic literature using Scopus undertaken in November 2022. It can be seen for all terms that the prevalence in the last five years (2018-2022) has been greatest, linking with the findings of the systematic reviews. Reference to the standards in the topic search is significantly lower than references to the other terms.

A review of the use of standards in citations is interesting; EN 15804 (the European Standard for construction product level EPD) has higher prevalence than EN 15978 (the standard for building level LCA) for both topic searches and citations (see Figure 5), and ISO 21930 (the International Standard for construction product EPD) is cited much less frequently than EN 15804 in the literature.
2.1.3. Approach to reviewing the grey literature

The following well recognised or authoritative sources of publication were considered. A snowball approach was used to find further grey literature.

- Government publications (UK Government, Scottish Government, Welsh Government, local governments in the UK (e.g. Greater London Authority) covering embodied carbon, whole life carbon, or the environmental impact of the construction industry;
- International standards from ISO and CEN covering building and product level LCA and embodied carbon assessment;
- Parliamentary Inquiries
- UK Industry publications, including from UK professional bodies, industry organisations such as the Green Construction Board, the Construction Leadership Council and UKGBC providing guidance on embodied carbon and EPD, and from trade associations;
- EPD programmes and organisations globally promoting EPD, e.g. ECO Platform, Carbon Leadership Programme;
- European commercial reports describing the use of EPD, building LCA and embodied carbon assessment.

The four themes of the literature review are now discussed below.

2.2. Findings from the meta-review

2.2.1. General themes relating to building LCA and embodied carbon assessment from the meta-review

**Strong growth in the academic literature:** The increase in recent academic publications in this area noted by Feng *et al.* (2022), Safari and Azariljafari (2021) and Cabeza *et al.* (2021) for example, suggests both a growing interest in this research field and a rapidly evolving research landscape. Therefore any literature review in this area should consider the use of older literature carefully to ensure its findings are still valid.

Drivers given in literature given for this growth include the use of LCA within green building rating schemes (Feng *et al.*, 2022), the publication of the CEN/TC 350 standards (Wise *et al.*, 2019), and an increasing focus on the potential of Building Information Modelling (BIM) and the work of IEA Annex 72 (Safari and Azariljafari, 2021). Malmqvist *et al.* (2018) says the growth in the literature reflects the interest from policy makers in embodied carbon and building LCA, with some European states having implemented regulation in the area. Wise *et al.* (2019) notes the need for legislation of embodied carbon but suggests more evidence is needed to build the case for policy makers that it should be included in regulation.

It would be useful therefore to consider if there is similar growth of academic literature relating to EPD and the use of the EPD standards, EN 15804 and ISO 21930.

**Gap between academic research and professional and industry practice:** There has long been concern about the gap between research and practice (e.g. Rynes, Bartunek and Daft, 2001), and the literature suggests this still seems to be an issue in embodied carbon research (e.g. Azari and Abbasabadi (2018), Nwodo and Anumba (2019), Anand and Amor (2017)). Although academic literature is becoming easier to access for professionals and industry due to greater use of open access publishing, both academic and grey literature often remains siloed, with academics ignoring grey literature as it is not ‘peer reviewed’ and industry not using academic research because it is not accessible to them (either literally, because it is behind a paywall, or because the terminology and approach are off-putting to non-academics). Given the importance of grey literature from trade associations and professional
institutions as a source of knowledge to the UK construction industry highlighted by Moncaster et al. (2010), it will therefore be important for this research to review and consider not only the academic literature but also the grey literature provided by professional and trade bodies to ensure that this gap is not perpetuated.

**Lack of recognition of International Standards for building and construction product LCA in academic studies:** The gap between academic research and professional and industry practice is also illustrated by the difference in approach to Standards. The lack of compliance with the International standards for LCA (ISO 14040 and ISO 14044) found by Safari and AzarJafari (2021) and lack of reference within academic studies to the use of international standards for building and construction product LCA, such as the European CEN/TC 350 standards EN 15978 and EN 15804, and ISO 21930 (Yılmaz & Seyis, 2021), is striking in comparison to the commonplace use of Standards in industry and regulation.

The CEN/TC 350 European Standards for sustainable construction have been developed by the industry at the request of the European Commission (via a mandate to CEN Technical Committee 350), to harmonise and standardise practice and improve consistency in application of built environment LCA (European Commission, 2004). The European standard EN 15978:2011 is widely used in national regulation of building LCA and embodied carbon (e.g. in Netherlands, France, Germany, Sweden, Finland, Denmark etc. (One Click LCA, 2022) and EN 15804 has been used to produce over 10,000 construction product EPD (POST, 2021) and is also referenced in product regulation in France and Belgium (One Click LCA, 2022).

European regulation must be based on European Standards (Leibrock, 2002). Although Malmqvist et al. (2018) suggests that interest in embodied carbon regulation is driving growth in the academic literature, within that literature, both the lack of reference to, and the limited use of the standards is problematic. It seems that many academic LCA studies in the construction field fail to comply even with the basic rules for LCA set out in the ISO 14040 and ISO 14044 standards, and the CEN/TC 350 standards, EN 15978, EN 15804 and ISO 21930, which have been developed to provide a consistent methodology for the construction sector, have, to a large extent, been ignored by the academic community.

**Lack of consistent methodology within LCA in the building assessment sector:** Perhaps unsurprisingly given the common non-compliance with ISO 14040 and ISO 14044 and the low use of the EN 15978 standard, a number of the systematic reviews report a lack of a consistent methodology for building LCA.

Many of the systematic reviews have included academic literature from before 2011 when EN 15978 was published, so it is not clear whether this finding would be less applicable to current assessments. The academic literature also largely ignores the grey literature. Thus it is difficult to know whether this theme of a lack of consistent methodology can be relied upon to apply across all LCA and embodied carbon assessments currently undertaken within the construction sector, or whether it is potentially only applicable within the academic literature. This should be considered in the literature review.

**Importance of BIM for facilitating building LCA:** Integrating BIM with LCA clearly provides an opportunity to reduce the effort required to undertake building LCA and increase its uptake (e.g. Anand and Amor (2017), Nwodo and Anumba (2019)). However there are problems in relation to integrating EPD and embodied carbon data at product level which are discussed below (see 2.2.2).

**Problems with uncertainty in building-level assessment:** Many of the reviews discuss uncertainty, and Feng et al. (2022) focussed their systematic review on this uncertainty. A wide variety of causes of uncertainty are suggested in the reviews, many of which relate to the use of product level data. A distinction is made in several of the reviews between aleatory uncertainty which is based on intrinsic randomness and thus cannot be reduced, and epistemic uncertainty which can be reduced as it is due
to a lack of data, problems with methodology etc. However none of the systematic reviews actually classify causes of uncertainty.

Anand and Amor (2017), Dossche, Boel and De Corte (2017), Azari and Abbasabadi (2018), Cabeza et al. (2021), Safari and AzariJafari (2020) and Hu and Esram (2021) all note the need for building level assessments to address and report their uncertainty, much of which is associated with data; and Feng et al. (2022) found the most common approaches used to address uncertainty were Monte Carlo Simulation (25 papers), sensitivity analysis (19 papers) and a pedigree matrix and data quality indicators (12 papers).

The types and causes of uncertainty associated with data are discussed further below.

2.2.2. Data related themes from the meta-review

The Role of EPD: The majority of literature is focused on embodied carbon of buildings, rather than on EPD of construction products. Dossche, Boel and De Corte (2017) note that the use of EPD is growing, incentivised by Green Building Certification credits for use of EPD, and Hu and Esram (2021) note the use of EPD in public procurement policies in the construction sector.

EPD are considered to be a ‘useful instrument’ (Dossche, Boel and De Corte, 2017) and their use is recommended because they are ‘reliable,’ being based on manufacturer information and standards (Nwodo and Anumba, 2019; Feng, Zhao, et al., 2022), with use of EPD particularly recommended during the later design stages when manufacturer specific data is preferred (Obrecht et al., 2020; Hu and Esram, 2021; Safari and AzariJafari, 2021).

Hu and Esram (2021) note that ‘data standardization and transparency’ of environmental data for materials needs to be improved and Azari and Abbasabadi (2018) discuss the diverse and inconsistent databases for material impacts used in building LCA and the uncertainty this causes. As with building level uncertainty, the distinction between epistemic uncertainty (from methodological differences and errors, which could be mitigated) and aleatory uncertainty (from innate differences in processes which are unavoidable) is important, but none of the reviews appear to classify the sources of uncertainty found at material level into these two types.

Dossche, Boel and De Corte (2017) discuss issues of consistency and differences in the Product Category Rules (PCR) used to formulate EPD. However, they also mention that when comparing EPD programme PCR in Europe to EN 15804, ‘more similarities than differences exist’ (Passer et al., 2015) and also describe how the ECO Platform organisation is seeking harmonisation of construction product EPD. As with the use of standards and methodology at building level, it is not clear if the problems of inconsistency and standardisation at product level are relevant to recent practice outside academia.

Limited use of EPD in the academic studies: The lack of reference to EPD in the systematic reviews studied, particularly those with a focus on data is striking, e.g. Cabeza et al. (2021) and Minunno et al. (2021) did not include any EPD in their reviews of construction product impacts, and Malmqvist et al. (2018), Duan, Huang and Zhang (2022) and Feng et al. (2022) noted less than 15% of the building-level case studies they reviewed used EPD as a data source. As EPD are considered to be reliable, are recommended for use and are stated to be growing in use in industry in some of the systematic reviews, it is startling that they are not more often referenced in the academic literature. However given the limited use of International Standards within the academic literature, it is perhaps not surprising that they don’t recognise this increasing resource.

In fact, given the recent profusion of systematic reviews found in the area of building LCA and embodied carbon (25 since 2017), it is surprising that there has not been a systematic review of the literature focussed on Environmental Product Declarations.
**Integrating EPD and BIM:** Several of the systematic reviews have considered BIM to be an important part of integrating LCA into the design process, with several authors looking to digitisation of EPD and the application of BIM to facilitate the use of EPD. A number of the reviews, for example Safari and AzariJafari (2021) and Xue et al. (2021), discuss the need for a solution, the ‘flawless exchange’ of data, which will allow automated mapping between EPD and BIM, which is otherwise very time consuming (Teng et al., 2022). Difficulties of finding EPD data when using BIM are mentioned by Safari and AzariJafari (2021), and Crippa et al. (2020) note the need for a properly standardized digitised format for EPD, whilst the EC3 tool is highlighted as a solution using digitised EPD for product comparison by Hu and Esram (2021).

With the integration of BIM with LCA highlighted as a key opportunity to increase the uptake of building LCA and embodied carbon assessment, these difficulties in mapping between EPD and BIM and in digitising EPD are clearly going to be problematic. And with the growing numbers of EPD, it is not clear whether this will make it easier to find EPD, or harder.

**Need for knowledge and experience:** The systematic reviews highlight the need to have knowledge and experience of both building materials, construction and of LCA; for example Nwodo and Anumba (2019) highlight the need for knowledge of LCA to inform decisions, Anand and Amor (2017) suggest a lack of experience is limiting adoption of building LCA in industry and Feng et al. (2022) state human related factors such as knowledge and experience are the main sources of uncertainty at the interpretation stage of building LCA. If we also bring in familiarity with BIM, given its role in facilitating building LCA and embodied carbon assessment, it is likely that this could be a probable barrier to the growth and uptake of building LCA and embodied carbon assessment. However, given the growing use of BIM, and potential solutions in the pipeline in terms of automated mapping and digitised EPD, this may become less of a problem in future.

**Scarcity of materials data:** Many of the systematic reviews noted a lack of data, highlighting structural materials (Cabeza et al., 2021), MEP (Nwodo and Anumba, 2019), and sustainable and traditional materials in particular (Crippa et al., 2020; Malmqvist et al., 2018). Problems were also noted in relation to a lack of transparency in databases and the need to maintain databases (Azari and Abbaspabadi, 2018; Dossche, Boel and De Corte, 2017; Hu and Esram, 2021). Data availability for certain regions, particularly for developing economies, was noted (Safari and AzariJafari, 2021; Dossche, Boel and De Corte, 2017; Roberts, Allen and Coley, 2020), and both Wise et al. (2019) and Anand and Amor (2017) discuss difficulties associated with using data from different locations.

Although it is clear that missing data has been shown in the academic literature to be problematic in the past, it is again not clear whether there is still a lack of product level embodied carbon data today in Europe, especially as we see that the amount of embodied carbon data is growing rapidly, e.g. as found by Cabeza et al. (2021) for structural materials and for EPD by Dossche, Boel and De Corte (2017). Also, noting that the academic literature has generally disregarded EPD, it is also difficult to know whether these findings can be applied outside the academic literature, given the large numbers of construction product EPD now available.

It also seems unfortunate that the academic community, which complains of a scarcity of data and lack of common methodology, does not make more frequent reference to EPD, which are both relatively abundant and use a common methodology.

**Variability or uncertainty of material impact data:** Many of the systematic reviews raise the issues of variation in product level data.

Some authors appear to suggest that epistemic uncertainty is behind the variation in product level data, for example Anand and Amor (2017) highlight that the variation found in EPD and generic data was due to a lack of a standard data collection methodology and insufficient guidance in the ISO
standards and note the need to check the quality of product level data. This is echoed by Dong, Ng and Liu (2021) who suggest that strictly following the standards and guidelines will help to address variation in data.

Azari and Abbasabadi (2018) note that a major source of uncertainty in building-level assessments are unrepresentative, diverse and inconsistent environmental data at product level. But they also say there could be differences in impact for the same building in different locations giving reasons which appear to be due to aleatory uncertainty, for example:

*varying sources of raw material and building products, transport types and distances, manufacturing technologies, electricity generation types, and other factors that would change with building location.*

Hu & Esram (2021) highlight in their review that the ‘inaccuracy’ of process LCA may be as high as 50% of the actual results, and say that due to the ‘imprecision’ of LCA, ‘huge’ differences are not uncommon which suggests that epistemic uncertainty is to blame. However they also discuss the EC3 tool which focusses on the ‘range of impacts that exist within a given product type (e.g., rebar or mineral wool) due to differences in manufacturing practices, supply chains, fuel mixes, etc.’ which would suggest there are aleatory causes of uncertainty is behind the variation.

In the two systematic reviews directly focussed on material impacts, neither of which included EPD, Cabeza et al. (2021) found wide variation in the embodied carbon and energy of structural building materials, which evidenced ‘the lack of standardization.’ Minunno et al. (2021) found that the embodied carbon and energy for concrete, reinforcement bars, structural steel, timber, bricks, tiles, expanded polystyrene insulation, and plaster in extant LCA studies ‘failed to provide a consistent picture’ due to the substantial variation of results, although they noted the variation for structural steel might be related to the geography of the study.

Firstly, it is not clear to what extent any academic findings about variation caused, for example, by ‘inaccuracy,’ ‘imprecision’ and ‘lack of standardisation’ can really be considered relevant to the use of EPD and building level assessments using EN 15978. Secondly, there are clearly differences in the literature between those that consider the variation in product impact to be epistemic in nature, and thus a problem to be reduced through improved and more rigorous application of methodology and better practice; and those that consider it to be due to differences in technology or geography and thus aleatory in nature, and not variability that can be reduced.

The literature review should therefore consider in more detail the types and causes of variation of impact in EPD, and whether they are epistemic or aleatory in nature.

2.2.3. Main findings from the meta-review

The increase in recent academic publications suggests both a growing interest in this research field and a rapidly evolving research landscape. However there has long been concern about the gap between research and practice (Rynes, Bartunek and Daft, 2001) and the meta review suggests this is certainly an issue in the area of embodied impacts of construction materials and buildings, also suggested by the lack of compliance with the International Standards for LCA and a noted lack of reference to EPD in the systematic review papers. Perhaps unsurprisingly, a number of the papers report a lack of a consistent methodology for building LCA. There are some concerns expressed in the systematic reviews around a lack of consistency and the need for data standardisation, and many of the reviews noted a lack of data, highlighting structural materials, MEP, and sustainable and traditional materials in particular. Problems were also noted in relation to a lack of transparency in databases, the need to maintain databases and problems with inconsistency of data. Data availability for particular regions, particularly for developing economies, was noted, and both Wise et al. (2019) and Anand and
Amor (2017) discuss difficulties associated with using data from different locations. Meanwhile it is evident that the use of EPD is growing, incentivised by Green Building Certification credits and public procurement policies. It is not clear therefore whether there is still a lack of product level embodied carbon data today, or whether this remains an academic perception which is no longer reality within industry practice.

Many of the review papers also discuss uncertainty (for example Feng et al., 2022), with a wide variety of causes of uncertainty suggested. There is a distinction between aleatory and epistemic uncertainty; however none of the systematic reviews classify causes of uncertainty in this way. It is also not clear to what extent any academic findings about variation caused, for example, by ‘inaccuracy,’ ‘imprecision’ and ‘lack of standardisation’ are relevant to the use of EPD and building level assessments using EN 15978, since academic studies don’t generally include primary data such as EPD. The wider literature needs to be considered to understand the types and causes of variation of impact in EPD.

2.3. Literature Review

2.3.1. The role of EPD in reducing embodied carbon

A number of authors have considered the various ways in which embodied carbon can be reduced, for example Malmqvist et al. (2018) used over 80 case studies to identify 11 reduction strategies for embodied carbon; Lupišek et al. (2017) presented groups of design strategies to reduce embodied energy illustrated with case studies from the IEA Annex 57 project and Pomponi and Moncaster (2016) reviewed 102 papers to identify 17 strategies to reduce embodied carbon, and suggested that no one approach was likely to be successful, instead a ‘pluralistic approach’ was required – in fact, 80% of the papers they reviewed suggested using more than one strategy.

A number of the mitigation strategies address issues which are covered by EPD (e.g. recycled content, durability or recyclability) or where EPD provide information (for example embodied carbon) that can allow the success of the strategy to be checked. The strategies from the literature are presented in Table 1 overleaf, showing the strategies and the papers which suggest them showing considerable overlap; those strategies shaded in black are materials-related and have the potential to be addressed by EPD, those which are buildings-related are shaded in grey.

Malmqvist et al. (2018) noted the limited number of studies which have actually calculated the embodied carbon reductions that a strategy could be assumed to achieve. Their study provided strong evidence that reductions in embodied carbon can be considerable for both new and refurbished buildings, and if the strategies they identified were used in all buildings and processes they would make a significant contribution to reducing climate change and improving resource efficiency. More recently, Hu, (2023) has compiled the expected range of savings for 19 mitigation strategies identified from the literature, with the largest savings coming from the reduction of premature demolition (70%), recycling and reusing materials (40-80%), use of low carbon materials (60-85%) and optimising the structural floor (53-58%). Lower levels of reduction have been suggested by Connaughton et al. (2015) who provided strategies for reducing embodied carbon, together with the possible carbon savings, based on the authors’ experience in practice in the UK. These included up to 20% savings from selecting materials with lower carbon intensity, up to 10% by reducing site waste, and up to 10% for using products with increased recycled content. Other recent academic papers which have provided quantification of embodied carbon savings for different reduction strategies include Rasmussen, Birkved and Birgisdóttir (2020).
Table 1 Analysis of embodied carbon mitigation strategies from the literature

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse and refurbishment</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Design optimisation</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Intensify building use</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Adaptability</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Material efficiency</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Lightweighting</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Service life and durability</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

| Strategies substituting conventional materials with alternatives with lower environmental impacts | Use of recovered material | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
|---|---|---|---|---|---|---|---|---|
| Bio-based materials | ✓ | ✓ | ✓ | x | x | x | x | x | x |
| Low carbon materials | ✓ | ✓ | x | x | x | x | x | x | x |
| Innovative materials | x | x | ✓ | x | x | x | x | x | x |
| Minimally processed materials | ✓ | x | ✓ | x | x | x | x | x | x |
| Use of short supply chains | x | ✓ | x | x | x | x | x | x | x |

| Strategies reducing the impact of the construction stage | Efficient construction | x | ✓ | ✓ | ✓ | ✓ | ✓ | x | x |
|---|---|---|---|---|---|---|---|---|
| Local sourcing | ✓ | x | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | x |
| Offsite fabrication | ✓ | x | ✓ | ✓ | ✓ | ✓ | ✓ | x | x |

| Strategies for a low-impact end of life stage | EoL reuse and recovery | x | x | ✓ | ✓ | x | ✓ | x | x |
|---|---|---|---|---|---|---|---|---|
| Design for deconstruction | x | x | ✓ | ✓ | x | ✓ | x | x | x |

<table>
<thead>
<tr>
<th>Strategies at policy or industry level</th>
<th>Work together</th>
<th>x</th>
<th>✓</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>✓</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offsetting</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Decarbonisation of grid</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Policy (Government)</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Policy (Industry)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Develop a database of materials and carbon</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Tools &amp; methodologies</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Discourage demolition and rebuild</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Note: Strategies shaded in black are materials-related, strategies shaded in grey are buildings-related

2.3.2. Awareness of construction product EPD in the literature

Waldman, Huang and Simonen (2020) explain how during early stages, different options for structure, façade and building configuration can be explored using LCA. Tozan et al. (2022) explain how generic data should be used for building assessments in the early design stages to provide an initial estimate of the impact. Then, as the project progresses, towards the final design stages when the model approximates to the as-built scenario, to achieve more realistic results the generic data should be
replaced with industry and product-specific EPD if they are available. There are numerous generic databases which offer embodied carbon or LCA data for construction materials for use in building life cycle assessment. For example, Pagnon, Mathern and Ek (2020) provide a review of 10 open access databases providing collectively over 20,000 generic datasets relevant to European construction, some of these databases also provide EPD.

Galindro et al., (2020) surveyed 55 professionals with an interest in EPD and LCA, mainly from Europe (the focus was on EPD and LCA generally, not just construction product EPD). Respondents used both EPD and LCA data, mainly to fulfil customer requirements, for environmental management systems, marketing, and for supplier requirements. Just over half used EPD to make comparisons and 2/3rds of these used analysis of EPD to identify lower impact products. The strengths of EPD noted by the respondents were credibility, transparency, decision support and usability for comparisons. In terms of weaknesses, comparability was the main issue for EPD.

Burke, Parrish and El Asmar, (2018) surveyed 880 architecture, engineering and construction (AEC) professionals in the US and found 75% of material manufacturers, but only 30% of architects and of interior designers, 15% of contractors, and 10% of engineers used EPD as a source of environmental information, however 87% of those familiar with EPD felt they brought value to the design process, and 36% that they brought value to the final building. Overall across all AEC professionals, EPD were the least used source, with LCAs, different types of content declaration and Certified Wood Declarations all being used more.

Jordan and Bleischwitz (2020) explain how manufacturers can use EPD to communicate environment improvements to their customers and supply chain. Andersen et al. (2019) interviewed Danish manufacturers with EPD and found the value of EPD was in the knowledge about the product and the transparency it demonstrated to customers, rather than in any increase in sales. In Denmark, it was ‘front runners’ which had EPD, with the main driver for EPD at that point being building certification. The main barriers identified were the cost of producing EPD and the lack of demand from authorities, and suggests digitalisation and regulation may address these barriers.

Jordan and Bleischwitz (2020) explain how EPD are cited as the source of environment data in the European Construction Products Regulation. They note that EPD do not set standards for the products but enable governments to draw on the data within EPD to enact policies. They suggest that EPD are ‘ideally positioned’ to provide evidence for the provision of benchmarks for use in Border Carbon Adjustment. Jordan and Bleischwitz (2020) also say the holistic nature of EPD which cover numerous environmental indicators means they have more acceptance and institutional endorsement than carbon footprints, however using multiple indicators creates a challenge in terms of accurate measurement and accounting. They note that primary data from the manufacturer is only required for the last manufacturing process in an EPD, and for products with long supply chains, use of secondary data for these upstream processes could ‘exclude a big chunk of emissions’, though it is less relevant for simpler products.

2.3.3. The availability of EPD

The meta review highlighted a scarcity of product level data and it is clear that the availability of EPD is seen as important prerequisite for undertaking building LCA. Bruce-Hyrkäs, Pasanen and Castro (2018) surveyed green building professionals and found 96% of respondents considered the availability of locally relevant EPD as important in achieving high quality LCA results. Rasmussen, Malmqvist and Birgisdóttir (2020) surveyed design professionals in Norway, Sweden, Finland, and Denmark and found the lack of data was the biggest barrier to adoption of LCA, noted by 35 of the 48 respondents. This mirrored the results of a similar survey in 2015 (Schlanbusch et al., 2016). However they found that
despite the lack of data and other barriers such as lack of incentive, the survey pointed to a strong commitment from design professionals to apply LCA anyway.

However, Pomponi and Moncaster (2018) reviewed the data used in a series of building LCA case studies and noted that embodied carbon coefficients of common construction materials were abundant, and data scarcity was only a problem in some life cycle stages, primarily those related to the use stage of a building and its end of life impacts.

Although only one of the systematic reviews discussed the increase in EPD Programmes (Dossche, Boel and De Corte, 2017), the academic literature more generally reveals a considerable increase in numbers of construction product EPD in recent years.

In their 2013 review, Bovea, Ibáñez-Forés and Agustí-Juan (2013) identified just over 500 construction product EPD; by 2014, Hunsager, Bach and Breuer (2014) found around 1200 construction product EPD; Giesekam, Densley Tingley and Cotton (2018) reported 3500 verified EPD and 2400 unverified EPD at the start of 2017; Toniolo et al. (2019) found 4888 construction product EPD; Adibi et al. (2019) reported that more than 5000 construction product EPD to EN 15804 were published and available in Europe in 2019; Rasmussen et al. (2021) stated that 2018–2020 saw a significant increase in the number of published EPD of structural wood products (60 of the 81 EPD found), and Božiček, Kunič and Košir (2021) reported that globally there were over 6000 construction product EPD to EN 15804 at the start of 2019. The most recent number reported was over 10,000 EPD to EN 15804 by Bahrar and Jusselme (2022).

These figures demonstrate awareness within the academic literature of the increasing numbers of EPD available, and suggests further that the European Standard (referenced in most of these papers) has been widely adopted across Europe.

2.3.4. Drivers of growth in EPD

A number of authors have looked to explain the increased of use and demand for EPD. Passer et al. (2015) find that the high number of EPD programmes obviously means there is a demand for construction product EPD; and Toniolo et al. (2019) echoes this, saying that high interest in EPD leads to the development of EPD programmes in a market and that there is ‘higher diffusion of EPD’ in countries with EPD programmes. However they note that it can take time for a new EPD programme to produce EPD, for example, in both Italy and Finland, there were still very few EPD a year after establishment of national EPD programmes.

Table 2 provides an overview of the factors found in the academic literature, both positive (+) and negative (-), that encourage or hinder the increase in numbers of construction product EPD.

Government action

The summary suggests that action by Government, in developing regulation and using green public procurement, and in working with industry to support life cycle management and sustainability, is one of the key drivers of increased EPD numbers. Lewis et al. (2021) described how EPD are being used in North America to provide the evidence to support public procurement initiatives for materials such as steel or concrete using limits on embodied carbon values. Toniolo et al. (2019) reported, for example, that 79% of the EPD they collected came from countries with National Action Plans and mandatory rules for GPP, although they note that there are countries such as Bulgaria and Croatia which have these in place but have only 1 EPD. Industry support is also important, and cost is noted as a significant barrier, especially to small and medium enterprises (SME).
<table>
<thead>
<tr>
<th>Table 2 Summary of factors from the academic literature affecting the growth of EPD (⁺ = growth factor, - = limiting factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPD Programme and PCR</strong></td>
</tr>
<tr>
<td><strong>Green Building Certification</strong></td>
</tr>
<tr>
<td><strong>Green Public Procurement (GPP)</strong></td>
</tr>
<tr>
<td><strong>Industry and Government Support</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
</tbody>
</table>
| + More and better information on how to read an EPD. + Informative campaign on the added value gained from LCA | - Complexity of EPD - Lack of knowledge of different key actors to use them | \begin{itemize} 
  \item + A strong platform of knowledge of LCA within the building sector
  \item - For SMEs and emerging economies, lack of expertise
\end{itemize} | \begin{itemize} 
  \item - Lack of knowledge of consumers about EPD
  \item - Existence of similar products with EPD showing better impact
\end{itemize} | \begin{itemize} 
  \item + Wide acceptance of EPD as a feasible communication format for environmental claims
\end{itemize} |
| Regulation | + Regulation of embodied carbon + Carbon tariffs + Border carbon adjustments with some mechanism for assessing the carbon content of imports + Stringent environmental monitoring requirements | + Building LCA, based on EPD. + Implementation of BRCW7 of EC CPR | + Regulation | + National regulations in public tenders requiring environmental labels | + Obtaining Government Incentives + Mandatory requirements | + Regulation requiring EPD to prevent greenwashing |
| Tools, data, and digitisation | + Use of conservative values if EPD are not available + Collective EPD tools + Sector data gathering | + Easier and more adapted tools and methods | - Limited availability of specific, high-quality material data | - Avoiding ‘safety margins’ for generic data + Automated EPD generation + XML export of EPD to building level LCA tools | | |
Jordan (2021) noted that diffusion of EPD across different countries was very different, and may be caused by both pull factors (such as green building certification schemes and green public procurement), and push factors which he deemed crucial, including more stringent environmental monitoring and use of environmental management systems. He also noted that in Germany and the UK, provision of sectoral EPD were a catalyst for the provision of manufacturer specific EPD, by spreading the cost of EPD creation across companies, and providing a benchmark to give specific EPD proving superior performance a stronger marketing value. He found that

‘mandating industry to commit to ambitious reduction targets and/or to provide benchmarking data on environmental performance brings industry actors in sector associations together to create data.’

However he suggested the most effective strategy for policy makers may be to use public procurement and standards to create direct demand for EPD, linked with support for small and medium-sized companies in EPD creation.

**Marketing**

Ibáñez-Forés et al. (2016) described how EPD are being used for marketing purposes. This was echoed by Yenipazarli (2015)’s findings on ecolabels generally, which explained that as there has been an increase in demand and willingness to pay for eco-labelled products, so has corporate interest in ecolabels increased. He stated that ecolabels are being used to raise customer awareness of their products, to maintain market share where there is a shift to sustainable products and to command price premiums.

**Green building certification**

Bruce-Hyrkäs, Pasanen and Castro (2018) found 84% of their respondents were motivated to assess whole building LCA because of the need to obtain green building certification. Green building certification (e.g. LEED or BREEAM) is seen to influence EPD numbers, mainly by providing credits for the use of products with EPD, but also through credits for products with lower impact which can be demonstrated using EPD (Gelowitz and McArthur, 2018). They claim, for example, that based on the increase in EPD for building products that occurred with adoption in LEED® v4, they expect numbers of construction product EPD will increase in proportion to adoption of EPD credits in other schemes. Feng, Kassem, et al. (2022) state that LEED, BREEAM and DGNB in Germany all encourage the use of materials that have EPD and Arvizu-Piña and Cuchi Burgos (2017) say that mandatory use of green building certification for public buildings is driving EPD numbers in those states. Jordan and Bleischwitz (2020) said that in interviews with DGNB, IBU and USGBC, EPD credits in green building certification were the ‘major driver’ for the increased number of EPD. Burke, Parrish and El Asmar, (2018) found that working on LEED certified projects was strongly correlated with familiarity with EPD, and LEED was seen to be a ‘catalyst for the AEC industry to use EPD.’ 56% of participants who had accessed environmental information were familiar with EPD, though less than half of this group had used them on projects (about half from early design stage), with only 18% incorporating EPD into specifications.

**BIM and Digitisation**

Passer et al. (2015) highlighted that automated generation of EPD will drive EPD numbers. Within the concrete sector, Potier (2012) described the development of the BETie EPD tool for producers in France, allowing many EPD to be produced at low cost. Other sectors and companies have also developed similar verified EPD tools which can be used in this way, for example Brankley et al. (2017) described a steel certification body’s reasons for developing an EPD tool for the steel producers that they certify and Sariola and Ilomaki (2019) explained how EPD tools can be used within the Finnish RT EPD programme.
Welling, Billstein and Erlandsson, (2019) described how EPD are being digitised together with data quality information to provide machine-readable data for use in BIM to ‘facilitate the seamless flow of information’ between actors. However they noted there is still a need for a classification and identification system to simplify and improve the process of finding EPD. Lützkendorf (2019) said the usability of EPD in BIM is the subject of international standardization through the development of ISO 22057, which has now been published (ISO TC59 SC17 WG3, 2021). Stapel et al. (2022) found nearly 1200 digital EPD (93% to EN 15804+A1, 7% to EN 15804+A2) when they reviewed the European EPD.

Feng, Hewage and Sadiq (2021) said that integration of BIM and EPD using whole building LCA would bring order to the process and improve the accuracy of results. This was supported by the survey and interviews undertaken by Bruce-Hyrkäs, Pasanen and Castro (2018) which found 86% of Green Building Professionals (mainly in Europe) thought BIM would ensure LCA could be used effectively during the building design process. Arvizu-Piña and Cuchi Burgos (2017) highlighted that building level tools such as ELODIE in France which rely on EPD data were driving the development of EPD.

**Availability of data**

However Gelowitz and McArthur (2018) noted that a lack of specific, high quality inventory data for input materials was also limiting progress with developing EPD. This was found to be an issue by Rønning and Brekke (2013) who pointed out that in the early days of LCA, it could take months to find the relevant specific and generic data, although they say extensive LCI databases have become available and manufacturers are more willing to share data. De Wolf, Pomponi and Moncaster (2017) also noted a lack of data for transport, construction and waste processes and suggest that regulations to mandate the use of background databases in EPD would address this.

Rønning and Brekke (2013) suggested that more product level studies will lead to greater availability for future assessments. As the number of EPD increases, it itself stimulates the increase in numbers of EPD because manufacturers start to compete using EPD, and more people become familiar with them and ask for them. As an example, a Norwegian Parliamentary report stated, ‘Today, there are few construction products with environmental declarations in Norway, and there is therefore little demand for them’ (Norwegian Parliament, 2011, chap. 4.6).

**Lack of knowledge**

Similar to the finding in the meta review, lack of knowledge was considered a hindrance to the development of EPD, in terms of both companies, lack of LCA practitioners, and in lack of understanding of EPD by the users. For example, Božiček, Kunič and Košir (2021) noted that building designers will need guidance when working with EPD, as they are ‘rarely LCA experts’ and interpretation of the results is complex.

**Comparability**

Several authors highlighted that a lack of harmonisation means that EPD cannot be compared, and that different PCR were a barrier to developing EPD (e.g. Ibáñez-Forés et al., 2016; Gelowitz and McArthur, 2018; Adibi et al., 2019). Moré, Galindo and Soares (2022) considered comparability for EPD for flooring, insulation and boards in the IBU and International EPD programmes and considered comparison between EPD was rarely possible. However they considered a lack of data on packaging or the need to convert an EPD using a declared unit of say mass, to a common functional unit of say, thermal resistance, meant that the EPD was not comparable. When these restrictive requirements were removed, comparison was found to be much more easy, for example, for flooring EPD moving from 0.7% comparability to 98.7% comparability. Passer et al. (2015) noted that EN 15804 and the work of ECO Platform (a trade body for EPD Programmes in Europe which aims to increase mutual recognition and harmonisation of EPD programmes) is intended to improve these aspects.
Waldman, Huang and Simonen (2020) looked at using EPD for comparison, explaining the importance of ensuring comparison of EPD are based on ‘the contribution they make to the environmental performance of the building’ according to EN 15804. However they were particularly concerned by comparisons of EPD with different levels of granularity, for example comparing the impact from a manufacturer EPD averaging several sites and products with one for one site and a specific product, highlighting how the average EPD may cover products with much higher or lower impact. They proposed a system of ‘Z-values’ to represent the different uncertainty associated with manufacturer-, site- and product-specific EPD which would then be used to adjust data when making comparisons.

Other issues

Adibi et al. (2019) looked at EPD use across Europe, and noted barriers including complexity and the problems that caused in using EPD for decision-making, a lack of regulation and cost. They recommended training and awareness raising and financially supporting companies to produce EPD.

Jordan (2021) identified a link between the industry’s provision of life cycle inventory (LCI) data (such as EPD) and the publication of best available technique reference (BREF) documents. However none of the reviewed studies have looked to relate the different measures said to drive EPD numbers over time with the actual numbers of published EPD in different geographies where these measures have been introduced. This is a gap that this thesis will look to address.

2.3.5. UK grey literature on measurement and reduction of embodied carbon

A review of the recent grey literature in the UK was undertaken using the approach in 2.1.3. The review found guidance on measuring embodied carbon and whole life carbon, on reducing embodied carbon; on the provision of targets for reduction, and found route maps to achieve the reduction of embodied carbon and the move towards net zero carbon.

As part of the review, two potential additional strategies related to the process of embodied carbon assessment were found in the grey literature which did not seem to fit within the classification within the mitigation strategies in Table 1. These were:

- ‘Tackle carbon early’— the earlier in the design process that embodied carbon is considered and assessed, the greater the reduction potential (HM Treasury, 2013)
- Identify the embodied carbon hotspots and focus on ‘big wins’ first (LETI, 2020).

An overview of the main grey literature, and its reference to EPD in particular, is provided below.

EPD generally

The Environmental Audit Committee undertook an inquiry into the sustainability of the built environment in 2022, and took evidence from manufacturers, architects, engineers, contractors and developers. In its report, ‘Building to net zero: costing carbon in construction’ it summarised the situation in the UK regarding EPD as below, making some strong recommendations:

‘162. There is a lack of Environmental Product Declaration (EPD) data for a wide range of materials, limiting the ability of developers to choose low-carbon materials. The UK is falling behind European counterparts where EPD data is far more widely available, resulting in developers choosing European materials over locally sourced UK products. The lack of EPD data makes conducting whole-life carbon assessments more laborious and expensive than necessary.

163. The Government should encourage development of a centralised national database of EPDs and, through its own procurement practices require the collection and publication of EPDs. The EPD database should be digital, freely available to end users, and user-friendly.'
164. To limit ‘greenwashing,’ the Government should introduce measures requiring suppliers who wish to make an environmental claim about a construction product to produce an EPD to substantiate it.

165. The Government should conduct a cost-benefit analysis of whether to provide advice or financial support to smaller manufacturers to enable them to produce EPDs for their materials.’ (Environmental Audit Committee, 2022a).

Measurement of whole life and embodied carbon for building, timber, building services and MEP and building structures

In regard to the measurement of carbon at building level, the Environmental Audit Committee inquiry found that ‘A broad cross-section of the construction industry is willing and able to undertake whole-life carbon assessments’ (Environmental Audit Committee, 2022a, para. 70). Hundreds of architects, engineers and others have signed up to Construction Declares, which for architects for example, includes a commitment to reduce embodied resource use by including whole life carbon modelling as part of their basic scope of work, (Construction Declares, 2019; Architects Declare, 2019).

The Royal Institute of Chartered Surveyors (RICS) has produced a Professional Statement providing a UK methodology for whole life carbon assessment compliant with EN 15978 (RICS, 2017) which the Royal Institute for British Architects (RIBA) have said is ‘the most comprehensive and consistent approach available to UK industry’ and have adopted it to assess embodied carbon within its Sustainable Outcomes Guide and its 2030 Climate Challenge (RIBA, 2019b, 2019a). The RICS methodology has also been adopted by the Greater London Authority in its regulation of embodied carbon for referable schemes (Mayor of London, 2022) and to assess embodied carbon in the Scottish Government’s Net Zero Carbon Public Sector Building Standard (Scottish Government et al., 2021). The Environmental Audit Committee inquiry stated, ‘In our view, the RICS Professional Statement on whole-life carbon assessments is fit for use and already familiar to UK industry’ (Environmental Audit Committee, 2022a, para. 79) and ‘the RICS Professional Statement on [Whole Life Carbon (WLC)] is used as the accepted industry methodology for WLC assessments’ (Environmental Audit Committee, 2022a, para. 79).

The RICS Professional Statement recommends a number of different sources of data for embodied carbon of construction products, in order of preference:

- EPD and datasets in accordance with EN 15804
- EPD and datasets in accordance with ISO 21930
- Carbon footprints and datasets in accordance with ISO 14067
- EPD and datasets in accordance with ISO 14025, ISO 14040 and 14044
- Carbon footprints in accordance with PAS 2050.

The RICS Professional Statement also recommends at early design stage, ‘generic data representative of standard, market average specifications’ should be used, and that the most recent geographically and technologically appropriate data should be selected. The RICS is consulting on an update to the RICS Methodology in Spring 2023 (RICS, 2023).

The TDUK guide to assessing the embodied carbon of timber (Anderson, 2021b) follows the requirements of EN 15804 and the standards for timber which interpret this (EN 16485 and EN 16499). The CIBSE guidance on assessing embodied carbon of mechanical, electrical and plumbing equipment (MEP) (Hamot and Baganal George, 2021) recommends the use of EPD, but provides a simplified methodology to assess the embodied carbon of MEP, noting the lack of EPD for these products and the barriers this causes to building level assessment. The Institution of Structural Engineers’ guidance on calculating embodied carbon for structures (Gibbons et al., 2022) and LETI (London Energy
Transformation Initiative, 2020) both recommend the use of EPD once the project has committed to specifying a particular product. The Centre for Window and Cladding Technology have produced guidance on calculating the embodied carbon of facades (Centre for Window and Cladding Technology Embodied Carbon Committee, Ladipo and Wild, 2022).

**Reducing embodied carbon**

The RIBA guidance on Whole Life Carbon (Sturgis, 2018) which says that typically, EPD are used to provide the embodied carbon data in whole life carbon assessments and that they are provided for an increasing number of products. The LETI guide to embodied carbon (LETI, 2020) recommends that Government mandate EPD for the materials used in sub-and super-structure; that designers ask for EPD from all their suppliers, and that they use them to compare products and inform specifications. The IStructE guidance on making low-carbon material choices uses EPD to provide the embodied carbon data for comparison. The Royal Academy of Engineering and National Engineering Policy Centre (2021) note in their report on decarbonising construction, that EPD ‘have a role in improving carbon performance.’ The UKGBC have published a number of publications providing guidance to the industry on embodied carbon assessment and procurement (UK Green Building Council and Crown Estate, 2015; UK Green Building Council, 2017). The Construction Products Association has provided guidance on EPD and embodied carbon for its members (e.g. Anderson and Thornback, 2012; Anderson, 2022b, 2023), as has the Alliance for Sustainable Building Products (e.g. Anderson, 2019a, 2020a). There has also been a report by the Parliamentary Office of Science and Technology setting out the background to whole life carbon reduction in buildings in the UK (POST, 2021).

**Management of whole life and embodied carbon in infrastructure**

PAS 2080:2016 recommended the use of data to EN 15804 (the EPD standard) and used a framework for the quantification of GHG emissions for an infrastructure asset which was based on EN 15804 and EN 15978 (Construction Leadership Council and The Green Construction Board, 2016)

**Targets or benchmarks for embodied carbon**

A number of publications have provided benchmarks for embodied carbon and upfront carbon (the carbon emitted up to practical completion for a project), e.g. London Energy Transformation Initiative (LETI) (2020); LETI, WLCN and Institution of Structural Engineers (2021); RIBA, (2021). These cover a range of building types, and the various bodies are starting to align.

At product level, the UK timber industry has used EPD to provide benchmark embodied carbon figures for various timber products for each information module of the life cycle (TDUK, 2022) and the Low Carbon Concrete Routemap has provided embodied carbon benchmarks for normal weight concrete by 28 day strength (Mullholland et al., 2022). The UK Government is also involved in the Industrial Deep Decarbonisation Initiative (IDDI) (United Nations Industrial Decarbonisation Organisation, 2022) which is aiming to define what constitutes decarbonised steel and cement and set targets for public procurement of green steel and cement, using existing frameworks such as EPD (United Nations Industrial Decarbonisation Organisation, 2022).

**Decarbonisation and Net Zero Strategies**

The UK cement, concrete and timber industries have produced net zero strategies (MPA, 2020; TDUK, 2022; Mullholland et al., 2022) which for cement and concrete commit the industry to transparent reporting and recommend the use of EPD for embodied carbon measurement. Earlier, DECC and BIS initiated decarbonisation roadmaps for key industrial sectors including cement, ceramics, glass, iron and steel (WSP Parson Brinkerhoff; and DNV GL, 2015).
UKGBC have produced a number of documents around the industry’s path to net zero (e.g. UK Green Building Council, 2020; ARUP, Giesekam and UK Green Building Council, 2021). The UK property industry is realising that embodied carbon is one of their major impacts (British Property Federation, 2021) and are requiring measurement to meet their environmental reporting requirements, with 23 of the UK’s commercial property owners committed to delivering net zero carbon real estate portfolios by 2050 (Branson, 2019). Large developers are requesting EPD for the products they procure (e.g. Lendlease Europe, 2021; Stanhope PLC, 2023), as are contractors (e.g. Balfour Beatty, 2019; Skanska UK PLC, 2021). The Future Homes Hub have produced an implementation plan to address embodied and whole life carbon.

A number of industry bodies (Better Buildings Partnership, BRE, Carbon Trust, CIBSE, IStructE, LETI, RIBA, RICS, UKGBC,) are now involved in the development of a voluntary UK Net Zero Building Standard (UK NZCBS, 2022), using the updated RICS Professional Statement as the measurement methodology. An in Scotland, the Scottish Government have already developed a Net Zero Carbon Public Sector Building Standard (Scottish Government et al., 2021), which uses the RICS Professional Statement as its measurement methodology.

In 2020, the Government set out its 10-point Plan for a Green Industrial Revolution, which set out the overarching aims for green building and industry (BEIS, 2020), followed by its Industrial Decarbonisation Strategy (HM Government, 2021) which discussed carbon pricing and measures to support the development of the market for low carbon products.

As signposted in the Industrial Decarbonisation Strategy, in 2021, BEIS undertook a call for evidence regarding the market for low emission industrial products. The summary of responses (BEIS, 2022) stated that across the responses from the construction sector, ‘there was support for EPDs and BS EN 15804 to be incorporated into any future approach’ to define low emission industrial products. A clear theme emerged among respondents that were involved in the construction products sector, with all 19 responding that they currently measure and report the embodied emissions of products using EPD.

The CO₂nstruct Zero Performance Framework has been developed for the Construction Leadership Council (CLC) by CO₂nstructZERO to provide the CLC with a sector level dashboard on its progress towards Net Zero, aimed at motivating businesses to action and to help those outside the sector understand its progress. It includes the Priority 7 Performance Framework Target that by 2030, every client will be provided with embodied carbon data for all construction products, with ‘Performance Framework Metric 20’ requiring that 40% of product portfolios should have EPD by 2025 and 100% by 2030, although it has not yet reported on performance against this metric (CO₂nstructZero and CLC, 2022). A mapping of the Framework against policy notes the Government’s industrial decarbonisation strategy and the BEIS call for evidence on the market for low emissions industrial products (The Green Construction Board et al., 2022).

### Embodied carbon regulation

In 2010, the Code for Sustainable Homes (DCLG, 2010) (mandatory for publicly funded housing) introduced an undemanding link to embodied impact performance3 through the Green Guide to Specification 4th Edition (Anderson, Shiers and Steele, 2009) but the Code was withdrawn in 2015 following the technical housing standards review (Gov.uk, 2015). The Low Carbon Route Map (The Green Construction Board et al., 2013) suggested that from 2017, declarations of embodied carbon for construction products should become mandatory (using EPD), alongside the measurement and reporting of embodied carbon associated with the construction projects.

---

3 The Code for Sustainable Homes required any buildings using the standard to confirm that no more than one of the key elements (external walls, windows, roof, upper floors, and internal walls) used a specification with the worst embodied impact rating (an ‘E’ from the Green Guide ratings range, A+ to E)
reporting of embodied carbon for public buildings, with mandatory reporting of embodied carbon for all buildings from 2022, however no action towards this has yet been taken.

In Scotland, the Scottish Government instituted an evaluation of approaches to regulation of embodied carbon (Davis Langdon LLP, 2009) but decided in 2011 to wait until requirements to consider embodied impact were proposed in European Regulations (Scottish Government, 2011). It has subsequently published a Net Zero Carbon Public Sector Buildings Standard which uses the RICS Professional Statement to assess embodied carbon (Scottish Government et al., 2021).

In Wales, the Welsh Government consulted on the possible consideration of embodied impacts in a replacement for the Code for Sustainable Homes in Wales, but concluded in 2017 that the subject ‘lacks maturity and presents significant issues that preclude a regulatory approach at this moment in time’ (Welsh Government, 2017). In 2021 however, they added a requirement for all social housing projects to consider assessing and reducing upfront and embodied carbon during the design and construction phases, and when undertaking refurbishment (Welsh Government, 2021).

The Committee on Climate Change, which advises Government on how to meet its Net Zero target, has highlighted the need to ‘improve focus on reducing the whole-life carbon impact of new homes, including embodied and sequestered carbon’ (Committee on Climate Change, 2019). And in their suggested policies for the 6th Carbon Budget, they suggested Government should:

- ‘Work with industry to agree a standard for the ‘whole life’ carbon footprint of buildings and infrastructure.
- Introduce mandatory disclosure of whole-life carbon in buildings and infrastructure to facilitate benchmarking as soon as possible.
- Work towards introducing a mandatory minimum whole-life carbon standard for both buildings and infrastructure’ (Committee on Climate Change, 2020, p. 108).

As part of its inquiry into sustainable construction, the Environmental Audit Committee has also called on Government to regulate embodied carbon (Environmental Audit Committee, 2022a), which recommended,

‘that the Government introduce, not later than December 2023, regulations to mandate whole-life carbon assessments for buildings above a gross internal area of 1000 m², or which create more than 10 dwellings’ (Environmental Audit Committee, 2022a, p. 66).

However, in its response to both calls, Government has raised concerns about both the robustness of embodied carbon data for construction products, its standardisation, and also its availability as a significant barrier to the introduction of any regulation of embodied or whole life carbon, for example:

‘To assess the embodied carbon of buildings a simple, standardised method of calculation would be required, supported by a robust evidence base.’ (HM Government, October 2020, p. 109)

‘...you need all the constituent data that then feeds into the process to be available,’ Eddie Hughes MP, Parliamentary Under-Secretary of State (Minister for Rough Sleeping and Housing), DLUHC (Environmental Audit Committee, 2022b, Q210)

‘inconsistencies in the interpretation and application of existing [whole life carbon] WLC standards have been identified’ (Cabinet Office et al., April 2022, p. 1).

In a written answer to a parliamentary question asking about regulation of embodied carbon in February 2020, Christopher Pincher, the Minister of State for Housing summed up Government’s concerns, saying that there is ‘currently no widely agreed standardised method for certifying the embodied carbon of building products,’ and that to assess embodied carbon of building, a standardised
methodology would be required, supported a ‘robust evidence base underpinned by widely adopted product standards.’

Although some individuals working on embodied carbon have developed an outline of how embodied carbon regulation could look in the UK (known as Part Z) (Arnold et al., 2022), and it has received wide endorsement from industry, and there has been a campaign to regulate Embodied Carbon (Architects Climate Action Network, 2020) there are very few indications that Government will act on these demands for regulation as quickly as hoped.

A recent Future Opportunities Notice issued by DLUHC for a project which is intended to report in 2024, ‘Measurement and Reduction of Embodied Carbon in New Buildings,’ explained, ‘there are questions about whether there is the critical mass of EPDs needed for the results of [Whole life carbon assessments] WLCAs to be valuable both to industry and to Government in using results to inform policy’ (DLUHC, 2022), emphasising their concern about the potential availability of data.

There are however recommendations from central government in the UK for the public sector to measure, though not yet to reduce, embodied carbon for large projects, as set out in the Construction Playbook (HM Government, 2020a) and the Infrastructure Projects Authority guidance on benchmarking (Infrastructure and Projects Authority, 2019).

In London, the RICS methodology has also been adopted by the Greater London Authority in its regulation of embodied carbon for referable schemes (Mayor of London, 2022). Other local authorities, for example Dundee, Guildford and Manchester have proposed embodied carbon assessments as part of their local plans.

2.3.6. UK construction product data

At the start of the millennium, the UK was one of the world’s leading players in terms of provision of EPD for construction products. Bogeskär et al. (2002) provided an overview of the EPD data for construction products available from the BRE Environmental Profiles EPD programme. The programme included 24 cradle-to-grave collective EPD, and noted 13 collective EPD which were still being processed. In addition, one manufacturer had registered 3 manufacturer-specific EPD and two further manufacturers were going through the process.

Table 3 Overview of the data and specifications within the Green Guide to Specification obtained by analysing the literature

<table>
<thead>
<tr>
<th>Green Guide Version</th>
<th>Materials data used</th>
<th>Number of Element Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE Green Guide to Housing Specification (Anderson and Howard, 2000)</td>
<td>13 product sectors provided EPD. Around 125 material datasets used.</td>
<td>Over 150</td>
</tr>
</tbody>
</table>
Various versions of the Green Guide to Specification (published by BRE from 1998 onwards) have used a database of UK materials data originally developed by Nigel Howard at Davis Langdon & Everest (Howard, Shiers and Sinclair, 1996). The data requirements are analysed in Table 3. For the 2009 version of BRE’s Green Guide (Anderson, Shiers and Steele, 2009), 19 UK trade associations provided manufacturing data used to provide LCA datasets for the assessment of different construction elements. In addition, six international trade associations provided data for more widely traded materials (e.g. metals, plastics etc).

The IMPACT project was funded by the Technology Strategy Board, and the partners, BRE, Integrated Environmental Solutions Ltd (IES), WD Rethinking Ltd and AEC3 (UK) Ltd developed a methodology for integrating building LCA within Building Information Modelling (BIM). As part of the project, BRE produced a materials database of around 300 datasets based on ecoinvent data, modified to reflect the UK electricity mix. IES provided the first tool using the methodology and database in 2013 as phase 1 of the project, in phase 2 other tool providers such as One Click LCA and eTool developed IMPACT compliant tools (Doran, 2015). IMPACT compliant tools must be used in BREEAM 2018 onwards to obtain materials credits for undertaking building LCA. The IMPACT database has been updated several times since 2013, v5 in 2018 had approximately 350 datasets (BRE, 2018). It is unclear whether the database contains any EPD.

In 2008, the University of Bath published the Inventory of Carbon and Energy (ICE Database) (Hammond and Jones, 2008), providing cradle-to-gate embodied carbon data for almost 200 different materials, derived from secondary resources in the public domain, including journal articles, Life Cycle Assessments (LCA’s), books, conference papers, but ignoring commercial databases. Known as the ICE Database, the data was intended to be representative of the British market, but the authors were unable to rely solely on data from the UK and in many cases, best available data from foreign sources such as European or global averages had to be adopted. The ICE database was updated in 2011 using the same methodology (Hammond and Jones, 2011) providing access to generic embodied carbon data, but shortly after, Moncaster and Symons (2013) highlighted the lack of manufacturer-specific data for the UK.

Metsims, the UK EcoLabel Centre and the EPD Registry have collected data for UKComDat, a database of mainly UK manufacturer-specific EPD, with some UK collective EPD and generic LCA data specific to the UK; in 2020 it listed 352 datasets (Pagnon, Mathern and Ek, 2020).

In 2019, the ICE Database’s embodied carbon factors for steel, cement, concrete, timber, aggregates, aluminium and glass were updated using a selection of available EPD, and data quality information was added (Hammond and Jones, 2019).

The Built Environment Carbon Database (BECD) project was initiated by a consortium of BRE, Carbon Trust, CIob, CIC, CIBSE, ICE, IStructE, RIBA, RICS and UKGBC to provide databases whole life and embodied carbon data for entities (i.e. buildings and infrastructure projects) which is intended to launch in Spring 2023 and a database for products which will follow later. The product database will ‘comprise product data imported from existing EPD and other LCA sources, such as the Inventory of Carbon and Energy’ and will be ‘fully digital to allow data import and export through appropriate data formats and dedicated APIs.’ (BECD, 2022).

The UK therefore currently has access to two databases of generic embodied carbon data for construction products, each containing at least 300 datasets, although the free database only includes cradle to gate data. There are also a significant number of EPD from UK manufacturers and sectors. It is hoped that the BECD will all bring these datasets together in one location and make generic cradle-to-grave data accessible for the UK market, both as a standalone tool, and through embodied carbon tools.
There is therefore an ambition from the UK industry to produce EPD at scale, and the BECD may provide the mechanism for making them accessible. What is lacking however is an understanding of how many EPD for UK construction products are currently available, which sectors they cover, what potential there is to increase the number of EPD, and what might drive this change.

2.3.7. What product level data is important globally, and in the UK?

At a global level, looking just at the materials used for construction, concrete (made with cement), steel and aluminium used in buildings account for 6% of global GHG emissions, brick and glass 3% (with glass less than 10% of this); a further 3% of global emissions are from other materials used in building and infrastructure projects (UN Environment Programme, 2022). Looking emissions from all global industrial processes, steel (25%) and cement (19%) dominate assessments of embodied carbon from industrial processes (Allwood and Cullen, 2012) with aluminium only 3% of industrial GHG emissions globally.

For the UK, Drewniok et al. (2022) have used a ‘bottom-up’ approach based on stock modelling for new construction (residential, non-residential and infrastructure) in the UK, together with estimated areas of roof, wall, floor etc. in each stock type, and the types of materials incorporated in each element to produce an overview of the materials used in UK new construction each year. They have then linked this with generic embodied carbon data from the ICE database and impacts for transport and wastage to provide an indication of the ‘upfront’ carbon, adding up to 25 Mtonne CO₂e, from extraction, manufacturing, transport and installation of construction products, as shown in Figure 6. From this, the key materials responsible for over 80% of construction product impacts in the UK are concrete (ready-mix and precast), structural steel and reinforcing steel, other cementitious materials (e.g. mortar, screed), clay products including bricks and tiles, and timber. Aluminium and glass are both relatively small contributors.

The approach used by their study, focussing only on new build construction and the main building elements, misses those finishing materials in buildings which are replaced frequently (like floor coverings or paints), MEP such as boilers, air conditioning plant and sanitary ware, and materials like pipework, guttering and wiring which may all have impacts.

![UK Upfront Carbon impacts by material 2018](image)

**Figure 6 Upfront carbon impacts by material for the UK, adapted from Drewniok et al. (2022)**

Figure 7 shows UK Embodied Carbon impacts broken down by material group, taken from the UKGBC Net Zero Whole Life Carbon Roadmap (ARUP, Giesekam and UK Green Building Council, 2021) which was based on a decomposition analysis of the UK multi-region input-output (UK MRIO) model from 2018 used to calculate the ‘UK’s Carbon Footprint’ (DEFRA, 2022). This is a ‘top down’ study but does
consider all the economic sectors (UK and overseas) that provide goods into the UK construction sector.

![UK Embodied Carbon by Material Group](image)

This study estimated that for the UK in 2018, materials extraction and production was responsible for 60% of embodied carbon impacts, and Cement and concrete was the material group with the largest impact (31%), followed by Timber (11%) and Steel and other metals (10%), together accounting for over 50% of embodied carbon. The remaining embodied carbon was from site activity (22%), transport of products and people (6%), design services (5%) and the remainder unspecified.

Although the exact percentages and quantities vary somewhat across the different studies, there is broad agreement from reviewing the studies that materials extraction and manufacturing is a significant source of embodied carbon in the UK, and that the materials groups, cement, concrete, steel, timber, and bricks and tiles are the significant sources of embodied carbon in the UK.

2.3.8. What the literature says about variation in product level data from EPD

There is considerable evidence of variation in material data, as the meta review noted. Before the introduction of EN 15804, different countries had different methodologies for product EPD and building LCA with varying approaches to indicators, system boundaries, allocation and other aspects, as discussed by Del Borghi (2013), Fet & Skaar (2006), Hunsager et al. (2014), Ingwersen & Stevenson (2012), and Minkov et al. (2015). The effect of these different methodologies was considered in a study by Kellenberger et al. (2004) comparing the impact for a nominal 'cube' building made of concrete using different national tools and databases developed in line with the relevant national methodologies. They attributed the variation in impact found to use of different regional databases, different cement contents for the concrete, production processes, the amount of steel reinforcement used, the recycled content of steel assumed, different allocation procedures for co-products and recycling, different global warming potential indicators, and differences in the underlying assumptions for scenarios from gate to grave.

Huijbregts (1998) says the variations seen in LCA studies can be considered to have two causes. Firstly, variability is the ‘inherent variations in the real world,’ which are caused, for example, by actual technical or geographical differences in product manufacture, and cannot be reduced by improving methodology or compliance. On the other hand, uncertainty, described as variation which comes from ‘inaccurate measurements, lack of data, model assumptions etc. that are used convert the real world into LCA outcomes’ can be avoided or reduced by improving methodology and compliance. Kiureghian and Ditlevsen (2009) use different terminology but the same concepts when they state uncertainties in LCA are considered aleatory if the modeler cannot see a way to reduce them, and epistemic if the modeler can see a way of reducing them by gathering more data or by refining models or methodology.
As the type of variation appears important, particularly if it is not possible to avoid aleatory uncertainty (Kiureghian and Ditlevsen, 2009) or variability (Huijbregts, 1998), the variation found in the literature will, where possible, be classified as either due to *aleatory uncertainty*, also known as *variability*, or *epistemic uncertainty*. This classification can be used for the main cause of variation suggested by the authors, with causes linked to actual differences in production classified as aleatory, and those due to methodology, epistemic.

For the causes of variation suggested by Kellenberger et al. (2004), this has been done in Table 4. However for some causes of variation, it is not always possible to make the classification – for example, the recycled content of the reinforcing steel varied across the different national databases. This might be because the typical recycled content of the steel actually varies across the different countries (aleatory), or it might be that it is the same across Europe, but the assumptions made for the different databases are different (epistemic). Similarly the end of life scenarios for concrete (which are based on current practice) may vary across the different countries (aleatory) or they may be the same but the assumptions about them vary (aleatory). The variation in national databases may be due to actual differences in production in the countries (e.g. different fuel use and efficiency for cement production) (aleatory), or due to assumptions within or the representativity of the data used within the database (e.g. recycled content of imported steel) (epistemic).

*Table 4 Classification of variation in Kellenberger et al. (2004) into aleatory and epistemic uncertainty*

<table>
<thead>
<tr>
<th>Aleatory Uncertainty (Variability)</th>
<th>Epistemic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual cement content within the concrete differs</td>
<td>Different allocation procedures for recycling</td>
</tr>
<tr>
<td>Actual production processes differ</td>
<td>Different allocation procedures for co-production</td>
</tr>
<tr>
<td>Actual amount of steel reinforcement in the concrete differs</td>
<td>Different global warming potential (GWP) indicators</td>
</tr>
<tr>
<td>Actually differs</td>
<td>Recycled content of steel</td>
</tr>
<tr>
<td>Actually differs</td>
<td>Gate to grave Scenarios, e.g. transport, end of life, lifespan</td>
</tr>
<tr>
<td>National databases: variation due to actual differences and/or different assumptions</td>
<td></td>
</tr>
</tbody>
</table>

Since the publication of EN 15804 in 2012, as national databases, methodologies and construction product EPD Programmes across Europe adopted EN 15804, they have moved to using the same methodological approach so many of the epistemic causes of variation found in Kellenberger et al. (2004) have been addressed. With the publication of the revision of ISO 21930 in 2017 which echoes EN 15804 in almost all aspects, as construction product EPD programmes globally adopted either EN 15804 or ISO 21930:2017, they all started to use a common methodological approach.

The literature review has therefore first focussed on studies that have considered the variation of impact for construction product EPD using either EN 15804 or ISO 21930:2017, but also on those which have explored the causes of variation in impact for construction products. Their descriptions of variation often vary, for example using mean or median, the minimum to maximum range, interquartile range, standard deviation or coefficient of variation\(^4\). This often makes it hard to make comparisons between the different studies or it is impossible to amalgamate the findings quantitatively without access to the underlying data.

---

\(^4\) A description of the different statistical approaches used in the literature is provided in *Appendix C: Statistical Terms*. 

32
Firstly, when studies compare the climate change (GWP) and energy related indicators from EPD to EN 15804, it is clear that there still significant variations in product impacts, for example variation is seen across both overarching product groups and their sub-groups\(^5\), as found in:

- Cement EPD (Cruz Juarez and Finnegan, 2021);
- Insulation product EPD (Galindro \(et \,al\.), 2020, Grazieschi, Asdrubali and Thomas, 2021, Hill, Norton and Dibdiakova, 2018, Welling & Ryding, 2020);
- Timber EPD (Rasmussen \(et \,al\.), 2021);
- Window EPD (Asdrubali, Roncone and Grazieschi, 2021);
- Various product group EPD (Ganassali \(et \,al\.), 2018, Jones, 2019).

The reasons given in these studies for the variation seen are classified in Table 5 below. Although all the studies list reasons for variation which could be classified as aleatory, with the exception of Hammond and Jones, 2019 which provide no reasons, there are still 3 studies which also list reasons classified as epistemic.

Cruz Juarez and Finnegan (2021) suggested that a disparity in the way emissions were measured could be the cause of differences in CO\(_2\)e emissions from cement, but they could also be the result of technological differences in production.

Grazieschi, Asdrubali and Thomas (2021) noted that the impacts were different for the different types of product, and that density affected variation within a product sub-type. However they did also find different variance across the different EPD Programmes, though they said it was ‘not very significant.’

As some of the EPD programmes considered were used were geographically focussed, it is not clear however that where variation is found between programmes, whether this might be due to geographical differences rather than methodological differences between the programmes, especially as they note the methodological harmonization efforts are likely behind the reduced variances seen across different programmes.

Hill, Norton and Dibdiakova, (2018) reviewed one cellulose insulation EPD which provided separate results using ecoinvent and GaBi databases, with a resulting 15% difference in GWP and 30% difference in the primary energy. This led them to suggest that use of different databases may be behind some of the variation seen, although most of the EPD they considered used GaBi. They note the findings of Herrmann and Moltesen, (2015) who reviewed 100 randomly chosen unit processes with ecoinvent using the Simapro LCA tool and the GaBi database and tool. They found the inventory flows were nearly identical, with the except of 6, none of which will affect embodied carbon. However looking at the effect of characterisation on one process in particular, they do note differences in characterisation of inventory flows, and that this causes significant differences in GWP.

There are also studies which have compared the impact of EPD and generic datasets for specific products, or just looked at generic databases, and all have found variation. For example:

- Crawford & Stephan (2022) compared impacts for Australia concrete from EPD and the EPIC hybrid LCA database.
- Emami \(et \,al\.) (2019) compared the use of the GaBi and ecoinvent databases using two case study buildings.
- Häfliger \(et \,al\.) (2017) reviewed variation in construction product datasets from EPD, KBOB (Swiss National Database) and the ecoinvent LCI database.

\(^5\) e.g. across the insulation product group generally, and across sub-groups like stone wool or expanded polystyrene (EPS)
Table 5 Classification of causes of impact variation from the literature considering EPD to EN 15804

<table>
<thead>
<tr>
<th>Study</th>
<th>Products</th>
<th>Epistemic causes mentioned in the literature</th>
<th>Aleatory causes (variability) mentioned in the literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruz Juarez and Finnegan (2021)</td>
<td>Cement</td>
<td>‘result of a disparity in the way emissions are measured’</td>
<td>The differences of over 500 kgCO$_2$e/tonne in embodied carbon coefficient could be the result of technological differences</td>
</tr>
<tr>
<td>Galindro et al. (2020)</td>
<td>Insulation, common EPD Programme</td>
<td>Not discussed</td>
<td>A linear correlation of 0.88 between the GWP indicator and the ADPF (fossil fuel depletion) indicator, suggesting differences in energy consumption were driving variation</td>
</tr>
<tr>
<td>Grazieschi, Asdrubali and Thomas, 2021</td>
<td>Insulation, different EPD Programmes</td>
<td>Variance due to the EPD Programme chosen was generally lower than the variance linked to the density and was ‘not very significant’</td>
<td>Density, which contributed a ‘significant amount of the variance’ Differences in the products (e.g. higher PENR for fossil derived insulation, higher PER for plant/animal derived insulation) Different impacts for raw materials and processing.</td>
</tr>
<tr>
<td>Hill, Norton and Dibdiakova, 2018</td>
<td>Insulation, different EPD Programmes</td>
<td>May be due to use of different databases, noting one EPD provided results using both databases and had a difference of 30% in GWP and 15% in primary energy</td>
<td>Insulation type, e.g. glass wool, EPS, cellulose Manufacturing process and raw material, e.g. wet virgin wood chip versus recycled paper for cellulose. Low variance found for glass wool might be due to ‘large economies of scale and production optimisation.’ Strong correlation of primary energy with GWP/kg.</td>
</tr>
<tr>
<td>Welling &amp; Ryding, 2020</td>
<td>Insulation, common EPD Programme</td>
<td>Not discussed</td>
<td>No commentary on possible reasons for this variation or non-normal distribution, although they did explain that separating the products into sub-categories, such as mineral wool and foam insulation, would have affected the distribution</td>
</tr>
<tr>
<td>Rasmussen et al., 2021</td>
<td>Timber, different EPD Programmes</td>
<td>Not discussed</td>
<td>Embodied carbon coefficient A1-A3 varied due to the density of the products. GWP life cycle impact (A1-C4) varied according to the different end of life scenarios modelled</td>
</tr>
<tr>
<td>Asdrubali, Roncone and Grazieschi, 2021</td>
<td>Windows, different EPD Programmes</td>
<td>Not discussed</td>
<td>Triple glazing had higher impact than double due to the extra pane of glass Different frame types clearly had an effect on impact with steel performing worse and timber best. Variance of impact for individual type not explored.</td>
</tr>
<tr>
<td>Ganassali et al. (2018)</td>
<td>Glass wool Insulation</td>
<td>Not discussed</td>
<td>Range of variation was generally small, but 4 Spanish EPD had values more than double the median GWP, single EPD from Austria, Finland and Norway had values 50% higher than the median GWP, and one Norwegian EPD had a value less than 10% of the median GWP, suggesting national benchmarks may be appropriate.</td>
</tr>
<tr>
<td>Hammond and Jones, 2019</td>
<td>Range of products</td>
<td>Not discussed</td>
<td>Not discussed</td>
</tr>
<tr>
<td>Study</td>
<td>Products</td>
<td>Epistemic causes mentioned in the literature</td>
<td>Aleatory causes (variability) mentioned in the literature</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Crawford &amp; Stephan</td>
<td>Concrete from EPD Australasia and the EPIC database</td>
<td>Likely to be a result of variability in the data source and supply chain coverage of EPD data</td>
<td>May be due to different manufacturing processes and efficiencies</td>
</tr>
<tr>
<td>Emami et al. (2019)</td>
<td>Range of construction products from GaBi and ecoinvent</td>
<td>Partially due to an absence of data for actual products</td>
<td>Partially due to actual differences in the proxy datasets chosen from each database. Potentially due to different geographical regions, with different electricity mix</td>
</tr>
<tr>
<td>Häfliger et al. (2017)</td>
<td>Range of construction products from EPD, KBOB and ecoinvent</td>
<td>Carbon sequestration methodology between EPD and databases</td>
<td>Use of specific data for manufacturing might account for lower impacts for EPD</td>
</tr>
<tr>
<td>Lasvaux et al. (2015)</td>
<td>Range of construction products from EPD and ecoinvent</td>
<td>Reporting of emission flows, e.g. manufacturers only measure what they are required to measure and may group emissions</td>
<td>Differences (±10%) in GWP and energy demand in energy datasets in underlying databases.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(e.g. TVOC v individual emissions) Extrapolated data in generic databases.</td>
<td>Electricity mix.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exclusion of capital goods (infrastructure) in EPD.</td>
<td>Water consumption, e.g. for river gravel v quarried gravel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recognition of Guarantee of Origin in some EPD.</td>
<td></td>
</tr>
<tr>
<td>Martínez-Rocamora et al. (2016)</td>
<td>Range of construction products from GaBi, ecoinvent and other databases</td>
<td>For EPS, ‘different assumptions must have been taken which would justify the variation.’</td>
<td>Recommends database datasets should be adapted to take account of national differences in fuels used, yield factors, transport, distances, and performance.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For energy demand, ‘it does not seem possible that the manufacturing characteristics for the different countries ... may vary that much.’</td>
<td></td>
</tr>
<tr>
<td>Pomponi and Moncaster (2018)</td>
<td>Range of construction products sourced from their use in building-level studies</td>
<td>Variation ‘is not easily linked to contextual variations such as geographical location or technological level.’</td>
<td>Notes the very different values of embodied carbon between virgin and recycled steel.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variation ‘cannot be justified solely by technological and geographic differences in the product processes’</td>
<td></td>
</tr>
</tbody>
</table>
• Lasvaux et al. (2015) considered GWP and a number of other indicators for 28 construction product types, and compared the results for ecoinvent v2.01 datasets and EPD from the French inies database.

• Martínez-Rocamora et al. (2016) explored the embodied energy, embodied carbon, and energy mix for construction material datasets from generic databases including GaBi and ecoinvent.

• Pomponi and Moncaster (2018) analysed embodied carbon factors for cement, concrete, masonry, virgin steel, recycled steel, and timber, drawn from academic studies which provided information on data sources, system boundaries and embodied carbon for modules A1-A3. The source data was not given but covered a mix of EPD and generic data.

• Takano et al. (2014) analysed the GWP values for various construction materials within five generic databases including GaBi 6 and ecoinvent 3.

The causes of variation described in these studies are provided Table 6 with all studies reporting both epistemic and aleatory causes.

Crawford & Stephan (2022) considered the differences for Australian concrete between EPD and the EPIC database which is a hybrid database compiled using a combination of Australian and international process data and Australian input-output data. They suggest the cut-off rules in EN 15804 must be being ignored because ‘EPD coefficients are on average 22% below those of the equivalent hybrid coefficients, meaning that more than 5% of processes are excluded.’ They also suggest there must be problems with the EPD because, for identical product specifications, impacts differ between ‘states/manufacturing plants, even for the same manufacturer,’ even though they admit variation may be due to different manufacturing processes and efficiencies. They suggest further in-depth analysis of EPD data is needed to determine the reasons for such high variability in embodied carbon coefficients.

Emami et al. (2019) were comparing datasets chosen from GaBi and ecoinvent to represent particular products in two case study buildings. In several cases, the difference between the datasets was because there wasn’t the exact product type in one or other of the databases, so a proxy dataset had to be chosen, and this was behind the variation seen. However where the same product was chosen, they noted this could be due to the different geographical regions, and electricity mix between the ecoinvent database, which was based on Swiss production, and the GaBi dataset, which was based on German production, although both now adapt the data to additionally provide ‘European’ datasets.

Häfliger et al. (2017) noted particular differences in the treatment of biogenic carbon sequestration between the ecoinvent database and EPD, which would cause significant differences in the GWP if the sequestration was not included for EPD assessments using ecoinvent according to the requirements of EN 15804 and EN 16485. As an example of technical differences, they noted significant differences in the amount of cement within concrete blocks between the various database and EPD.

Lasvaux et al. (2015) found numerous aleatory causes of variation, including the fact that underlying LCI databases may have up to 10% variation in GWP for raw material and energy datasets which feeds through to differences at product level. In relation to epistemic causes, they said that there may be differences in the emissions included in the datasets, as different manufacturers are required by regulators to measure and report different emissions, and this may change indicator results, though it is not likely to significantly change the GWP, as CO₂ emissions are normally calculated based on fuel used rather than measured. They noted the same problem as Häfliger et al. (2017) for concrete blocks, and also highlight the use of extrapolated data in databases, for example ecoinvent’s roof tile data dataset which was extrapolated from data for brick production with a 50% increase in fuel use to account for the need to provide frost resistance. They said this may account for the doubling of impact for ecoinvent compared to the EPD modelled on current production of roof tiles. They noted that EPD
exclude capital goods (e.g. the building of factories and the roads used to transport goods). However as all EPD do this, this is not likely to be a significant cause of variation across EPD. They also note that EPD are starting to account for use of Guarantee of Origin by manufacturers, whereas this is not considered in ecoinvent.

Martínez-Rocamora et al. (2016) suggest that manufacturing characteristics in different countries could not vary enough to justify the variation in impact seen in construction product impacts in different databases, but they do recommend that if using a database, datasets should be adapted to take account of national differences in fuels used and yield factors for example. They also provide some examples of differences between the databases, for example for both steel and aluminium, it reports use of different recycled contents and use of % of fossil fuel energy between the datasets, and note a lack of transparency about modelling which makes it difficult to assess exact causes of variation.

Pomponi and Moncaster (2018) similarly consider that the variation found in construction product GWP cannot be explained by geography and technology alone. However they are comparing, in some cases, very different products, for example for concretes: precast and ready-mix concrete, with and without reinforcement, and of strengths given from C30 to C80; for masonry: brick, aircrête and concrete block; for timber: softwood, glulam, plywood and fibreboard.

Takano et al. (2014) considered technical and geographical differences were behind the variation found, for example for timber. They noted that the data that for sawmills in Finland, 75% of total fuel in sawmills is biofuels, whereas in Japan, 80% of timber is air dried with the reminder kiln dried with fossil fuels (e.g. heavy fuel oil); and for steel reinforcing rod, German electric arc furnace (EAF) steel was used in GaBi but in ecoinvent, a mix of 37% EAF and 63% global basic oxygen furnace (BOF) was used. Like Emami et al. (2019), Takano et al. (2014) also had problems in finding datasets to match the products used, and thus found variation in impact. They noted a Japanese database excluded transport impacts, and were not able to find evidence of differences in allocation due to a lack of transparency, and but noted it can have significant impact.

Reviewing the literature looking at variation for EPD and generic data, it is thus clear than many authors attribute much of the variation to aleatory causes related to differences in the product type, production technology or geography, rather than epistemic causes. This is supported by studies investigating this such as AzariJafari et al. (2021) who used probabilistic approaches to assess all the possible variation for a theoretical concrete EPD, and found the impact of methodological choices (choice of allocation approach for GGBS, database choice, treatment of biogenic carbon, treatment of recycling) on the variance was trivial and variance was in fact dominated by the variability of Portland cement content in the concrete.

Large differences in production impacts are also highlighted in the technical literature, for example Chen, Habert, Bouzidi, & Jullien (2010) used data on direct CO₂ emissions for cement plants producing CEM I or CEM I and CEM II from the European Pollutant Emission Register (therefore using a common methodology) together with production quantities and found that the average direct CO₂ impact for cement production had a mean of 782 kgCO₂/tonne and standard deviation of 141 kgCO₂. Keys et al. (2019) explain that glass wool is commonly produced by either gas-fired or electric furnaces, which each have different impacts, added to which are the differences in electricity impacts in different countries. Pomponi et al. (2017) used 200 sets of process data for items within the supply chain of the manufacture of a flat glass cladding system, to consider the distribution of embodied energy for each process for a common functional unit. For three processes illustrated, the distribution was normal, with a range of 0.5-5 kWh/unit, 0.5-2 kWh/unit and 3-30 kWh/unit, showing technical differences could be highly likely to affect environmental impact, particularly when these differences in embodied energy may be magnified when converted to embodied carbon coefficients due to the different carbon intensity of energy sources.
However, many of the causes of epistemic variation given in the literature are also shown to cause variation, though EN 15804 is intended to reduce this likelihood by restricting methodological choices. For example Linkosalmi et al. (2020) shows the variation in impact from using different allocation approaches for timber; and Frischknecht et al. (2007) reviewed the influence of including capital goods infrastructure for a wide range of processes. For the GWP of construction materials generally, it accounted for an average of 4% of impact, but for wooden construction materials 11.3%, paints 8%, glass 7.4% and insulation 5.7%.

There are also a number of studies which have suggested that large numbers of EPD do not meet the requirements of ISO 14025, for example Moré, Galindro and Soares (2022) checked the meta data provided in 400 EPD to EN 15804 and found very few met what they called the ‘essential requirements,’ though several of these are not required in EN 15804. Gelowitz & McArthur (2017), similarly reviewed the meta data for EPD to both EN 15804 and ISO 21930:2007, to consider whether EPD could be compared, but noted, for example, being unable to compare two EPD directly because one reported water consumption in gallons and one in litres, and for EPD for insulation, being unable to make comparisons because of the use of different declared units (e.g. mass and area) without even attempting to convert to a common functional unit (thermal resistance). As these studies only reviewed meta data, and appear to be slightly flawed, it is not clear whether either study can be considered reflective of any potential methodological problem with the impacts reported in EN 15804 EPD. Both studies recommend that EPD Verification processes become stricter and that EPD provide all the required meta data.

Although Jordan and Bleischwitz (2020) explain that EPD have ‘scientific-technical accuracy’ and can provide the ‘viability and validity’ that are required to ensure political support for adoption of embodied carbon policies based on EPD, they suggest there may be problems of structural bias when EPD verifiers are paid by manufacturers, rather than the EPD programme, however they provide no evidence that verification is not robust.

**Variation in due to type of EPD (granularity)**

A further type of variation is described by Hodková and Lasvaux (2012) as ‘granularity.’ They illustrated granularity by showing how an individual manufacturer’s data sits within the range of values for a group of manufacturers, and the group sits within a wider of values for a sector average EPD covering all manufacturers (see Figure 8). Thus, as the EPD becomes more specific, its variance decreases, and its representativeness increases. This was also described by Gantner et al. (2018), who also illustrated how as a project progresses, the knowledge about the product being used increases – and that this specificity can be matched by using data with an increasing level of representativeness, for example moving from generic data to average data to specific product and plant data.

![Figure 8 Relation between the different types of EPD data for each building material, from (Hodková and Lasvaux, 2012)](image-url)
Granularity is due to differences in the sites and products covered by the EPD, so is aleatory, but as a manufacturer can choose the granularity of the EPD they produce and thus the impacts they report, it is also epistemic.

**Using data on variation**

Emami et al. (2019) used data from GaBi and ecoinvent databases to assess the case study houses and apartment blocks of concrete and of timber, and found for a concrete apartment building, GaBi was 16% better than using ecoinvent, for the timber house, 13% worse than using ecoinvent.

Häfliger et al. (2017) reviewed variation in datasets from EPD, KBOB (Swiss National Database) and the ecoinvent LCI database and looked at the effect of data choice on 4 case study buildings, finding that due to their contribution to impact and variation, ‘Wood and wood products,’ ‘Insulation materials’ and ‘Windows and doors’ displayed the strongest sensitivity to database choice.

Waldman, Huang and Simonen (2020) have been concerned about the way comparisons between EPD with different granularity may be misleading, and have addressed granularity and the lack of information on variation in EPD by suggesting ‘uncertainty factors’ which can be applied to EPD to account of this variation depending on whether the EPD relies on data for one or several products, one or several sites, one or several manufacturers etc and whether it relies on specific supply chain data or not. They further add an additional uncertainty factor based on whether the EPD addresses production specific to the product being used (for example a particular batch of concrete or recent production data for the carpet rather than data from previous years). This is similar to the Swedish Q Metadata approach (Erlandsson, 2018) which differentiated between EPD with less than, and greater than ±10% variation, based on the requirement in the Swedish EPD Programme to produce separate EPD if the variation in embodied carbon coefficient between products is greater than ±10%. These factors are combined using the root mean square method to give the overall uncertainty for each EPD, and Waldman, Huang and Simonen (2020) suggest that this should be used to increase the impacts given in the EPD to a conservative value reflecting the underlying variance, that this conservative value should be used for product comparisons and selection.

Marsh, Orr and Ibell (2021) used the coefficient of variation (CoV) provided by the ICE database (Hammond and Jones, 2019) for concrete (25%), CLT (11.3%), structural steel (27.2%) and reinforcing steel (67.9%) together with Monte Carlo analysis to consider the effect of product level variation at building level, finding a resulting 10% CoV for a full assessment of an educational building and 11.9% CoV for an assessment limited to just the sub- and super-structure of the building.

Moncaster et al. (2018) used the data provided in Pomponi and Moncaster (2018) to calculate the mean and interquartile range of embodied carbon per kg for each product, then used this data with estimates for transport and material quantities for a concrete, load-bearing masonry, timber and steel framed version of the same student housing project to assess the projects using a number of different scopes (A1-A3 / A1-A5 / A1-A5+C1-C4, structure only/shell and core/up to finishes). The difference in GWP between the options using the lower quartile data and the upper quartile data were over 3 times higher for CLT and for steel, up to 10 times higher. This range seems much higher than the variation seen in Marsh, Orr and Ibell (2021), suggesting Monte Carlo analysis provides perhaps a more realistic approach to exploring the effect of uncertainty for individual parameters on overall impact.

To summarise, the academic literature recognises there is often significant variation in the embodied carbon coefficients reported for construction products. Some academics (e.g. Pomponi & Moncaster, 2018; Martínez-Rocamora et al., 2016) suggest that differences in technology and geography cannot alone be responsible for the variation that is seen in the datasets studied and that different applications of methodology must responsible. This could be the case in academic studies which rarely follow consistent methodologies such as EN 15804. However the academic literature also shows
considerable variation between EPD within product groups. In some cases, some of this variation can be attributed to the different types of products covered by a product group such as insulation (e.g. EPS, XPS, PU, stone wool, mineral wool, wood fibre insulation etc) as seen in (Welling and Ryding, 2020). When considering concrete, AzariJafari et al. (2021b) found that the variation in cement impact, and Chen, Habert, Bouzidi, & Jullien (2010) found a coefficient of variation of 18% in direct CO$_2$ emissions from different cement plants. Pomponi et al. (2017) found considerable variation in the embodied energy of processes used to manufacture glazed cladding units with similar trends in embodied carbon, and Galindo et al. (2020) found that differences in non-renewable primary energy consumption drove the variation in GWP impact for insulation materials, a finding echoed by Silvestre et al. (2015) for stone wool insulation, and the finding of Takano et al. (2014) that differences in technology and geography drove differences for steel and timber datasets.

Although in much of the literature, variation is noted, in many cases the reasons for variation are not mentioned. However when it is discussed, there seems to be disagreement as to whether actual differences in technology and geography can be large enough to be driving the variation that is seen in embodied carbon data for construction materials, or whether it is exacerbated by problems with methodology and the implementation of standards. Other causes of variation mentioned are granularity (the specificity of the EPD).

It is also clear from the academic literature that the range of variation seen is not consistent across all construction products; with many also displaying non-normal distribution. The use of default uncertainty factors such as provided in Waldman et al. (2020) and Gantner et al. (2018) may be penalising some products with smaller variations, however this may be overcome if EPD provided greater transparency regarding variance, although this could really only be possible for a collective EPD if all products, sites and manufactures calculated all site specific product specific impacts and then calculated the mean and variation.

As the number of construction product EPD is increasing rapidly (Toniolo et al., 2019), the EPD themselves, with the information they report covering both impacts such as GWP, but also the amount and type of energy used, and use of secondary material, provide a rich source of data to investigate whether technological differences such as the technology and types of energy used, the efficiency of the process and the inputs, really can be responsible for the range of variation seen in EPD.

2.4. Research questions arising from the literature review

This research intends to consider how the growing resource of data from Environmental Product Declarations (EPD) for construction products can be used to reduce embodied carbon in the built environment. The literature review has revealed a growing interest in the embodied impacts of buildings, and an associated growth of both academic papers discussing building LCA and in materials data in the form of EPD. However there is a noticeable gap between the academic literature and what is happening in construction practice. The small amount of academic literature that is focussed on EPD themselves, still often suggests that materials data is inadequate for purposes of either regulation or building assessment. The literature also highlights the variation of impact across EPD for specific products and, while suggesting a number of reasons for this variation, doesn’t develop a systematic typology nor investigate comprehensively what might be learnt from the variations. This literature has therefore led to a number of research questions (RQ) as follows:

**RQ1** How are EPD being used in practice in the UK?

This question uses a qualitative analysis approach to explore the experience of expert practitioners in embodied carbon in the UK, to understand how they are using EPD and embodied carbon data in their practice, and whether EPD have a role in reducing embodied carbon.
RQ2  What EPD data exists at present?

This question explores the availability of EPD globally, how it has changed and what is driving any change. Looking at countries where embodied carbon assessment has already been mandated, it considers their requirements in terms of EPD, and generic data in the absence of EPD. Specifically for the UK, it looks at what EPD and generic data are available for construction products used here, and whether this is adequate to mandate embodied carbon assessment at building level. This question draws on a range of qualitative and quantitative analysis approaches.

RQ3  What are the causes of variation in EPD?

This question seeks to understand to what extent aleatory uncertainty, also known as variability, can explain the variation seen in EPD. It looks to classify the causes of aleatory variability seen in EPD using a quantitative analysis of data from all the published EPD for a number of key construction products to illustrate the types of variation found.

RQ4  What additional information can an analysis of EPD for a particular product group give us?

Using the impact data provided by the large amount of EPD now available, this question explores what we can learn from a deeper quantitative analysis of this data.
3. Research Design

3.1. Epistemology and approach

The research considers how people like architects and engineers, use data such as EPD to quantify and then reduce embodied carbon in the built environment. As such, both positivist and constructivist research approaches are relevant.

In relation to quantification and reduction of embodied carbon, the literature shows broad consensus that such research requires the use of quantitative analysis methods rooted in positivism (Richardson, 2017). Such methods are characterised by, amongst others, a ‘focus on deduction, confirmation, theory/hypothesis testing, explanation, prediction, standardized data collection, and statistical analysis’ (Johnson & Onwuegbuzie, 2004, p. 18).

However the research is also focussed on the behaviour of people, and their interactions with non-human actors such as embodied carbon data and tools. It thus has a social and behavioural perspective and qualitative methods based on constructivism are often considered most suitable (Lincoln and Guba, 1985). These methods are characterised by Johnson & Onwuegbuzie (2004, p. 18) as using ‘induction, discovery, exploration, theory/ hypothesis generation, the researcher as the primary ‘instrument’ of data collection, and qualitative analysis.’

To deal with the inability of either of these two research paradigms to address the questions alone, the thesis uses a mixed methods research approach, defined by Johnson and Onwuegbuzie (2004) as:

‘the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study.’

Mixed methods research is entirely suitable for researching in an applied field such as design in the built environment (Koskinen et al., 2011) and is a pragmatic method according to Johnson and Onwuegbuzie (2004) that can be more workable and produce a ‘superior product’ than qualitative or quantitative research alone.

The research thus takes a pragmatic approach to each research question, using different methods to collect data, discover patterns, develop hypotheses and testing these against the data to find the best explanation to understand the findings.

Figure 9 The Mixed Methods Research Approach, derived from Johnson and Onwuegbuzie (2004)

Section 3.2 sets out the mix of research methods used which have been determined by the individual research questions.

3.2. Research methodology generally

A number of different methods have been applied to address the various research questions, depending on the type of data required and whether a qualitative or quantitative analysis approach is required. As these methods are used in different combinations, the various data collection
methodologies have been described individually in section 3.3 and the data analysis methodologies have been described separately in section 3.4. The combination of methods for each research question is set out in Table 7 below. The research timeline is set out in section 3.5.

3.3. Data collection methodologies

3.3.1. Data on the views of embodied carbon expert practitioners

A research interview has been defined as ‘a two-person conversation initiated by the interviewer for the specific purpose of obtaining research-relevant information, and focused by him on content specified by research objectives of systematic description, prediction, or explanation’ (Cannell and Kahn, 1968). Tuckman (1972) comments that the interview, ‘by providing access to what is ‘inside a person’s head,’ makes it possible to measure what a person knows (knowledge or information), what a person likes or dislikes (values and preferences), and what a person thinks (attitudes and beliefs).’

According to Cohen, Manion and Morrison (2011), the advantages of interviews over questionnaires are that if necessary, the questions can be explained, the interviewer can probe answers more deeply if required, and the interview (if semi-structured) can be adapted to the respondent; once an interview has been arranged, it is likely to yield data which will be valuable. However they say interviews are time intensive, and the number of respondents as a result is limited; the interviewer is also likely to introduce bias. Kitwood (1977) states, ‘each participant in an interview will define the situation in a particular way.’ The likelihood of interview bias is relevant for any interview. Fowler (2009) discussing bias in interviews generally, suggests that the more prompting and probing done by the interviewer, the more chance of bias. He favours using standardised wording, with the possibility of providing further explanation if respondents are unclear about the question.

Cohen, Manion and Morrison (2011) state,

‘The more one wishes to gain comparable data – across people, across sites – the more standardized and quantitative one’s interview tends to become; the more one wishes to acquire unique, non-standardized, personalized information about how individuals view the world, the more one veers towards qualitative, open-ended, unstructured interviewing.’

Ideally for this research, we would want comparable data, which provides the personalised views of the respondents. Semi-structured interviews therefore seem most appropriate and are a common approach in social science research where both quantitative and qualitative research are integrated (Bryman, 2006). Semi-structured interviews use fixed, open-ended questions, but the sequence of questions and exact wording does not always have to be followed. Cohen, Manion and Morrison (2011) suggest an interview plan for semi-structured interviews would include:

- ‘the topic to be discussed;
- the specific possible questions to be put for each topic;
- the issues within each topic to be discussed, together with possible questions for each issue;
- a series of prompts and probes for each topic, issue and question.’

It was therefore decided to conduct semi-structured interviews with relevant experts, using an interview plan as suggested by Cohen, Manion and Morrison (2011). Initially there were going to be face-to-face interviews, but as discussed below, online interviews were used due to the COVID-19 pandemic.
<table>
<thead>
<tr>
<th>Question</th>
<th>Data required</th>
<th>Data Collection</th>
<th>Analysis Approach</th>
<th>Research Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RQ1 How are EPD being used in practice?</strong></td>
<td></td>
<td></td>
<td></td>
<td>Chapter 4</td>
</tr>
<tr>
<td>1a) What is the experience of Embodied Carbon Expert Practitioners (ECEPs) in the UK?</td>
<td>Views of ECEPs</td>
<td>Semi-structured Interviews (3.2.1)</td>
<td>Thematic analysis (3.4)</td>
<td></td>
</tr>
<tr>
<td>1b) How do EPD play a role in embodied carbon reduction?</td>
<td>EPD and embodied carbon data search</td>
<td></td>
<td>Worked examples</td>
<td></td>
</tr>
<tr>
<td><strong>RQ2 What EPD data exists at present?</strong></td>
<td></td>
<td></td>
<td></td>
<td>Chapter 5</td>
</tr>
<tr>
<td>2a) How many EPD for construction products are available globally and how has this changed over time?</td>
<td>Data on numbers of EPD over time</td>
<td>Historic data collection and grey literature review (3.3.2)</td>
<td>Statistical analysis</td>
<td>5.2</td>
</tr>
<tr>
<td>2b) What is driving growth in EPD numbers?</td>
<td>EPD numbers (see 2a)) Timeline of relevant events</td>
<td>Grey literature search and personal communication (3.3.3)</td>
<td></td>
<td>5.3</td>
</tr>
<tr>
<td>2c) How much product level data is required to mandate embodied carbon assessment at building level?</td>
<td>Availability of data in other countries that mandate Embodied Carbon assessment at building level</td>
<td>Grey literature review (3.3.5)</td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>2d) What EPD and other embodied carbon data for construction products is available for assessments in the UK?</td>
<td>UK Construction product consumption EPD Embodied carbon data</td>
<td>Grey literature review and personal communication (3.3.6)</td>
<td>Analysis of Trade Statistics Product datasheets</td>
<td>5.5</td>
</tr>
<tr>
<td>2e) Is the available EPD and embodied carbon data in the UK adequate to mandate embodied carbon assessment at building level?</td>
<td>Results of 2d) and 2e)</td>
<td>2d) and 2e)</td>
<td>Comparison</td>
<td>5.6</td>
</tr>
</tbody>
</table>
### RQ3 What are the causes of variation in EPD?

| 3a) | Can aleatory uncertainty (variability) explain the variation in embodied carbon coefficients provided in EPD data for key construction products? | EPD | Grey literature review and manual data extraction from EPD into spreadsheets (3.3.7, 3.3.8) | Use of various types of data visualisation and statistical analysis to look for pattern in the data, e.g. distribution using *Box and whisker charts*, correlation using *XY Scatter graphs*, the *Pearson correlation coefficient* (*R*) and the *Coefficient of determination* (*R*²) | Chapter 6 |

### RQ4 What additional information can an analysis of EPD for specific products give us?

| 4a) | What does an analysis of Cement and Concrete EPD tell us? | EPD for cement and concrete | See 3a) | Use of various types of data visualisation to look for pattern in the data, together with statistical analysis approaches, e.g. correlation using the *Coefficient of determination* (*R*²) | Chapter 7 |
| 4b) | What is the role of renewable energy in construction product impact variability? | EPD | See 3a) | Use of various types of data visualisation to look for pattern in the data, together with statistical analysis approaches, e.g. correlation using the *Coefficient of determination* (*R*²). | Chapter 8 |
Online interviews

As a result of the COVID-19 pandemic, the UK Government instituted ‘social distancing’ regulations which prevented the use of face to face interviews, so to ensure that progress with the PhD was maintained, online interviews were used instead. Salmons (2015) provides guidance on designing and conducting online interviews, or ‘computer-mediated communication’, with the interview technique used classified as synchronous video-conferencing. Both video-conferencing and multi-channel meetings (in this case, audio-conferencing with the potential addition of screen-sharing and video) are appropriate, according to Hewson (2010) for Internet-mediated Research, ‘to gather original data via the Internet with the intention of subjecting them to analysis to provide new evidence in relation to a specific research question.’ Video-conferencing provided a number of advantages over audio-conferencing: the opportunity to study the participant’s non-verbal communication and as its ‘free-flowing, conversational’ character was closest to the face to face interview (Salmons, 2015). Both video and multi-channel audio conferencing offered the opportunity to include shared screens so allow details of a report or tool output to be shared. Salmons found interviewers were able to collect the data that they required for their studies using either technique, suggesting, ‘the technologies did not present an impediment to the real dynamic of interviewer–interviewee rapport at the heart of the in-depth interview.’

Iacono, Symonds and Brown (2016) looked at conducting interviews using skype and commented that building rapport with participants can be an issue with skype, and suggested using email communication before the interview to create a connection.

It was therefore decided to use video conferencing to undertake semi-structured interviews as this seemed to offer the closest experience to a face-to-face interview and was not considered to interfere with the rapport between interviewer and interviewee. Email was used before the interview to build the connection with interviewees, though in many cases, interviewer and interviewee were already known to each other through their work in the field of embodied carbon.

Human research ethics

In August 2019, a submission in relation to the interviews described in 3.2 was submitted to the OU Human Research Ethics Committee. It was reviewed and received a favourable opinion – HREC reference number: HREC/3325/Anderson.

Semi-structured interviews with Embodied Carbon Expert Practitioners (ECEPs)

Semi-structured interviews were conducted by video conference with Embodied Carbon Expert Practitioners (ECEP) based in the UK, with experience of developing building LCA or embodied carbon assessment tools. Before the interviews, following the advice of Iacono, Symonds and Brown (2016), email communication was used to invite the ECEPs to participate, and to build the connection with each participant. The interview plan (as suggested by Cohen, Manion and Morrison (2011)) including interview questions and probes used for the semi-structured interviews is provided in Appendix B: Questionnaire for Interviews.

The ECEPs were selected from those involved in a number of groups active in the field of embodied carbon including LETI, Architecture Declares, Architects Climate Action and the Whole Life Carbon Network. They are responsible for embodied carbon tool development, working for leading engineering and architectural consultancies with known expertise in embodied carbon, and are considered to be at the forefront of the movement to assess embodied carbon in the UK.

The expert interviewees are described in Table 8 below.
**Table 8 Interviewees and their background**

<table>
<thead>
<tr>
<th></th>
<th>Role and Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Structural Engineer. Worked since 2014 as LCA and ECO₂ consultant for an architectural practice in Europe, then consulting engineers and after LCA tool developer in UK. Developed an in-house BIM integrated LCA tool for the practice.</td>
</tr>
<tr>
<td>B</td>
<td>Mechanical Engineer. Worked since 2018 as Sustainability lead for architectural practice in the UK. Developed an in-house early design stage tool for the practice.</td>
</tr>
<tr>
<td>C</td>
<td>Structural Engineer. Worked in UK since 2015 as engineer and sustainability consultant for an international engineering consultancy. Developed an in-house embodied carbon tool for the consultancy.</td>
</tr>
<tr>
<td>D</td>
<td>Architect. Worked in UK since 2014 as an embodied carbon consultant for an embodied carbon consultancy, research body and then engineering practice. Worked on the ongoing development of an in-house embodied carbon tool for the consultancy.</td>
</tr>
<tr>
<td>E</td>
<td>Architect. Worked since 2017 as Sustainability Design Advisor for an architectural practice in the UK. Worked on the ongoing development of an in-house embodied carbon tool for the practice.</td>
</tr>
<tr>
<td>F</td>
<td>Structural engineer. Worked since 2011 as engineer and sustainability consultant for US façade and structures consultancy. Developed an in-house early design embodied carbon tool for the consultancy.</td>
</tr>
<tr>
<td>G</td>
<td>Architect since 2007. Leading on implementation of embodied carbon assessment within a medium sized architectural practice, including bespoke integration of a commercial embodied carbon tool.</td>
</tr>
</tbody>
</table>

**Limitations of the interviews**

Interviews were only conducted with 7 individuals so only provide a snapshot of the views of Embodied Carbon Expert Practitioners.

Bias needed careful handling as the researcher is known to be active in the field of EPD, building LCA and embodied carbon. Value Belief Norm theory suggests that people are more likely to undertake a behaviour if they think others want them to do it (Stern et al., 1999) – in interviews therefore, it is likely that respondents may provide responses they think the researcher wants them to provide. Cohen, Manion and Morrison (2011) says, ‘During the interview the biases and values of the interviewer should not be revealed, and the interviewer should avoid being judgemental.’ In this research however, the respondents were often aware of the researcher’s work; the researcher in this case is therefore a participant observer who may affect the research process (Verschuren, 2003). This potential for bias has addressed by respondent checks and through reflexivity, defined as ‘an effort to reflect on how the researcher is located in a particular social, political, cultural and linguistic context’ (Alvesson, 2002). Throughout the interviews, the researcher made clear their role in any tools and standards discussed, that they were very open to criticism of them and that there were no right or wrong answers to any of the questions posed.

3.3.2. Data on the availability of Environmental Product Declarations (EPD) globally

Initially when the first survey of EPD was undertaken in 2011, EPD programmes were identified from the researcher’s network of contacts in EPD standardisation and knowledge of activities in different European countries. Over time, additional EPD programmes for construction products were included in the survey by reviewing the members of ECO Platform (ECO Platform, 2019b), the North American catalogue of Product Category Rules (PCR) (Sustainable Minds, 2019), the LCA Database (Metsims, no date) and the EC3 tool (Building Transparency, 2023). According to ISO 14025, EPD programmes must ensure that EPD are published and are independently verified. EPD programmes were only added to the survey if the programme followed this requirement. The list of EPD Programmes found as part of
this research was published by the Alliance for Sustainable Building Products in 2020 to assist the industry in accessing construction product EPD (Anderson, 2020b).

In 2011, the identified EPD were using the draft standard, prEN 15804:2010, and after the publication of EN 15804:2012, identified EPD used this standard or its successors, EN 15804:2012+A1:2013 or EN 15804:2012+A1:2019, or the international standard, ISO 21930:2017. Internet searches for ‘EPD Programme’ AND (15804 OR 21930) have been undertaken periodically to look for new EPD programmes, but as described above, all the EPD programmes covered by the survey must ensure that their EPD comply with ISO 14025.

It is possible that this survey may have missed EPD programmes, or EPD produced outside of EPD Programmes, however it is considered that these are not likely to be very numerous, given the time it has taken for established EPD programmes to include substantial numbers of EPD. EPD programmes exist to make their EPD available to manufacturer’s customers, so it is in their interests to ensure that their EPD are visible.

In 2011, the numbers of EPD were obtained from the EPD Programme website if the information was available, or by personal communication otherwise, for example, where the programme listed some EPD separately in more than one language (e.g. IBU in Germany), or did not provide a full listing of EPD (e.g. the International EPD® Programme more recently). Where some EPD were listed in more than one programme through ‘mutual recognition’ between programmes, only the listing in the programme organising verification was considered if this was possible to identify, or the EPD programmes were asked to provide this information.

Some EPD programmes allow separate environmental data for two or more different products and/or products from different sites to be provided in one EPD; in some cases there could be over 100 datasets provided. However due to the time it would take to identify this information (which would have required each EPD pdf file to be opened and a search for the number of separate datasets included to be undertaken), only the number of EPD has been recorded. From 2021, additional data recorded as part of the process included the number of EPD available digitally for each programme (either directly via the programme or through the ECO Portal of the ECO Platform, the InData website (InData, 2019) or the EC3 tool (Building Transparency, 2021). In 2022, the larger EPD programmes in Europe were contacted regarding the number of EPD produced from pre-verified EPD tools and this information was integrated into the study.

Counting the numbers of EPD was undertaken by physically counting the number of EPD listed and recording the information in a spreadsheet. Each time data was collected (annually from 2017), more data was added to the spreadsheet.

The findings of this analysis are described in section 5.2.

3.3.3. Data on the availability of EPD by product group

At the start of 2019, the number of EPD for each different product family was identified for the EPD listed on the listed on the ECO Platform Registry (ECO Platform, 2019a) by using the Registry’s ‘search by product group’ function and counting the number of EPD found for each product group. This was recorded in a spreadsheet.

3.3.4. Data on the drivers for growth of EPD

Further to the literature review, a deeper review of grey literature such as legislation, green building certification documentation and other industry reports was undertaken to identify key events and activities in the countries where there were the largest number of EPD (see findings in 5.2 (i.e. France, Germany, Norway and the US)), identified through the analysis of availability of EPD undertaken first.
The types of events and activities considered was informed by the drivers for EPD growth found in the literature. In addition, personal contact with stakeholders in these countries (described in Table 9) was used to review the findings of the literature review and identify any further events or activities which have been considered to drive the growth of EPD.

Table 9 Stakeholders contacted to review national drivers for EPD growth

<table>
<thead>
<tr>
<th>Country</th>
<th>Stakeholder</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>Gerard Senor</td>
<td>Chair, AFNOR (French Standards) Mirror Committee for Sustainable Construction</td>
</tr>
<tr>
<td></td>
<td>Philippe Osset</td>
<td>Convenor, ISO TC59 SC17 (Sustainable Construction)</td>
</tr>
<tr>
<td>Germany</td>
<td>Alexander Roeder</td>
<td>CEO, IBU EPD Programme</td>
</tr>
<tr>
<td>Norway</td>
<td>Håkon Hauan</td>
<td>CEO, EPD Norge EPD Programme</td>
</tr>
<tr>
<td></td>
<td>Anne Rønning</td>
<td>Convenor, ISO TC59 SC17 WG3, EPD verifier, EPD Norge</td>
</tr>
<tr>
<td>USA</td>
<td>Meghan Lewis</td>
<td>Senior Researcher, Carbon Leadership Forum</td>
</tr>
<tr>
<td>UK</td>
<td>Pat Hermon</td>
<td>Manager, BRE EN 15804 EPD Programme</td>
</tr>
</tbody>
</table>

3.3.5. Data on the availability of generic embodied carbon data in European national databases used for regulation

Databases of environmental data for construction products in use in various countries in Europe with embodied carbon regulation were identified through a combination of web searches and use of grey literature describing the regulation of embodied carbon assessment in different countries (e.g. Pasanen and Bruce-Hyrkäs, 2016; Bionova Ltd/One Click LCA, 2018; One Click LCA, 2022; Röck et al., 2022) and on databases, e.g. (Pagnon, Mathern and Ek, 2020; Brightworks Sustainability and WAP Sustainability, 2021). Where possible, the availability of data for each database was checked by counting and recording the number of different types of datasets (e.g. specific EPD (from a single manufacturer), collective EPD (e.g. a EPD provided by an industry sector), sector datasets (data provided by an industry sector but not via a verified EPD), generic datasets (datasets provided for the database when EPD or sector datasets are not available) within each database. Additionally, searches of the academic literature were undertaken to obtain historic data on the number of datasets that had been provided over time.

The approach to generation of generic datasets was also reviewed by checking any literature provided by the database operator.

Where the database itself was not accessible, available literature provided by the database was checked to obtain numbers, or the database operator was contacted for the information. As part of the process and using the same sources, data for each database was also collected in terms of the following criteria:

- The funding of the database;
- Access via the web (Yes if public access via the web, no if access only via tools);
- Digital access (via API for tools);
- Date since which the database has been used in regulation;
- Scope (e.g. cradle-to-gate, cradle-to-grave etc.);
- How generic datasets are generated;
- Whether penalty factors are used for generic datasets.

3.3.6. Data on the availability of embodied carbon data and EPD in the UK

Embodied carbon data (e.g. EPD or generic datasets) for construction products manufactured in the UK were identified by a combination of activities:
• Review of the interviews with ECEPs (see 3.2)
• Review of the EPD programmes identified in in 3.3.2;
• Check of the LCA Database (Metsims, no date) and EC3 (Building Transparency, 2022b)
• Review of the academic literature.

For EPD which covered UK production, the following information was recorded:

• Product type (e.g. aggregates, plastics, metals etc.);
• Type of EPD (e.g. collective for UK or EU etc.);
• EPD owner;
• Number of EPD and product(s) covered;
• EPD Programme used.

To find EPD which covered UK production, for smaller programmes, the EPD owners for each EPD listed were checked for UK companies or product names. For larger programmes, the listings were checked by searching for ‘United Kingdom,’ ‘UK,’ ‘GB,’ ‘British,’ ‘Ltd’ and ‘Limited’ in relevant search fields.

For databases the data collected was:

• Number of collective EPD included;
• Number of specific EPD included;
• Number of generic datasets;
• Approach to generation of generic datasets;
• Funding;
• Access to the public (free or paid);
• Digital access (via API for tools);
• Scope (e.g. cradle-to-gate, cradle-to-grave etc.); and
• Whether penalty factors are used for generic datasets.

3.3.7. Data on cradle-to-gate impacts from EPD (Modules A1-A3)

Cradle-to-gate (Modules A1-A3) environmental data from EPD for a number of different products groups have been analysed as part of this research. Modules A1-A3 provide the impact data for extraction of raw materials, transport to the manufacturing site, and all manufacturing processes, thus they should show any variability in impact due to differences in, for example, technology or geography.

As the provision of data for modules A4-A5, B1-B7, C1-C4 and Module D is voluntary within EPD to EN 15804:2012+A1:2013 and ISO 21930, and as many EPD do not report these modules, or use different scenarios (see findings in section 6.4.3) this study has only reviewed the reported results for modules A1-A3.

The product groups were identified through the literature review as the types of construction products having the largest impacts in terms of climate change in the UK. The detailed product types and sub-types considered are described in Table 10. Table 11 describes the detailed cement classifications used.
### Table 10 Product types and sub-types analysed

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Sub-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>CEM I, CEM II, CEM III, CEM IV, CEM V, White Cement, other cementitious material (see Table 11 below)</td>
</tr>
<tr>
<td>Concrete</td>
<td>Ready-mix concrete</td>
</tr>
<tr>
<td>Steel</td>
<td>Structural steel, Reinforcing Steel</td>
</tr>
<tr>
<td>Timber</td>
<td>Kiln dried sawn timber, Glulam, LVL, CLT</td>
</tr>
<tr>
<td>Brick</td>
<td>Facing brick, Ziegel brick</td>
</tr>
</tbody>
</table>

### Table 11 Cement classifications from EN 197-1:2011

<table>
<thead>
<tr>
<th>Cement Classification</th>
<th>Description</th>
<th>e.g.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I Portland Cement</td>
<td>Portland cement and up to 5% minor additional constituents</td>
<td>limestone, fly ash or ground granulated blast furnace slag (GGBS)</td>
</tr>
<tr>
<td>White Cement (CEM I)</td>
<td>Cement made from pure, non-iron containing raw materials (e.g. china clay and white limestone)</td>
<td></td>
</tr>
<tr>
<td>CEM II Portland composite cement</td>
<td>Portland cement and up to 35% of certain other single constituents</td>
<td></td>
</tr>
<tr>
<td>CEM II/A</td>
<td>CEM II with clinker content 80-94%</td>
<td></td>
</tr>
<tr>
<td>CEM II/B</td>
<td>CEM II with clinker content 65-79%</td>
<td></td>
</tr>
<tr>
<td>CEM III Blast furnace cement</td>
<td>Portland cement and over 35% blast furnace slag (GGBS)</td>
<td></td>
</tr>
<tr>
<td>CEM III/A</td>
<td>CEM III with PC clinker content 35-64%</td>
<td></td>
</tr>
<tr>
<td>CEM III/B</td>
<td>CEM III with PC clinker content 20-34%</td>
<td></td>
</tr>
<tr>
<td>CEM III/C</td>
<td>CEM III with PC clinker content 5-19%</td>
<td></td>
</tr>
<tr>
<td>CEM IV Pozzolanic cement</td>
<td>Clinker and over 35% pozzolana</td>
<td>As CEM II</td>
</tr>
<tr>
<td>CEM IV/A</td>
<td>CEM IV with PC clinker content 65-89%</td>
<td></td>
</tr>
<tr>
<td>CEM IV/B</td>
<td>CEM IV with PC clinker content 45-64%</td>
<td></td>
</tr>
<tr>
<td>CEM V Composite cement; Portland cement and</td>
<td>Portland cement and combinations of blast furnace slag and pozzolana or fly ash</td>
<td></td>
</tr>
<tr>
<td>CEM V/A</td>
<td>CEM V with 40-64% PC clinker content</td>
<td></td>
</tr>
<tr>
<td>CEM V/B</td>
<td>CEM V with 20-39% PC clinker content</td>
<td></td>
</tr>
</tbody>
</table>

EPD for specific product types were sourced from the EPD programmes identified in 3.3.2. Within each programme, searches were undertaken by means of the PCR used (e.g. for structural metals, timber), by searching for product names (e.g. steel, timber) and translations in the languages of the relevant EPD Programmes (e.g. French for the EPD Programme ‘inies’ in France). For the EPD for cementitious materials and ready-mix concrete products described in Chapter 6, Chapter 7, and Chapter 8, EPD Programmes were accessed in August 2019 and all relevant published EPD were downloaded. A further check was undertaken in November 2019 to download any further EPD published in the interim. For
the EPD for steel products, bricks, and structural timber products described in Chapter 6 and Chapter 8, EPD programmes were accessed in December 2020 and all relevant published EPD were downloaded.

For each downloaded EPD, data were extracted according to a defined set of criteria into excel spreadsheets. The data extraction criteria were intended to provide data that could be relevant for further analysis, and ensure a solid foundation for the research.

The data extraction criteria covered:

- Product type and sub-type (timber and CLT, or steel and reinforcing steel, or cement and CEM I for example);
- EPD Programme and EPD reference number;
- ISO or EN Standard used, and amendment used (e.g. EN 15804+A1);
- EPD type (manufacturer specific or collective);
- Number of site(s) and/or manufacturers providing data;
- Name of the product;
- Organisation providing the EPD (e.g. manufacturer or trade association);
- Country(s) of the site(s) providing data;
- Date of the EPD (for cement and concrete) or the year of data collection for other EPD;
- Declared unit (e.g. per tonne, per kg, per m³ etc.);
- Mass of declared unit (for non-mass declared units);
- For Modules A1-A3, the environmental data:
  - Embodied carbon (the Global Warming Potential indicator from the EPD);
  - Primary Energy Renewable (Total) (PERT);
  - Primary Energy Non-Renewable (Total) (PENRT);
  - Use of Secondary Fuels (renewable) (RSF);
  - Use of Secondary Fuels (non-renewable) (NRSF).

For cement EPD, the following additional data were extracted:

- Use of secondary material (SM) indicator results;
- Embodied carbon impact attributable to use of waste/secondary fuels and whether this was included or excluded from the reported embodied carbon results (if given);
- Clinker content (if given);
- Approach to allocation for the use of GGBS or PFA (if given);
- Life cycle inventory (LCI) database and version used.

For concrete products, the following additional data were extracted:

- Use of secondary material (SM) indicator results;
- 28-day strength;
- % cement replacement (if given);
- Size of aggregate (minimum and/or maximum dimensions) (if given).

For steel products, the following additional data were extracted:

- Use of secondary material (SM) indicator results;
- Recycled content (if given).

For timber products, the following additional data were extracted:

- Primary Energy Renewable (Energy) indicator results;
- Primary Energy Renewable (Materials) indicator results which provides the energy content of the timber product itself;
• Moisture content (if given);
• Density (if given);
• Content of any resins or adhesives used (if given);
• Sequestered carbon within the timber (if given).

The sequestered carbon for the declared unit was checked for plausibility if provided, or if not provided, calculated using the equation below, based on the approach in EN 16449 (CEN/TC 175, 2014) if the required data on density, moisture content, resin/adhesive content were given.

\[
\text{Biogenic carbon (in kg CO}_2\text{/m}^3\text{)} = \left(\frac{\rho}{100\% + mc} \times \frac{100\% - A}{100\%}\right) \times 0.5 \times \frac{44}{12}
\]

\(mc\) = moisture content provided as a % of dry mass of timber
\(A\) = content of resins or adhesives as a % by mass of structural timber as delivered
\(\rho\) = density of structural timber as delivered in kg/m\(^3\)

For each product, a common declared unit was chosen and if necessary (for example where some steel EPD reported results per kg), indicator results were converted to apply to that unit, as shown in Table 12.

\textbf{Table 12 Product Types and Sub-types and the Declared Units used for this study}

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Sub-type</th>
<th>Declared Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>CEM I</td>
<td>Tonne</td>
</tr>
<tr>
<td>Steel</td>
<td>Structural steel</td>
<td>Tonne</td>
</tr>
<tr>
<td></td>
<td>Reinforcing steel</td>
<td>Tonne</td>
</tr>
<tr>
<td>Brick</td>
<td>Facing brick</td>
<td>Tonne</td>
</tr>
<tr>
<td></td>
<td>Ziegel brick</td>
<td>Tonne</td>
</tr>
<tr>
<td>Structural timber</td>
<td>Kiln dried sawn timber</td>
<td>Cubic metre</td>
</tr>
<tr>
<td></td>
<td>CLT</td>
<td>Cubic metre</td>
</tr>
<tr>
<td></td>
<td>Glulam</td>
<td>Cubic metre</td>
</tr>
<tr>
<td></td>
<td>LVL</td>
<td>Cubic metre</td>
</tr>
</tbody>
</table>

When all products groups have been analysed together, structural timber impacts have been converted from per cubic metre to per tonne using the typical density of the timber.

\textbf{Treatment of outlying datasets}

In the process of analysing data within the studies discussed, several datasets from were found which were significant outliers, and in these instances the relevant EPD programmes were contacted to check if there were possible errors in the published EPD. In several of these cases, errors were identified and revised EPD have been issued.

\textbf{Limitations of the study}

Although the study includes all the EPD for key product groups published within known EPD programmes globally at the time of assessment, it should be recognised that the EPD included in the study are not likely to be a complete representation of product manufacturing for these product groups by any means. This is for a number of reasons:

• In terms of geographical representativity, there were no EPD found for products produced in Africa, central America, China, or other parts of Asia. There are many more EPD for Europe and North America than there are for other parts of the world. This is largely due to the fact that it
is only in Europe and North America that there is regulation in the area of building and product impacts, although these do not require the production of EPD.

- EPD are currently voluntary in all countries. France and Belgium are the only countries which have any regulation to require the production of EPD if you make public environmental claims about a construction product, but there is no requirement to make these claims, so EPD remain voluntary.
- Although the cost of EPD has reduced significantly due to the use of EPD tools provided by LCA tool providers such as One Click LCA or Climate Earth, or by industry associations such as WBCSD CSI, producing EPD still has a cost which may be prohibitive to SMEs or smaller players.

### 3.3.8. Data collection to consider of end of life data in EPD

EPD for two types of polystyrene insulation (expanded polystyrene (EPS) and extruded polystyrene (XPS)) and for four types of wood panel products (Oriented strand board (OSB), plywood, medium density fibreboard (MDF) and chipboard or particleboard) were identified from those available in the public domain between December 2018 and January 2019. The identification of EPD was made by reviewing the EPD programmes identified as discussed in 3.3.7. For each EPD found, the product (e.g. EPS or XPS), the EPD programme and the location of the manufacturer were recorded and the provision of scenario data for any of the end of life modules C1-C4 and Module D was checked. Where Module C and/or Module D was declared, the scenario(s) for Module C and Module D were classified into one of the types below:

- ‘100%’ scenarios: where only one approach is reported for the module or modules in the EPD, e.g. 100% of the product is sent to landfill. These scenarios can cover consecutive processes in one or more modules, for example, where 100% of the waste is used for energy recovery in C3 and then the resulting incinerator ash is landfilled in C4, and the output of recovered energy is considered in Module D; or where in C3, the waste is transported first by road and then by sea to waste treatment.
- ‘Mixed’ scenarios: where a combination of two or more approaches is considered in a single scenario reported for the module in the EPD, with a proportion using each approach – e.g. 50% of the EoL product is sent to landfill (C4) and 50% is recycled (C3), or 25% is sent to landfill (C4) and 75% sent to incineration without energy recovery (C4). These scenarios are often used to represent a typical national situation;
- ‘Multiple’ 100% scenarios: where two or more 100% scenarios are reported for the module in the EPD, e.g. the EPD reports the both the impacts of sending 100% of the waste to be recycled (C3) and of sending 100% to landfill (C4).
- ‘Mixed+100%’ scenarios: where a mixed scenario is reported for the module in the EPD together with 100% scenarios for the contributing approaches, as described in CEN/TR 15970 clause 6.3.8.

Additionally, for each module, the scenarios were described, as EN 15804+A2 7.3 states that if any module in Module C is reported,

> information shall be provided for all construction products to specify the end-of-life scenarios used or to support development of the end-of-life scenarios at the building level.

For example for C2 the distance and capacity of any road transport from the site to the point where demolition/deconstruction waste is processed or incinerated were recorded, for C4 the use of landfill or incineration was recorded.

Module not declared (MND) was used if this was used for the module in an EPD. If the indicators for the module were not assessed in the EPD and INA was used, INA was recorded. If no information was
provided in an EPD to describe the scenario that supported a declared module in the EPD, ‘no info’ was recorded.

The results were recorded in a table for all the EPD found for each product group.

**Limitations of the Study**

See 3.3.7.

### 3.4. Data analysis methodologies

#### 3.4.1. Thematic analysis of interviews

Irvine (2011) explores the use of thematic analysis, as shown in Figure 10, noting that though the process automatically reduces the amount of data used in the final report compared to that provided in the original interview, the loss ‘might be considered to be minimal,’ if the interviewer ensures the key themes are covered to an extent that meets the project’s requirements.

![Thematic Analysis Diagram](image)

*Figure 10 Data reduction in thematic qualitative analysis, from (Irvine, 2011) based on Hinds et al. (1997)*

Using the thematic qualitative analysis approach suggested by Irvine (2011), the interviews were transcribed, and then synthesized and analysed using a process similar to that outlined in Braun and Clarke (2006). This method is a pragmatic and realistic research approach, particularly appropriate in a practice-based and complex contexts such as decision-making in the construction industry. Initial codes were derived based on the subjects raised in discussion and very often as a literal code from the content. Themes were then identified based on similarities of this content, followed by a review that considered differences in themes between interviewees.

This provided a number of themes identified across the interviews and these themes and the findings are presented and discussed in Chapter 3.5.

#### 3.4.2. Types of data visualisation used to aid analysis and interpretation of data

The following types of data visualisation have been used to aid analysis and interpretation of EPD data in Chapters 6, 7 and 8.

**Stacked area chart**

These charts (see Figure 11) have been used to show the number of EPD within a country’s EPD Programme(s) at each point when data has been collected. By using the month and year of data collection on the x axis using a continuous timescale, the evolution in EPD numbers within the different programmes can be clearly illustrated over time.
Stacked bar chart

These charts (see Figure 12) have been used to show the numbers of EPD within each programme cumulatively over time.

Box and whisker charts

Box and whisker charts (see Figure 13) have been used to show, for example, the distribution of GWP from EPD for a product. A brief overview of the statistical terms used in the thesis is given in Appendix C: Statistical Terms. The shaded box shows the interquartile range. The median of the data is shown by the horizontal line across the shaded box. The mean of the data by the cross within the shaded box. The range is shown by the vertical line, these upper and lower ‘whiskers’ extend to the minimum and maximum values in the range which are not outliers, following the Tukey industry rule, which states that values are considered outliers only if they lie 1.5 times the interquartile range from either end of the interquartile range. An indication of any outlier values is given by the small circles.

EPD Landscapes

Box and whisker graphs have been used to provide EPD Landscapes, showing the variation between the embodied carbon coefficient for products with EPD, for example classified by the amount of recycled content used for steel, or the cement type.

XY Scatter Graphs

Scatter graphs have been used to consider any correlation between variables, for example between Primary energy consumption and Global Warming Potential for a product type.
The degree of linear correlation has been considered by the coefficient of determination \((R^2)\) which is the square of the Pearson correlation coefficient \((R)\), both of which are described below. The degree of linear correlation which can be seen using \(R\) and \(R^2\) is illustrated in Figure 14.

**Pearson correlation coefficient \((R)\)**

The Pearson product-moment correlation coefficient (or Pearson correlation coefficient, for short) is a measure of the strength of a linear association between two continuous variables and is denoted by \(R\).

\[
R = \frac{\sum (x_i - \mu_x)(y_i - \mu_y)}{\sqrt{\sum (x_i - \mu_x)^2 \sum (y_i - \mu_y)^2}}
\]

\(R\) = Pearson correlation coefficient
\(x\) = values of the \(x\)-variable in the sample
\(\mu_x\) = arithmetic mean of values of \(x\)
\(y\) = values of \(y\)-variable in the sample
\(\mu_y\) = arithmetic mean of values of \(y\)

**Coefficient of determination \((R^2)\)**

The degree of linear correlation between two datasets can be considered by finding the linear regression for the variables considered and using the square of the Pearson correlation coefficient \((R)\), to measure the linear regression. As a square, the coefficient of determination \((R^2)\) is always positive.

**Treemap chart**

Treemap charts have been used to visualise the number of EPD for the different types of construction products. The identified EPD for the UK were then grouped into product groups (Finishes and fittings, Concrete and its raw materials, Metals, Windows, and glass etc., Gypsum products, Timber products, Panel products and Other) and relevant sub-product groups, such as Flooring and suspended ceilings for Finishes and fittings. Data were then sorted on the number of EPD per product category and sub-product category, and excel was used to create the treemap chart.

![Example treemap chart](image)

**Figure 15 Example treemap chart**

3.4.3. Data visualisation used to aid analysis and interpretation of renewable energy consumption and non-renewable energy consumption

A specific data visualisation has been developed as part of the research to analyse the use of renewable and non-renewable energy, see Figure 16. Renewable and non-renewable energy data (excluding primary energy used as material, e.g. PERM for timber) from the EPD, both from primary energy and secondary fuels for each product type and sub-type are shown on an XY scatter graph. Added to the graph is:

- the average energy consumption for the product sub-type per relevant declared unit (shown by the thick black line in Figure 16 representing an average total energy demand for the example product sub-type of 20000 MJ/tonne)
- 50% of the average energy consumption for the product sub-type per relevant declared unit (shown in Figure 16 by the thin black line representing 10000 MJ/tonne), and;
• lines showing 10%, 20%, 33% and 50% renewable energy usage as a percentage of total energy usage, (shown by the thin blue lines in the example in Figure 16).
• Energy consumption above the average is highlighted by the pink colour on the graph;
• Energy consumption below 50% of the average is highlighted by the yellow shading on the graph, and
• Renewable energy consumption above 50% of total energy consumption is highlighted by the green shading on the graph;
• Where the yellow and green shading overlaps to give a lime green colour, it highlights where both energy consumption is less than 50% of average energy consumption, and renewable energy is more than 50% of total energy.

This visualisation approach allows the distribution of renewable and non-renewable energy to be considered consistently for each product. The findings are discussed in Chapter 8.

![Energy per tonne (A1-A3)](image)

*Figure 16 Example of the data visualisation developed to consider the distribution of renewable and non-renewable energy use consistently for key construction product groups*

3.4.4. Embodied Carbon ProductDatasheets developed to consider the availability of embodied carbon data in the UK

Embodied Carbon Product Datasheets have been developed as part of the research to provide information on the availability of embodied carbon data for different product groups and sub-groups. The example Product Datasheet overleaf shows the information provided in the Datasheet and its source.
<table>
<thead>
<tr>
<th>Product Group</th>
<th>e.g. Cement and concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Sub-Group</td>
<td>e.g. Cement</td>
</tr>
<tr>
<td>UK Product Sub-Group value in 2021</td>
<td>Source: Office for National Statistics (2022)</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>Source: Office for National Statistics (2022)</td>
</tr>
<tr>
<td>UK imports (2021)</td>
<td>Value of imports of the product into the UK in 2021, including their value as a percentage of total construction product imports, source: BEIS (2023)</td>
</tr>
<tr>
<td>One of the top 30 UK construction product imports?</td>
<td>Identifies whether the product is one of the top 30 construction products in terms of the value of imports, and its % of UK construction product imports overall, source: BEIS (2023)</td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>Availability of any EPD produced by trade associations or sector bodies for the Product Sub-Group</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td>Access to pre-verified EPD tools arranged by the UK Sector</td>
</tr>
<tr>
<td>Other pre-verified EPD tools</td>
<td>Availability of verified EPD tools which could be used to generate EPD for the UK</td>
</tr>
<tr>
<td>UK generic data (not EPD)</td>
<td>Any datasets in the ICE database (Hammond and Jones, 2019) or BRE IMPACT database (BRE, 2020) or other datasets produced by the sector for the UK</td>
</tr>
<tr>
<td>EPD for UK Manufactured Products</td>
<td>Any valid manufacturer specific EPD found for UK manufactured products at the start of 2023</td>
</tr>
<tr>
<td>Availability of other specific EPD and embodied carbon data</td>
<td></td>
</tr>
<tr>
<td>Collective EPD for imports (EU)</td>
<td>Collective EPD from the EU or EU countries identified in ‘source of any imports in 2020’</td>
</tr>
<tr>
<td>Specific EPD (EU) from key import markets</td>
<td>Manufacturer specific EPD for production in relevant European countries identified in ‘source of any imports in 2020’</td>
</tr>
<tr>
<td>Collective EPD for imports (non-EU)</td>
<td>Collective EPD from regions or non-EU countries identified in ‘source of any imports in 2020’</td>
</tr>
<tr>
<td>Specific EPD non-EU from key import markets</td>
<td>Manufacturer specific EPD from relevant non-EU countries identified in ‘source of any imports in 2020’</td>
</tr>
<tr>
<td>Other generic data from outside the UK</td>
<td>Availability of other generic data (not EPD), e.g. from national databases in other countries</td>
</tr>
<tr>
<td>Datasheet developed by:</td>
<td>Jane Anderson</td>
</tr>
<tr>
<td>Valid at</td>
<td>March 2023</td>
</tr>
</tbody>
</table>

The embodied carbon product datasheets are discussed in chapter 5.5.

3.5. Research timeline

The data collection and analysis of EPD numbers has been ongoing since 2011, when I charted the number of EPD in different European EPD programmes as part of a publication for the Construction Products Association (Anderson and Thornback, 2012). Data collection and analysis of EPD numbers has been ongoing with regular annual collection since January 2017. This analysis then generated the data on EPD numbers which was used to identify the countries with the EPD Programmes with the largest number of EPD, and this data was used as the basis of the investigation into the growth of EPD in these countries.

As one of the most impactful materials globally, EPD for concrete and its main constituent in impact terms, cement, were the first to be collected in Summer 2019 and initially analysed in the following months. Subsequently, EPD for steel, brick and timber were collected at the end of 2019, with a further
check for cement and concrete EPD, and were analysed in early 2020. Further analysis of EPD has been undertaken using the same data from the end of 2019 over the period of the PhD.

Interviews with expert practitioners in embodied carbon (ECEPs) were undertaken in May and June 2020. Further data collection and analysis for the other research questions has been ongoing since then.

In the following chapters, the findings from the research are presented.
4. Use of EPD in practice

4.1. Introduction

This chapter responds to the first research question: How are EPD being used in practice?

Embodied carbon assessment, including its use of Environmental Product Declarations (EPD), is an evolving field, and has become more prominent in the UK construction industry in recent years, but as with all new concepts, adoption has not been uniform. Leading architectural and engineering practices and consultancies have been the first to embrace the idea, often developing their own tools to consider embodied carbon, alongside use of commercial embodied carbon tools. As the literature review highlighted, for embodied carbon, as for the construction industry generally, there is a significant divide between, for example, the use of standards for embodied carbon assessment in academic practice, and that of practitioners within industry. Through interviews with Embodied Carbon Expert Practitioners (ECEPs) - experienced practitioners in the UK who have developed embodied carbon tools and are championing the use of embodied carbon assessment in their organisations - the intention has been to build a fuller picture of emerging practice and design decisions at the leading edge of embodied carbon assessment in the UK and gain a valuable insight into the direction of the industry. The findings have also given direction to the overall research presented in the thesis.

The chapter is based on a qualitative analysis of the attitudes and views, experiences and knowledge expressed by these ECEPs during semi-structured interviews. The methodology for the interviews is described in section 3.3.1 and the analysis in 3.2.

4.2. Embodied carbon: knowledge and intuition

Knowledge of working with embodied carbon varies and currently comes from a range of sources

In an emerging field like embodied carbon assessment, it is important to understand how practitioners have obtained the knowledge they need to make assessments and advise on reducing impact. All the Embodied Carbon Expert Practitioners (ECEPs) were initially asked about when and how they had obtained their knowledge of embodied carbon. ECEP’s embodied carbon knowledge came from a range of sources and practices. Only one ECEP, an architect, was taught about embodied carbon at university, though others were taught about material efficiency or materials processing, one saying they were ‘too old.’ The role of experience in developing embodied carbon knowledge is explored further below, but there was some evidence that skills were often handed from person to person, for example one had ‘great colleagues who helped me learn all that they knew about it.’

However a key finding was that several of the ECEPS highlighted the utility and value that the actual process of developing an embodied carbon tool had on their knowledge of embodied carbon, and the speed with which that knowledge was imparted. ECEPs variously observed that the embodied carbon tool development process ‘was very, very useful,’ ‘fundamental,’ ‘probably the most useful exercise I did.’ One commented, ‘I think it’s really interesting that so many people have developed their own tools. I wonder if it’s a bit about knowledge generation internally as well as just the process of making it, [it] means that we’re also skilled up in it very quickly.’

Although it wasn’t the subject of a direct question, two of those interviewed highlighted the need to have a good knowledge of construction to consider embodied carbon – warning both consultants coming to embodied carbon assessment from a background in life cycle assessment (LCA), and even some architectural staff, don’t always have that understanding of how buildings are put together, and that often, architects don’t know ‘how long bits of buildings last for.’ A lack of knowledge about construction means that tool users may not be able to identify the need to adjust volumes of materials in the studies, for example where a tool takes quantities from a CAD or BIM model, the double glazing
might be modelled as solid material rather than as two sheets of glass with an air gap. Both embodied
carbon tools and guidance need to ensure that they can be operated successfully by users without
detailed knowledge of both LCA and construction.

Perceptions of the difficulty of working on embodied carbon varied. One ECEP mentioned that it was
not that hard to calculate embodied carbon, ‘Actually embodied carbon isn’t difficult. If you’ve got the
figures, it’s multiplying two numbers together’ and another highlighted ‘these kinds of tools are easy
to learn anyway.’ But others hinted at the difficulty, saying, for example, ‘there was a very steep
learning curve,’ ‘it does require a bit of practice in doing the calculations.’ The complexity of assessing
and reducing embodied carbon was exemplified through some of the difficulties described by ECEPs
within their own work, described below.

No simple answers

Both tacit knowledge and guiding principles can be ways to work with complex systems, like
construction, and they are often used because there are rarely simple, universal solutions. This was a
point made separately by many of the participants. As an example, three of the ECEPs discussed the
difficulties of reducing the embodied carbon of structures by reducing column grid spacing, with one
saying:

‘I would expect that by reducing the [column] grid, you would get lower impacts. But after a point,
if you reduce it too much, then you might get more impact again because you increase the [number
of] columns [across a given floorplate].’

Another highlighted how the optimal solution found for one building might not work for another, with
a different floor plate and/or loading:

‘I do framing analysis or different grid comparisons and so many people think, ‘Well, that’s just the
answer.’ No, you can’t, it doesn’t count. Not one size fits all.’

And another explained the complexity of embodied carbon recommendations based on standardised
structural solutions, ‘If it’s just a standard building, then it’s always going to be like that, isn’t it? But
no building is ever like it.’ This is echoed by another of the ECEPs who highlighted that, ‘the complexity
of projects, I think it does change the story all the time.’

Similarly, there were several discussions around difficulties with particular materials. One engineer
pointed out that although ‘they roughly go hand in hand, volumes of materials, and embodied carbon;
obviously there are some exceptions, you get different materials that are really high.’ Another drew
attention to the embodied carbon intensity of aluminium in particular; ‘everyone uses aluminium
framing for everything these days,’ but ‘no one knows that aluminium is terrible.’

There were also concerns around the general assumption that using of timber was beneficial for
embodied carbon. Although one ECEP mentioned that ‘using timber is a great thing if you want to
reduce your embodied carbon,’ another highlighted, ‘I was pretty surprised when I first started learning
more about timber emissions and understanding that a [cradle-to-grave] assessment for timber … can
be worse than a steel frame and concrete slab building or a fully concrete building.’

Also illustrative of the difficulties of assessing embodied carbon are the comments made by ECEPs
about their reviews of work by those newer to embodied carbon assessment, discussed below.

Experience, Intuition and Tacit Knowledge

Many of the ECEPs discussed the usefulness of experience, particularly in identifying problems and
errors in assessments, with one ECEP commenting, ‘What I notice when I’m reviewing the younger
staff’s work, they don’t have a feel for the numbers, so I can look at numbers in the quantities of carbon
for different materials and you immediately get a sense of ‘that seems incredibly high’ or ‘why is it like that’; another said, ‘You just get a sense of those numbers after a while’ and another, ‘I think it’s just a mixture of experience of knowing, being around those numbers and seeing again in a sense check, if something doesn’t feel right.’

Tacit knowledge is defined by Howells (1996) as ‘non-codified, disembodied know-how that is acquired via the informal take-up of learned behaviour and procedures.’ The use of phrases like ‘feel for the numbers,’ ‘you get a sense of that seems incredibly high,’ ‘if something doesn’t feel right,’ suggest that tacit knowledge and intuition play a strong part in reviewing the results of embodied carbon studies and providing guidance on reduction, and when several ECEPS were asked directly, they agreed, with one ECEP saying, ‘there’s certainly an element of intuition.’ It was clear however that the tacit knowledge gained from experience was key to developing this intuition although there were varying views on how long this could take, for example: ‘you just get a sense of those numbers after a while’; ‘if you have assessed 20 buildings...I think you can have intuition about the results’; ‘if you have carried out a few projects over a few RIBA stages, you can have intuition.’

Using intuition can be a useful and even necessary part of any design process, particularly during the early stages when much information about the building and its materials is uncertain. It can, however, be negative, when it means the decision-making process is hidden and becomes invisible in the design process. How practitioners deal with ensuring the appropriateness of intuition becomes important. This was recognised by some ECEPs. One ECEP, for example, was concerned that intuition is what has been used to address embodied carbon in most buildings for the past 40 years, ‘it’s just been done through intuition.’

4.3. The complexity of using guiding principles

One ECEP observed a link between intuition and another well-known mechanism in design decision-making, ‘I think a lot can be done by intuition, if you know the general principles.’

Using guiding principles in design, for example heuristic strategies such as rules of thumb, is a well-used approach to decision making in design (Lawson, 2005, pp. 184–185). The interviews with ECEPs have suggested a number of ‘guiding principles’ to reduce embodied carbon, many of which align with the mitigation strategies found in the literature review (see Table 13).

Table 13 Some Mitigation Strategies from the Literature and corresponding Guiding Principles suggested by the ECEPs

<table>
<thead>
<tr>
<th>Mitigation Strategy from Table 1</th>
<th>Guiding Principles mentioned by ECEPs</th>
</tr>
</thead>
</table>
| Challenging the Client Brief    | ‘Sometimes it’s common sense like thinking about do we need to do this’  
                                    | ‘Using a hierarchy based on the PAS 2080, ‘Build nothing, build less, build clever framework’ |
| Reuse and refurbishment         | ‘I think that we should think of those projects [retrofits of historic buildings and large-scale refurbishments] as huge key carbon saving projects’ |
| Using biobased materials        | ‘Using timber is a great thing if you want to reduce your embodied carbon.’ |

However the ECEPs also raised a number of examples where the use of these principles could result in increased embodied carbon. In this section, these guiding principles have been explored in more detail to illustrate the complexity of embodied carbon assessment, drawing on the ECEPs comments where
relevant. These highlight the need to make assessments using embodied carbon data for products, such as from EPD, rather than use guiding principles without measurement.

**Low carbon materials**

A particularly simple example of using a guiding principle is using materials with a lower carbon intensity (e.g. kgCO₂e/tonne). However, even with this simple example, it is also important to take into account the quantity of the lower carbon material that will be required, as this example shows. If a comparison was made on a per tonne basis, for reinforced concrete, glulam timber and structural steel, concrete would be seen to be the low impact material, with impacts around 152 kgCO₂e/tonne for reinforced concrete with 1.6% steel reinforcement, compared to glulam at 512 kgCO₂e/tonne and structural steel at 1550 kg CO₂e/tonne (using the Institution of Structural Engineers’ generic data for these materials provided in Arnold et al. (2021). However, per tonne comparisons are rarely useful, because comparisons should be made on the basis of the functionality provided by different materials.

Because so much more concrete is needed to provide the same structural performance as a beam made of steel or glulam, steel, glulam, and concrete can in fact can have very similar embodied carbon when considered in terms of their structural performance as a beam. This is shown in the example provided in Table 14 below which has been developed by the Institution of Structural Engineers for beams with a 9 metre long span and a common loading (Arnold et al., 2021). It should be noted however that comparisons for a different span and loading may not result in the three materials having similar impacts.

*Table 14 Comparison of functionally equivalent steel and concrete beam for modules A-C, sourced from Arnold et al. (2021)*

<table>
<thead>
<tr>
<th>Element</th>
<th>Source</th>
<th>Cross sectional area (m²)</th>
<th>Mass of 9 m long beam (kg)</th>
<th>Embodied Carbon (A-C) per kg (kgCO₂e/kg)</th>
<th>Embodied carbon of beam (A-C) (kgCO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel beam, UKG 610x178x82</td>
<td>Average European steel, Bauforumstahl EPD.</td>
<td>0.01</td>
<td>738</td>
<td>1.13</td>
<td>830</td>
</tr>
<tr>
<td>Glulam beam (750x480mm)</td>
<td>100% FSC/PEFC</td>
<td>0.36</td>
<td>1620</td>
<td>0.512</td>
<td>830</td>
</tr>
<tr>
<td>Concrete beam, 600x400mm 1.6% reinforcement</td>
<td>C32/40 concrete, 25% GGBS UK Cares average collective EPD</td>
<td>0.24</td>
<td>5184</td>
<td>0.12</td>
<td>830</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.004</td>
<td>271</td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

Several of the ECEPs mentioned they had undertaken building level comparisons of concrete and timber or steel structures, and although they have such different carbon intensities at material level, there wasn’t any clear solutions found across all ECEPs: for example,

‘So we started swapping out much of the frame for different materials ... and ended with quite a heavy amount of timber with other different kinds of things. So yeah, it was quite complicated, although the concrete was generally lower than any other options.’

‘We kept the concrete core and other things, for fire regulations, ...but they were higher in embodied carbon than using steel and fibreboard’

‘sometimes steel is worse than concrete’

As even a simple guiding principle like use of low carbon materials doesn’t necessarily result in straightforward solutions, some of the more complex guiding principles may be even more difficult to apply universally.
Using Biobased products

The lack of a clear winner when structures are compared highlights the potential problem with using biobased products as a mitigation strategy, with one ECEP saying,

‘I was pretty surprised when I first started learning more about timber emissions and understanding that a [cradle-to-grave] assessment for timber ... can be worse than a steel frame and concrete slab building or a fully concrete building.’

And another ECEP expressed concern that natural products did not always have lower impacts, saying, ‘there’s probably an assumption that if it’s natural, it’s better.... whether there’s numbers to back it up or not.’

The reasons for specifying biobased materials are various in the literature – but the main ones given are that it locks in sequestered carbon for the life of the building, and it can have lower embodied carbon than non-biobased alternatives (e.g. Spear *et al.*, 2019; Pomponi *et al.*, 2020). However, as seen in the example for use of low carbon materials above, a timber structure does not always provide a lower embodied carbon alternative than steel or concrete, although it will store sequestered carbon out of the atmosphere over the lifespan of the structure. It is therefore important to assess whether bio-based solutions really do reduce embodied carbon, and to quantify the amount of sequestered carbon they might store and what benefit it might bring. EPD are intended to provide reliable information on both the embodied impacts of manufacturing biobased materials and their sequestered carbon content, allowing fact-based comparison with non-biobased products and consideration of the benefit of carbon storage.

Minimally processed materials

Like biobased materials, perceptions of how much processing different materials require, and how much impact these processes have may not be supported by the actual evidence.

For example, the architect, Amin Taha, has said ‘Stone is versatile, has strength, longevity, is plentiful, cheap and, with zero embodied carbon, well placed for a renaissance’ (Ravenscroft, 2020). Yet the processes of cutting and finishing stone can be both energy intensive and wasteful, and as demonstrated below using data from EPD for UK Brick and Portland Stone, far from having zero embodied carbon, stone can have nearly double the embodied carbon of brick in a comparable wall with the same thickness (102.5 mm).

Table 15 Comparison of embodied carbon for Brick and Portland Stone using EPD

<table>
<thead>
<tr>
<th></th>
<th>Density kg/m³</th>
<th>Mass for 1 m² @102.5mm (kg)</th>
<th>A1-A3 ECO₂e/kg</th>
<th>A1-A3 ECO₂e/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK Brick EPD</td>
<td>1485</td>
<td>148.5</td>
<td>0.213 kgCO₂e</td>
<td>32.9 kgCO₂e</td>
</tr>
<tr>
<td>UK Portland Stone EPD</td>
<td>2300</td>
<td>235.75</td>
<td>0.268 kgCO₂e</td>
<td>63.2 kgCO₂e</td>
</tr>
</tbody>
</table>

This example in Table 15 shows how preconceptions of materials impacts can be mistaken, and emphasises the importance of using accurate data for manufacturing impacts to make assessments. As “minimally processed materials” can often be considered “natural”, like stone, the ECEP’s concern made earlier is equally justified here, ‘there’s probably an assumption that if it’s natural, it’s better.... whether there’s numbers to back it up or not.’
Use of secondary material

According to the CEN/TC 350 standards, secondary material is ‘material recovered from previous use or recovered from waste.’ The two types of secondary material commonly used for construction are reused material and recycled materials.

Using reused materials

For reused construction materials, there is general consensus that they have lower impact than their primary (virgin) alternative, as they require so very little processing to enable reuse in comparison to the impacts of primary manufacture. There are a small number of EPD for reused materials, two of which have been used in Table 16 and Table 17 below to demonstrate that the impacts of their reuse are very low in comparison to primary production.

Table 16 Comparison of impact of reused and virgin bricks using EPD

<table>
<thead>
<tr>
<th>Per tonne bricks</th>
<th>Use of Secondary Material</th>
<th>ECO₂ (A1-A3)</th>
<th>Total Primary Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamle Mursten ApS Re-used brick (EPD Danmark EPD MD-16007-EN)</td>
<td>1000 kg</td>
<td>2.7 kgCO₂e</td>
<td>819 MJ</td>
</tr>
<tr>
<td>UK Average brick (BREG EN EPD No.: 000002 Issue 4)</td>
<td>0 kg</td>
<td>213 kgCO₂e</td>
<td>2550 MJ</td>
</tr>
<tr>
<td>Reduction in impact for reused product</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>98.7%</td>
<td>67.9%</td>
</tr>
</tbody>
</table>

Table 17 Comparison of reused and virgin access flooring using EPD

<table>
<thead>
<tr>
<th>Per panel (600x600 mm)</th>
<th>Use of Secondary Material</th>
<th>ECO₂ (A1-A3)</th>
<th>Total Primary Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMF Eco Range reused access flooring panels (International EPD S-P-02586 (V2.0))</td>
<td>10 kg</td>
<td>0.429 kgCO₂e</td>
<td>105 MJ/m²</td>
</tr>
<tr>
<td>Kingspan Access Flooring FDEB_H Access Floor Panels (International EPD S-P-02814)</td>
<td>1.46 kg</td>
<td>17.8 kgCO₂e</td>
<td>602 MJ/m²</td>
</tr>
<tr>
<td>Reduction in impact for reused product</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>75.9%</td>
<td>82.5%</td>
</tr>
</tbody>
</table>

Using recycled materials

The mitigation approach assumes that using recycled inputs reduces primary material resource use and can reduce impact, however this does depend on the product and processes required. For some materials, recycling can have the same, or even greater impacts than primary production. For example, recycling concrete and masonry to produce recycled aggregate requires very similar energy for crushing and sorting as processing primary aggregate and the embodied carbon coefficient can, in fact, be higher, as shown in Table 18, which uses data sourced from Swiss trade association EPD.

Table 18 ECO₂ for aggregates from Swiss Collective EPD

<table>
<thead>
<tr>
<th>EPD</th>
<th>Product</th>
<th>ECO₂ (A1-A3)/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSKB-2018-1-ECOINVENT</td>
<td>Typical Swiss crushed natural aggregate</td>
<td>1.81 kgCO₂e</td>
</tr>
<tr>
<td>FSKB-2018-1-ECOINVENT</td>
<td>Typical Swiss round natural aggregate 0/4 mm</td>
<td>1.71 kgCO₂e</td>
</tr>
<tr>
<td>FSKB-2018-1-ECOINVENT</td>
<td>Typical Swiss crushed recycled aggregate 0/x mm</td>
<td>2.2 kgCO₂e</td>
</tr>
</tbody>
</table>

The IStructE note that aggregates, although 80% of the mass of concrete cause less than 5% of its embodied carbon, with cement causing typically nearly 60% (Astle, 2021). If additional cement or
admixtures are required to make use of recycled aggregates in concrete for example, then this could actually mean the embodied carbon impacts of using a recycled aggregates could further increase.

It is therefore important that embodied carbon is calculated taking account of both the impact of the recycled product (as provided in EPD) and any implications of its use, (such as increased cement use in concrete) to ensure that it is a beneficial solution.

Secondly, there is a concern that encouraging the use of products with recycled content can increase impact where:

- the product with recycled content is a different type of product from the one with primary content or
- different densities may mean that recycled content as a percentage is not a good indicator of the use of recycled content by mass.

For example, in Table 19 below, UK manufactured precast concrete blocks and aerated concrete blocks are compared, both using EPD from the trade association, British Precast. The aerated concrete block has more than double the recycled content of the precast block as a percentage, but per square metre, actually uses only fractionally more secondary material by mass and has a nearly 30% higher embodied carbon impact. This emphasises the need to consider recycled content using assessments accounting for both the mass of recycled content used and the environmental impact of the resulting product, using EPD.

<table>
<thead>
<tr>
<th>Per m² @ 100mm thickness</th>
<th>Recycled content</th>
<th>Embodied Carbon (A1-A3)/m²</th>
<th>Mass/m²</th>
<th>Use of Secondary Material kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK Manufactured Precast Concrete Blocks (IBU EPD-BPC-20170092-CCD1-EN)</td>
<td>27.5%</td>
<td>13 kgCO₂e</td>
<td>142.5 kg</td>
<td>39.1 kg</td>
</tr>
<tr>
<td>UK Manufactured Precast Aerated Concrete Blocks (IBU EPD-BPC-20170093-CCD1-EN)</td>
<td>65.8%</td>
<td>16.8 kgCO₂e</td>
<td>60 kg</td>
<td>39.5 kg</td>
</tr>
</tbody>
</table>

Thirdly, where the amount of available secondary material is constrained, increasing recycled content may just be “burden shifting”. For example, although Wang et al. (2021) showed the amount of end of life steel arising had risen from 100 to 400 million tonnes per year over the period 1969 to 2015, the corresponding recycling rates did not increase, fluctuating between 70-80% over the same period. In many cases, unless new sources of recovered steel are found, specifying steel with increased recycled content to reduce impact will merely displace the use of steel scrap elsewhere, potentially also increasing impacts from importation. There is also a danger that retrofit and refurbishment, which one of the ECEPs showed for one project had ‘an over 50% reduction in embodied carbon per m², for A1-A5 by refurbishing and extending rather than building from scratch,’ may not be considered if an increased demand for steel scrap means that disused buildings with steel structures will be demolished to recover the scrap value of the steel before these options are contemplated.

One ECEP expressed concern that LEED credits were encouraging this type of burden shifting behaviour, noting for one project they reviewed, ‘the recycled content of the steel in the baseline was 40%. And then in the design they were doing 90% recycled content.’ To address this issue, the IEA have suggested the use of emissions intensity targets for steel which are differentiated by recycled content.
as shown below in Figure 17. In this way, products are selected on the basis of low emissions for a given recycled content, and emissions reduction is encouraged, rather than the use of recycled content. A similar chart has been provided for performance levels for crude steel GHG emissions intensity by ResponsibleSteel (2022).

![Figure 17: Emissions intensity ranges for low emission steel production, sourced from IEA (2022) (fig 3.7)](image)

**Material efficiency and lightweighting**

These approaches describe using less material to provide similar or greater functionality. Several of the ECEPs mentioned these approaches using these guiding principles, for example;

‘Using less material is good’

‘Making your designs more efficient and having deeper beams uses less material’

Where lightweighting and material efficiency strategies reduce the amount of a particular material (for example the amount of concrete in floor slab), then this measure should reduce impact, and may even have further positive benefits as suggested by this example from an ECEP:

‘What reduced the carbon the most was ... actually structural efficiencies like using a BubbleDeck®, that type of system or pre-tensioned concrete, ways of reducing the weight effectively, and the knock-on effect on foundations.’

However if the reduction in mass is achieved by changing material, then it becomes important to check if the replacement material may have higher impact, as pointed out by this ECEP:

‘They roughly go hand in hand, volumes of materials, and embodied carbon. Obviously there are some exceptions, you get different materials that are really high.’

This is echoed in the mitigation strategy provided by (Azari and Abbasabadi, 2018) which also considers whether there are negative ‘knock on’ effects, ‘Ensure lightweight materials have lower embodied energy than concrete and that secondary beams are not required.’

For example, 1 m² of 0.7mm aluminium profiled sheet roofing will have around 25% of the mass of 1 m² 0.9mm steel profiled sheet roofing, but will have a higher impact because the impact per kg aluminium (13 kgCO₂e/kg World average for aluminium sheet from ICE Database) is so much greater than steel (3.06 kgCO₂e/kg World Steel Global Average for hot dip galvanised steel sheet) (see Table

---

6 Note however that the scope of assessment used by the IEA approach varies from that used in EPD so the target ranges cannot be used directly with EPD.
However reducing the mass of the roof may also reduce the mass required for the building’s foundations, so this should also be taken into consideration.

Table 20 Comparison of steel and aluminium profiled sheet roofing using generic global data

<table>
<thead>
<tr>
<th>Per m²</th>
<th>thickness (mm)</th>
<th>m³/m²</th>
<th>density kg/m³</th>
<th>ECO₂/kg</th>
<th>ECO₂/m²</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.9</td>
<td>0.0009</td>
<td>7889</td>
<td>7.1001</td>
<td>3.06</td>
<td>21.7 kgCO₂e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>World steel: steel, hot dip galvanised, global</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.7</td>
<td>0.0007</td>
<td>2700</td>
<td>1.89</td>
<td>13</td>
<td>24.6 kgCO₂e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ICE v3, aluminium sheet, global</td>
</tr>
</tbody>
</table>

As in the discussion of previous guiding principles, these examples emphasise the need, particularly when swapping one material for another, to make embodied carbon assessments using EPD if available, to check the actual consequences rather than relying on guiding principles.

**Efficient construction**

Estimates of wastage on construction sites vary, but 5-10% is a common assumption (e.g. Construction Resources and Waste Platform, 2010), though one of the ECEPs highlighted the difficulty of ‘getting hold of the figures… we’re struggling with site wastage…’ Off-site prefabrication, sometimes known as modern methods of construction (MMC) is expected to reduce waste on site to much lower levels, but should be associated with reduced waste in the factory, although there is very little evidence to support this, as described in CWCT, Ladipo and Wild (2022).

There have been a number of studies looking at prefabrication and off-site construction in terms of embodied carbon, e.g. as described in Kamali and Hewage (2016) and Chen et al. (2022). The studies however often compare different cases, for example a steel modular building with a concrete conventional building, or an off-site timber building with conventional masonry construction. They also do not provide a consistent answer, with the off-site construction having higher embodied impacts than the conventional in several studies (e.g. Aye et al. (2012); Han et al. (2022). One of the ECEPs raised the much higher impact of a prefabricated masonry wall using brick slips on an aluminium support framework which was introduced as an alternative to a more conventional masonry wall, saying, ‘we saw almost three times more embodied carbon with the brick slips’, adding that ‘whoever does that and makes those decisions, the developer and the designers should be held responsible for that.’

It is therefore important to check that there is not greater resource intensity or carbon impact for off-site prefabricated alternatives, for example due to the need to provide stability during transport or from duplication of structure for modular units, which may result in increased impact even if overall waste is reduced. There are also concerns about the difficulty of deconstruction and recovery of modular construction at end of life (Green Construction Board, 2020). It is thus unclear whether offsite construction does offer advantages in reduced embodied carbon when all aspects of material usage, factory impacts, waste and transport are taken into consideration.

**Local sourcing**

Projects like BedZed promoted the use of local sourcing to reduce impacts from transport (Lazarus, 2002). Generally however, the impacts of transport are small in the context of manufacture except for products which have very low impact, and which are used in bulk, such as aggregates, where transport can be the major impact. One ECEP compared the impact of using local homegrown timber with imported CLT, and explained, ‘the transport impact didn’t seem to be as significant as we assumed it would be.’ EPD do not have to provide information on transport, but those which do enable an
understanding of the significance of transport impacts from factory to site, and allow more accurate comparisons of similar products from different locations, taking account both manufacture and delivery.

For example, generally the impacts of typical transport to site are small in the context of manufacture (up to 4% for concrete, brick, and steel as shown in Table 21 overleaf). As discussed in the literature review (Section 2.3.8), the impact of construction products from different manufacturers and factories can vary, with differences of ±10% common. Table 21 shows the road transport distance associated with the same carbon impact as 10% of the typical manufacturing impact. So for example, for UK ready-mix concrete, if a product had a GWP 10% better than the average, you could source it from up to 131 km further by road without it having greater impact than the average. For reinforcing steel, you could source a product with 10% lower GWP from up to 1610 km further by road.

However, if Table 21 is considered from a different perspective, if you sourced a product very locally to the construction site, for the overall embodied carbon coefficient of production and transport to still be better than sourcing the average product from the typical distance, the local manufacturer’s impacts could only be 0.9% worse in terms of GWP than the average ready-mix concrete producer, 2.2% worse than the average reinforcing steel manufacturer and 3.7% worse than the average brick producer, meaning that by specifying local products without looking at manufacturing impacts, it could be quite easy to increase embodied carbon, not decrease it.

Discussing concrete and the possible impact of transport, one ECEP said, ‘there might be a fantastic method of building concrete, but it’s a heavy material. If there isn’t a local supply that could still just push the carbon impact up to so much that you don’t see the benefit from those savings.’

For aggregates, it is clear that sourcing locally will reduce embodied carbon, but aggregates typically travel short distances by road in any case (the average for the UK is 28 miles (45 km) (MPA, 2022)). But for other products, it is important to understand both the relevance of transport impacts, and the likelihood that the local supplier has higher impact, before using local sourcing to reduce embodied carbon.

**Service life and durability**

Increasing the service life of a component will mean it will not need to be replaced so often over the building life cycle, reducing impact. Ensuring designs are low maintenance reduces the chances that components will fail and need replacement, or poor maintenance will reduce the service life of the building. Increasing the service life of the building will also spread the time that the embodied carbon of construction provides utility. When comparing different alternative specifications, it is important to take account of their durability. For example, one ECEP explained that when looking at alternatives to brickwork external walls, ‘timber cladding of suitable durability’ was considered, to ensure that regular replacement was not required. EPD covering the full life cycle normally provide information on the expected service life and any required maintenance or installation requirements to achieve that.

Buildings sometimes reach the end of their life not because they have problems associated with service life, but because they are not flexible or adaptable, or perhaps because land values mean that a larger building will bring in more revenue. Increasing initial embodied impact to achieve a longer service life may incur higher impacts if the building is not likely to be useful for a similar time period.
### Table 21 Impact for transport for common construction materials

<table>
<thead>
<tr>
<th>Product and source of data</th>
<th>Typical transport distance to site</th>
<th>kgCO₂e A1-A3 per tonne</th>
<th>kgCO₂e A4 per tonne</th>
<th>Km ≈10% A1-A3</th>
<th>% increase in A1-A3 impact ≈ sourcing from 0 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK Crushed Rock (Mineral Products Association (MPA), 2022) (BEIS and DEFRA, 2021)</td>
<td>45 km</td>
<td>3</td>
<td>30.8 *</td>
<td>0.44 km</td>
<td>1030%</td>
</tr>
<tr>
<td>UK Ready-mix concrete EPD (British Ready-Mixed Concrete Association, 2018)</td>
<td>12 km</td>
<td>77.7</td>
<td>0.71</td>
<td>131 km</td>
<td>0.9%</td>
</tr>
<tr>
<td>UK kiln dried timber EP (Wood for Good, 2017)</td>
<td>292 km</td>
<td>107**</td>
<td>7.76</td>
<td>402 km</td>
<td>7.25%</td>
</tr>
<tr>
<td>UK Generic Brick EPD (The Brick Development Association, 2019)</td>
<td>97 km (Lazarus, 2002)</td>
<td>213</td>
<td>7.8</td>
<td>265 km</td>
<td>3.7%</td>
</tr>
<tr>
<td>CARES Reinforcing Steel EPD (UK CARES, 2017)</td>
<td>350 km</td>
<td>760</td>
<td>16.5</td>
<td>1610 km</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

*Transport impact calculated using average laden rigid lorry over 17 tonnes GLW.

** excluding sequestered carbon
4.4. Assess, don’t guess: measurement versus intuition

Although one ECEP said that once you had more knowledge, ‘you can make those kind of intuitive decisions without having to do the calculations,’ a number of the ECEPs emphasised the need for measurement and numerical assessment to check the actual impact of reduction strategies on embodied carbon. For example,

‘I need to assess the building itself because there are so many variable parameters that could change drastically the results.’

‘If you don’t measure [embodied carbon], then you’re not able to say with certainty if what you’re doing is good, or how good it is.’

‘We’ve been very strong on [this] within our office because of how much people do use intuition at the moment, and we’re saying no, [embodied carbon] has to be a number.’

Section 4.3 offered numerous examples, many provided by ECEPs, where the complexities of embodied carbon mean use of guiding principles without measurement may result in increased embodied carbon, rather than reductions. Use of intuition and guiding principles needs to be balanced with assessments, to check whether embodied carbon reductions can really be achieved for the specific project. EPD provide verified and consistent data on embodied carbon, both for manufacturer specific products, and for industry average or representative products, allowing detailed assessments of embodied carbon reduction strategies and material choices to be evaluated.

The next section examines the views of the ECEPs on embodied carbon data generally, followed by a more detailed analysis of their views on concrete, as one of the most commonly used construction materials with a high impact at building level. It also explores the ECEP’s views on using cement replacement as a mitigation strategy or guiding principle.

4.5. Embodied carbon: the role of data

When discussing the role of data in their evaluation of tools, a number of the ECEPs highlighted the importance of access to large numbers of datasets and EPD. For example, in relation to developing their tool, one highlighted the work they had gone through to include an EPD database within it was ‘gigantic.’

One Click LCA, a commercial tool, was described by one ECEP as ‘probably the most prominent [embodied carbon tool] in the industry,’ with another ECEP saying ‘it’s asked for by our clients sometimes because they know it’s got the BREEAM accreditation and it’s got a huge materials database to draw from,’ with another ECEP pointing out, ‘the amount of EPDs or the size of the database was I think one of the best around,’ and another highlighting the value of its data, ‘You do have a lot of information in there, which is valuable to us.’

ECEPs clearly considered data quality of the sources of embodied carbon data that they used, and valued transparency. For example, there were also concerns with the data in One Click LCA. As one ECEP said,

‘I think OneClick really, it sort of sells itself on, “you’ve got lots of comparisons, lots of EPD in the database”, but some of those shouldn’t even be in the same dropdown, you know ... I’m really sceptical of their own developed OneClick EPDs. I don’t trust those numbers,‘

explaining further,

‘So the OneClick [EPDs] that they put in there, I will compare to other EPD, and they rarely match up and it’s only OneClick, their ones that sort of tie in together. And so it makes me
nervous. And I know I like that tool to use, but I’m not sure I trust the guys behind it at times because I think they’re driven by trying to show a tool that shows more reductions than you can get.’

Another ECEP confirmed they thought the One Click LCA datasets were different to others, ‘I think [One Click LCA] enriched their database with generic datasets, basically. Not EPD but datasets that they created themselves for the various countries.’ There were also concerns about other databases, with one ECEP raising ‘all the kind of baggage that [the Inventory of Carbon & Energy (ICE) Database] brings,’ although clarifying its positive points - ‘it’s transparent, it’s clear, you can interrogate it to find out a bit more about it, if you’re interested.’ Another, talking about the BRE IMPACT database used in BREEAM assessments said, ‘I’m not sure about how good those numbers are in IMPACT.’ Concern with the scope of the IMPACT database was mentioned by another ECEP who said that if you were claiming credits in BREEAM, then you have to use the IMPACT database, but otherwise, ‘you use e-tool databases, it’s better because there is a wider variety of carbon data.’

In terms of assessing the quality of data, one ECEP specifically explained, in relation to the Canadian Athena LCA database, how they ‘trust its data more than anybody else really, because I know the guys involved in it,’ but also highlighted the functionality of the US EC3 tool and database in addressing data quality when searching for EPD, because it ‘will give a sort of validity to the quality of that EPD and what life cycle stages it has in it because some of them are more thorough than others.’ Another highlighted the need for verification of the data used in tools to improve the robustness and transparency, and that using ‘once we start getting to that situation, that’s where we start to pull in your proper EPDs, for instance, where you want to have that chain of visibility or something.’

In addition to concerns with the quality of data, the lack of both EPD and generic data for both natural materials and mechanical, electrical and plumbing (MEP) equipment was highlighted by several ECEPs.

‘a lot of our favourite natural materials really don’t have EPDs or anything we can be reliably informed on, because you know they are from smaller providers.’

‘the potential contribution of MEP, especially to refurbishment project’s overall embodied carbon - it can be quite significant, even though we don’t have loads of data on it.’

However, another ECEP, discussing how they had previously omitted all building services from their assessments, ‘because simply the data didn’t exist in the software,’ added ‘now it seems that they’ve added a bit more data on that in the software. So we’re hoping to go back and add those components in, to get a better picture.’

Even though there were some concerns about the lack of data for some product groups, and many of the ECEPs stressed the value of access to large numbers of EPD, several of the tools developed by the ECEPs limit the number of materials that are available within their tools, for example, ‘we have a set of around 50 materials as a standard’ and another said, ‘we also confine our BIM library of materials, basically. So it is always picking up what we want it to pick up.’

Building information Modelling (BIM) and BIM Interoperability - the process of first defining the individual materials in a CAD or BIM model and then mapping them to suitable material datasets or EPD in an embodied carbon tool - is one reason behind why the number of materials has been limited in some tools, and was seen by one ECEP as ‘the biggest challenge.’ Another explained how they had to make ‘a kind of key that connects the Revit library with the database.’ One ECEP mentioned that to avoid this process, ‘what I normally end up doing with it is just taking any materials impact data from [the tool] and just putting it into an Excel spreadsheet, and doing quick little analyses myself outside of the tool, because it’s a bit quicker to do little elemental comparisons.’ The problem of identifying the actual materials for any mapping is further increased during early design stages, as one ECEP said, ‘it
made probably things a bit difficult, mostly because we didn't have that information at [RIBA] Stage 2.’ Almost all ECEPs mentioned a preference for using generic data during assessments in the early design stages, often when building their first baseline carbon model as a basis for assessing reductions as the project progresses.

‘I always preferred and continue to prefer to use generic datasets I think, at this early stage when you don’t really know what exact product you’re using.’

‘normally, it is good to use market standard embodied carbon values.’

‘so it was trying to select realistic embodied carbon factors that were appropriate to the level of certainty of material specification that we had at [RIBA] Stage 3.’

‘it’s mostly generic data that we’ve used so far.... we haven’t got that many specific products yet... We’re pretty confident that the concrete will come from somewhere around London and other material facade materials, we don’t yet have specification on those, so mostly taking generic assumptions for the moment.’

In summary, ECEPs valued access to large quantities of EPD, and were interested in the quality and transparency of the data they used, with concerns about some generic datasets such as those provided by One Click LCA, the ICE database and BRE IMPACT. The availability of data for MEP and natural building materials were both commented on, although MEP data was becoming more easily available recently. At early design stage, generic data was favoured by the ECEPs, but EPD were valued in the later design stages.

However, several ECEPs mentioned the difficulties inherent with included large numbers of EPD and generic data within their tools, with the need to link the objects in the BIM or CAD models with the relevant datasets taking a lot of time. This was seen as the ‘biggest challenge,’ and was given as the reason for limiting the amount of data to 50 generic datasets in one embodied carbon tool. CO2nstructZero, set up by the Construction Leadership Council, has a target that 40% of UK construction product portfolios should have EPD by 2025 and 100% by 2030 (CO2nstructZero, 2021). If so many EPD are to be provided, and are to provide useable information for practitioners looking to assess and reduce embodied carbon, this is a problem that will need to be addressed.

In the next section, the ECEPs views related to concrete are explored, as one of the most ubiquitous construction materials, with significant impact.

4.6. An exploration of expert views on concrete

Concrete is one of the most commonly used construction materials, and its key input, cement, is responsible for 7-8% of global anthropogenic CO₂ emissions (Andrew, 2019). And as one of the ECEPs mentioned in relation to the various possibilities of mix design and concrete plant, ‘obviously there’s an infinite number of different concretes depending where you get everything from.’ It was therefore a material which was explored in greater detail through the interviews.

One of the consistent themes in the interviews was the use of cement replacement as an embodied carbon reduction strategy – as one of the ECEPs mentioned, ‘it’s the one thing that everyone knows about embodied carbon.’ The review of mitigation strategies summarised in the literature review (in Table 1) didn’t identify the use of cement replacement as its own mitigation strategy, but on further investigation, it was included as part of different mitigation strategies in four of the papers, as shown in Table 22.
Table 22 The use of cement replacement in the literature on mitigation strategies

<table>
<thead>
<tr>
<th>Source</th>
<th>Mitigation Strategies affecting cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hu, M. 2023</td>
<td>MS6: Use substitution of materials for cement – this is estimated to achieve 12% savings in embodied carbon compared to conventional building.</td>
</tr>
<tr>
<td>Rodrigo et al., 2019</td>
<td>An expert round table highlighted it was good to ‘reduce highly carbon intensive materials such as cement’</td>
</tr>
<tr>
<td>Malmqvist et al., 2018</td>
<td>Substitution of cement by industrial by-products, such as fly ash and slag was considered under Mitigation Strategy ‘Using recycled and reused materials/ components’</td>
</tr>
<tr>
<td>Akbarnezhad and Xiao, 2017</td>
<td>Substituting Portland cement fully or partially with supplementary cementitious materials (SCMs), including fly ash, GGBS, and amorphous silica (silica fume), together with hydraulic cements and geopolymer concrete, considered under Mitigation Strategy ‘Low Carbon Materials’</td>
</tr>
<tr>
<td>Pomponi and Moncaster, 2016</td>
<td>Reduced use of Portland cement and its substitution with blended cement, which has a higher content of fly ash and blast furnace slag considered under mitigation strategy ‘MS3: reduction, re-use and recovery of EE/EC intensive construction materials’</td>
</tr>
<tr>
<td>PE International, 2013</td>
<td>Increasing use of pulverised fuel ash (PFA) in cement from 12% to 20% was considered under the Mitigation Strategy ‘Increase use of secondary / recycled materials’</td>
</tr>
</tbody>
</table>

By-products from other industries, such as ground granulated blast furnace slag (GGBS) from BF/BOF steel production and pulverised fuel ash (PFA) from coal fired electricity production and other materials such as ground limestone, can be used as cement replacements, reducing the impact of concrete by substituting higher impact Ordinary Portland Cement. In the interviews with ECEPs, this strategy was often mentioned, and sometimes cited as the main strategy for embodied carbon reduction on a project, and in particular, ECEPs often mentioned that very high levels of GGBS cement replacement were used in projects:

‘the vast majority of the reduction was because of the specification of GGBS and PFA’

‘the most important one, that was enough to achieve the reduction target, which was the cement replacement’

‘because we used a metal deck and because we made it like a permanent formwork, with a deck, we could put high levels of GGBS in there. So we went from 60 to 80 percent replacement in that’

‘for some about BREEAM projects that 50% GGBS is quite common. And on some of the BREEAM outstanding projects even higher’

‘for the actual foundations themselves we ended up making concrete with, I think it was, between 30 and 40% GGBS replacement’

‘we based on concrete specification assumptions for the LCA model based on that specification and which was pushing up as high cement replacements as possible.’

---

7 The average rate of cement replacement across all UK concrete was 25.8% in 2019 (Sustainable Concrete Forum, 2021) and (Gibbons et al., 2022) suggest GGBS is the main cement replacement used. Globally, (Mullholland et al., 2022) suggest the cement replacement rate is only 11%, split between GGBS and PFA, showing the already much higher levels of GGBS used in UK concretes.
Having access to concrete datasets with differing amounts of GGBS and PFA seemed to be important to the ECEPs. For example, one was in the process of moving their tools’ underlying database from ICE Database V2 (Hammond and Jones, 2011) to ICE Database V3 (Hammond and Jones, 2019), ‘partly because that’s just a lot more flexibility with your percentage of GGBS and PFA, and concrete grades in ICE version 3 data.’ Another used the IMPACT database, but ‘basically created a few concrete templates, particularly varying the amount of GGBS into the concrete mix.’

One ECEP noticed that,

‘from the latest assessments that I did it with OneClick that there were lots of available datasets for various GGBS contents, PFA contents or Portland cement for various countries as well’,

another highlighting there were ‘actually quite impressive amount of data points for concrete’ in the tool and another saying, ‘there were plenty of options.’ Several ECEPs also mentioned that many of One Click’s concrete datasets were not EPD, but generic datasets that had been generated by the One Click LCA team, echoing concerns with trust in the data raised in Section 4.5.

One ECEP based in the South West of the UK, decided against the use of PFA as cement replacements, ‘We were thinking of fly ash, coal power stations, probably on the line in terms of availability. And then we felt GGBS supports the local steel economy.’

One of the ECEPs who often worked on projects in North America drew attention to the EC3 database, which he stated had over 20,000 EPD for concrete which were ‘not driven by cement replacement,’ but just related to all the different mix designs available from the large number of companies and their respective sites.

Concerns with cement replacement as a mitigation strategy were expressed by several ECEPs. One pointed out that high proportions of cement replacement were ‘not a long-term solution,’ due to the limited availability of both PFA [from a rapidly diminishing number of coal fired power stations] and GGBS [also limited as a by-product of the production of steel through the blast furnace route]. He mentioned that his company were looking away from cement replacement as a mitigation strategy towards material efficiency,

‘looking at different floor systems using concrete, showing just how good a waffle slab is, for example, how much material you can save. Hopefully we’ll see those coming back into fashion.’

Another ECEP echoed this,

‘What reduced the carbon the most was not things like fly ash replacement, but it was actually structural efficiencies, ... ways of reducing the weight effectively, and the knock-on effect on foundations.’

Another ECEP expressed concern that some tools were so focussed on cement replacement as a mitigation strategy that other options were not offered or highlighted – ‘I don’t value some of the tools in what they have in there because they only have cement replacement as an incentive.’ They were also worried that in the US, the LEED credit for embodied carbon improvement over baseline had been abused as ‘I still think people will be putting in 0% fly ash when industry average is 20% probably, in some [US] states,’ and thus their baseline assessment would show higher than average impact making it much easier to show improvement by moving to a concrete with average fly ash content.

There was also evidence that concrete manufacturers were starting to be challenged to produce lower carbon concrete, and that cement replacement was not their immediate solution. One of the ECEPs noted that rather than specifying the amount of cement replacement, they had now ‘started doing performance-based specs, so setting concrete providers embodied carbon targets,’ explaining,
we actually then went to a concrete provider and said, can you help us with this? ...And we did some assessments with them, and they actually found out that they could get below industry average, they could get a 25 percent reduction on embodied carbon just by the mix. Not replacement. Not carbon curing. And that was far better performance than if we had just put in 20% fly ash or 20% GGBS.’

Although many UK concrete producers have pre-verified EPD tools to provide EPD for concrete mixes on demand (see section 2.3.4 of the literature review), the ECEP described getting in contact with the right person at a concrete producers to obtain carbon data was a problem. ‘we get quite a bit of a block. And you get no reply... It’s just really hard to find the right people.’

However although working with concrete manufacturers on embodied carbon was not common; one other ECEP stated,

‘I don’t think that generally happens. ... we haven’t spoken to concrete mix suppliers yet. But I think it would be a good thing to do and very soon.’

In summary, use of cement replacements was widely recognised by the ECEPs as a common strategy for reducing embodied carbon, and several highlighted how they had been used to reduce carbon significantly on their projects, often using high percentages of cement replacement. ECEPs valued access to databases which allowed them to model different concrete mixes for example covering different cement replacements, but there was concern about the availability of some the replacements such as PFA as coal fired power stations closed and GGBS as the steel industry decarbonised. However several ECEPs discussed how they were now focussing on other strategies than cement replacement to reduce the impact of concrete, with several mentioning the use of material efficiency strategies. Although they expressed difficulties in finding the right people to speak with at concrete producers about EPD and embodied carbon, one ECEP had started to work with a producer on specifying concrete which met performance requirements with reduced embodied carbon, and had found the concrete supplier was able to do this through mix design rather than use of cement replacement, whilst another suggested that working with concrete producers would be a good thing to do in future.

4.7. Discussion

The complexity of embodied carbon assessment means that practitioners need knowledge, experience, and judgement alongside suitable data and methods. Very few ECEPs had had any formal education in embodied carbon; several of the ECEPs explained how they had learnt about embodied carbon from colleagues, and most had found that the process of developing embodied carbon tools itself had been extremely helpful in increasing their understanding. A number of ECEPs highlighted the complex nature of embodied carbon assessment, pointing out that practitioners need to understand both buildings and LCA, and that whilst in theory it is easy, just ‘multiplying two numbers together,’ it requires practice and comes with a steep learning curve.

In discussing how they checked embodied carbon assessment undertaken by others, the language used by ECEPs suggested there was a clear use of intuition in spotting errors, an ability which ECEPs suggested which was strongly linked to their experience of doing assessments themselves – through the tacit knowledge gained from the process – although ECEPs suggested obtaining the necessary experience could take just a few projects to 20 projects.

The difficulty of embodied carbon assessment was also evident in the use of guiding principles discussed by the ECEPs, many of which were common embodied carbon mitigation strategies mentioned in the literature. In many cases, ECEPs observed that these were rarely universal solutions, and that there were often complexities with application to individual projects and counter-intuitive findings. These issues have been discussed, for example in section 4.2 around column grid spacing,
section 4.3 generally, and in section 4.6 around the use of cement replacement. A number of the ECEPs emphasised the need to assess embodied carbon to ascertain whether strategies really reduced embodied carbon, rather than relying on intuition and guiding principles. As shown in the examples, data on the embodied carbon of products is essential to undertake these assessments and EPD play an essential role in providing independently verified embodied carbon data.

There was general agreement that generic data was the preferred data to use during early-stage assessments. A number of generic databases were mentioned, including BRE’s IMPACT database and the Circular Ecology ICE Database (both of which are specific to the UK), the oekobau.dat database from Germany, and the Athena database from Canada. ECEPs identified a lack of embodied carbon data for natural materials and MEP equipment, though one noted that there seemed to be more data for MEP becoming available.

For the later design stages, the manufacturer specific data provided by EPD became more important. Many of the ECEPs valued the choice of data provided by the OneClickLCA tool with its ‘huge numbers’ of EPD, particularly, for example, the range of concrete mixes provided, with some identifying this as one of the reasons for using particular tools; however others expressed scepticism about the quality of some of the datasets developed by One Click LCA themselves, and particularly about the way in which invalid comparisons could be made using the tool. ECEPs clearly considered data quality of the sources of embodied carbon data that they used, and valued transparency, and trust in the people developing the data was mentioned by several ECEPs. The EC3 tool (a US based embodied carbon tool) was highlighted as being key to being able to make use the large numbers of US EPD for embodied carbon of concrete included in the tool, enabling benchmarking and product selection by performance and location for example.

BIM Interoperability, described by one ECEP as ‘the biggest challenge,’ was one reason behind why the number of materials has been limited in some tools, with one ECEP noting that their in-house tool only used around 50 material datasets as standard. The contradiction between the value seen in having access to large numbers of datasets, and the difficulty of being able to make tools useable without limiting access to data, was clearly seen in ECEP responses and is a problem that will need to be addressed if the Construction Leadership Council’s target of 40% of UK product portfolios having EPD by 2025 and 100% by 2030 (CO2nstructZero, 2021) is to provide information that will actually be useable within industry.

Looking specifically at concrete, as one of the most used and most impactful construction materials, ECEPs outlined different approaches to reducing embodied carbon which again illustrate the lack of simple answers. For example, cement replacement was described by one ECEP as the ‘one thing that everyone knows about embodied carbon.’ The majority of the ECEPs explained how they had used cement replacements to reduce embodied carbon, with this being one of the first reduction approaches that they used, and one which brought about the greatest reduction for some of their projects. Levels of cement replacement were highlighted, one noted that use of 50% GGBS or higher was common in projects addressing BREEM, another said they had used 60-80% GGBS for concrete in a floor deck with steel permanent formwork. However, two ECEPs shared concerns about the focus on use of cement replacements like GGBS and fly ash to reduce embodied carbon, due to their limited availability. One also expressed concern that some tools only incentivised cement replacement, meaning other reduction strategies such as resource efficiency and low carbon mix design were ignored. These ECEPs had used these different approaches successfully, for example where they were able to reduce the impact of concrete to a greater extent than through use of cement replacement by employing BubbleDeck® and waffle slabs, or through engagement with concrete suppliers, set concrete providers embodied carbon targets and allow them to use other mix design approaches to reduce cement use and embodied carbon without specifying cement replacement levels.
Most ECEPs did not talk directly with suppliers about embodied carbon and EPD, for concrete or any other products, with the one ECEP who had done this, noting difficulties in finding ‘the right person’ to talk to. However, as discussed above, this ECEP had found supplier engagement to be an effective reduction strategy, and by setting performance specifications based on embodied carbon targets and had found useful reductions in embodied carbon. Another echoed this, saying ‘we haven’t spoken to concrete mix suppliers yet. But I think it would be a good thing to do and very soon,’ suggesting that supplier engagement and the use of performance specifications could be additional mitigation strategies to add to those identified in the literature review.

4.8. Conclusion

In summary, the interviews with ECEPs have built a fuller picture of emerging practice at the leading edge of embodied carbon assessment in the UK and have provided a valuable insight into the direction of the industry. The ECEPs interviewed had all learnt about embodied carbon by experience rather than being taught it at university for example, and many highlighted the utility and value that the actual process of developing an embodied carbon tool had had on their knowledge of embodied carbon, and the speed with which that knowledge was imparted through the process. The ECEPs all discussed the value of experience in being able to identify errors and problems with assessments, and several mentioned the need to have an understanding of buildings and construction when working on embodied carbon assessments.

There was general agreement amongst ECEPs that it was important to assess the embodied carbon consequences of design decisions, rather than to use intuition or to follow carbon reduction strategies without thinking through the consequences. This is reflective of the finding that there are rarely simple answers nor indeed single solutions when looking to reduce embodied carbon; projects will have different contexts and there are often multiple factors to consider which cause complexities around the use of guiding principles, as were illustrated in section 4.3. There is always a need to check whether proposed reduction strategies will be successful for a particular project, and embodied carbon data and EPD are key to being able to make these assessments and check whether reduction strategies are realising actual reductions in embodied carbon in practice.

EPD provide independently verified data on the embodied carbon of manufacturing products, their use of secondary material and biobased content and their mass, and may provide information on transport and technical performance data (e.g. thermal resistance, expected service life and any required maintenance or installation requirements to achieve that). This information is essential to be able to accurately assess the impacts of different reduction strategies, select products and identify lower carbon construction solutions.

Although ECEPs valued having good availability of data, they also valued transparency so they could judge data quality. Trust in data providers was mentioned by two ECEPs as a way of assessing the quality of data. As the amount of EPD available for use in tools has grown, ECEPs noted the problems this caused in efficiently linking data with the modelled design – one noted that that as a result of these difficulties, they have undertaken most standard assessments using only 50 generic datasets in their in-house tool. With the number of EPD in the UK expected to grow rapidly if the industry meets the targets set by the Construction Leadership Council (2021), this is a problem which will need to be addressed.

In looking specifically at concrete, the lack of simple answers to reducing embodied carbon was illustrated. Whilst the use of cement replacements was often mentioned, several ECEPs expressed concerns about the effect of limited availability on this strategy, with fears that it may have no overall benefit if other projects were using higher amounts of cement as a result. These ECEPs also explained
how they were concerned that the focus on this within tools was blinding practitioners to other effective ways of reducing the impact of concrete, such as material efficiency and lightweighting strategies, and the use of supplier engagement and performance specifications, the latter of which could be additional mitigation strategies to add to those identified in the literature review having been successfully used by one ECEP.

To summarise, assessing embodied carbon is necessary to ensure embodied carbon reductions are being realised. Embodied carbon assessment should ensure practitioners use the relevant data such as EPD in the specific context for their building, for example accounting for transport and the level of performance that is required. Guiding principles such as the mitigation strategies identified in the literature and through the interviews are useful ways to start to consider embodied carbon reduction, but they are no simple answers, and the context and consideration of multiple factors is necessary to ensure that real reductions are achieved. Embodied carbon data for products, and EPD in particular as they provide verified data for specific products to allow these assessments to be undertaken, is essential, but data quality and trust in the data provider are important. The greater availability of EPD is valued, but the utility of providing ever larger numbers of EPD, until tool providers can find better ways of handling them, will be a problem which needs to be addressed by the industry.

In the next chapter, the availability of EPD both globally and in the UK is assessed, the drivers for growth are analysed and other countries which have implemented embodied carbon regulation are examined to understand how much embodied carbon data is required.
5. Environmental Product Declarations and Embodied Carbon Data: Growth and Needs

5.1. Introduction

This chapter responds to the second research question: What EPD data exists at present?

Two types of product-level data are required for building-level embodied carbon assessments and life cycle assessments – manufacturer-specific data such as Environmental Product Declarations (EPD) and generic data which is not specific to any particular manufacturer or product.

This chapter firstly explores the most commonly used and robust source of specific embodied carbon data for construction products, EPD. It analyses their availability globally, their numbers in different regions and countries and how this has changed over time. It considers which drivers have influenced the availability of EPD, and provides three case studies exploring the role of different drivers at national level and their impact on EPD numbers.

Looking at the situation in jurisdictions where building level embodied carbon assessment has been regulated, it explores the availability of both EPD and generic data before regulation was introduced, and how data availability has changed.

Finally, taking the UK as a case study, it explores what data is available (both EPD and generic data) for construction products in the UK market, both in terms of depth and breadth; and considers what further data may be needed if regulation is introduced.

This chapter has drawn on qualitative document analysis, web scraping and personal communication together with quantitative data analysis. The methodologies used are described in more detail in section 3.3.2, 3.3.4 and 3.3.5 for the collection of data, and section 3.3.6, 3.4.2 and 3.4.4 for the analysis of data.

5.2. Availability of EPD for construction products: a growing resource

The number of EPD to EN 15804 has been tracked since 2011 (Anderson and Thornback, 2012), when only three EPD programmes had produced Product Category Rules to align with the 2011 enquiry draft of the EN 15804 standard which was then published as a European Standard in 2012. Today, there are over 30 EPD programmes, mostly in Europe and North America offering EPD to the standard. The International EPD® programme now has sub-programmes and hubs in Turkey, Australasia, India, Brazil, Latin America and South East Asia, and there are new EPD programmes using EN 15804 in China (EPD China) and Australia (Global Green Hub), meaning the use of EN 15804 is now global. The growth in registered EPD to EN 15804 from 2011 onwards is shown in Figure 18. The dominant programmes, in terms of numbers, remain those that first introduced EPD to EN 15804 – Fiches de Déclaration Environnementale et Sanitaire (FDES) in France, International EPD® (based in Sweden), EPD Norge in Norway, IBU in Germany and UL Environment in the US.

Most construction product EPD programmes are national, run by a range of organisations, including certification bodies (e.g. BRE Global and UL Environment), industry owned associations (e.g. IBU), or Government Research Bodies (e.g. ITB in Poland). The trade associations European Aluminium, Cembureau and Eurima all have their own sectoral EPD programmes; IFT Rosenheim specialises in EPD for a particular sector, and Tata Steel has its own company EPD Programme.
EN 15804 EPD and the numbers of products covered

Most EPD programmes to EN 15804 allow a single product or average product to be covered in each EPD, however several (e.g. International EPD®, and EPD Ireland) allow separate product datasets for similar products within a product group to be provided in one EPD. This means that the number of EPD given in Figure 18 will be less than the number of product datasets available to EN 15804.

In addition, it should be recognised that a single EPD, particularly an average EPD, could cover many individual products. The French EPD programme tracks the number of ‘références commerciales’ (commercial references) that are covered by its EPD – it stated that in December 2022, the 2076 registered EPD (of which 382 were collective) covered 637,026 commercial references, meaning each EPD, on average, covered 306 individual products (inies, 2022). In terms of what may be this may mean in practice, according to the inies Database Coordinator:

‘Some EPDs (mainly collective and range ones) covered more than one product reference on the market. We call that information commercial references. They may be different color of the same product, different commercial names, different product reference declared in the same EPD (for example for water or gas networks), different sizes, thicknesses in the same EPD range...It can also be only the number of companies participating in a collective EPD.’ (J Chevalier 2023, personal communication, 9 February).

Certain product groups also tend to consistently have more EPD. For example, Figure 19 shows the breakdown of ECO Platform EPD by product type at the start of 2019. In fact, across almost all of the ECO Platform EPD programmes, seven products (insulation, wall and floor coverings, gypsum products, paint, precast concrete and ready-mix concrete and mortars and metal products) were responsible for more than half of each programmes’ EPD at the start of 2019, and the same is true for the ECO Platform
EPD in 2015, shown in Figure 20, with the biggest growth in EPD seen for insulation and gypsum products, both increasing by over 400% in number.

Figure 19 ECO Platform EPD at the start of 2019 by product type

Figure 20 ECO Platform EPD in September 2015 by product type

Unregistered EPD from Verified EPD Tools

In addition to registered EPD which are verified by EPD programmes and published by them, some EPD programmes (e.g. inies, IBU, International EPD*) verify automated EPD tools which manufacturers or trade associations can use to produce EPD ‘on demand.’ These are commonly used by manufacturers to provide EPD for particular products if they have a large product range, or for project specific products, e.g. concrete mixes. These EPD are not registered with the EPD Programme or listed on their websites, but due to the management and verification processes for these automated EPD tools, give authoritative information about the products which can be used in the same way as a verified EPD. To give an indication of the numbers of EPD that could covered in this category, we can look to France and Germany, where the number of EPD that have been made using these verified tools for use in 2022 is over 22,000 (S Zwerenz, personal communication, 16 December 2022; JM Potier, private communication, 21 December 2022; N Decousser, private communication, 19 December 2022; E Vial, private communication, 16 December 2022; F Rossi, private communication, 16 December 2022), as shown in Figure 21.
Data from these two programmes would suggest that there are significantly more EPD to EN 15804 than are shown on in Figure 21, although not all programmes have verified these types of automated EPD tool. The use of automated EPD tools is further described in section 5.3.

**EPD to ISO 21930**

Although EN 15804 has been widely adopted outside Europe, ISO 21930:2017, the International Standard for construction product EPD, is commonly used in North America, particularly in the United States of America (US). The North American PCR Catalogue provides an overview of the EPD Programmes and their construction product PCR (Sustainable Minds, 2023) and shows that the US has the most construction product EPD programmes of any country. Many of the US EPD programmes are operated by certification bodies, and some offer EPD to EN 15804 or ISO 21930. For EN 15804 EPD, they draw on PCR from Europe (for example UL Environment uses the IBU PCR), but for EPD to ISO 21930, they often look to adopt common PCR across all programmes.

The striking difference for EPD to ISO 21930 compared to the number of EPD to EN 15804 are the sheer numbers of registered EPD, most particularly for EPD from automated EPD tools for concrete, as shown in Figure 22. The reason for this is that in the US, various EPD programmes have used digitisation of EPD platforms to register thousands of EPD from verified automated EPD tools. This is further discussed in section 5.3 below.

**5.3. Drivers of growth in EPD numbers**

Looking at Figure 18, there has clearly been growth in the number of EPD. In 2014, the major programme in terms of numbers was IBU in Germany (383 EPD), followed by FDES in France (250 EPD) and UL Environment (170). These programmes, together with EPD Norge (100 EPD) and the International EPD® programme have expanded significantly over the intervening years, and new programmes have joined them, with PEP EcoPassport being the largest new programme. However the core 5 programmes have continued to provide over 50% of EN 15804 to the current day.

The Norwegian Parliament noted in their 2011 report that, ‘*Today, there are few construction products with environmental declarations in Norway, and there is therefore little demand for them*’ and stated that Statsbygg (the State real estate company) would therefore require EPD for the 5-10 most used construction materials in new build and retrofit projects (Norwegian Parliament, 2011, para. 4.6) and Grønn Byggallianse (the Green Building Alliance), a network of the largest developers and building managers in Norway also started to require EPD at this point (Norwegian Parliament, 2011, para. 4.6).
These policies were intended to increase the number of EPD, and hence the demand for them more generally.

Table 23 is based on the factors influencing EPD numbers identified in the Literature Review (Table 2), and looks at the ways in which these strategies have been applied in the countries with largest number of EPD, and the wider initiatives which may also have played a part. This has been drawn from qualitative document analysis, web scraping and personal communication with key players in the various countries (personal communications: H Hauan, 6 February 2023; P Hermon, 6 February 2023; M Lewis, 10 February 2023; P Osset, 7 February 2023; A Rønning, 8 February 2023).

It is clear that for most of the countries with the largest number of EPD, a number of the strategies that are considered to increase EPD have been implemented.

Beneath the table, a series of case studies are used to describe how the implementation of these strategies has impacted the number of EPD in France, Germany, and the United States. This is followed by section 5.4 which considers how much product level data is actually required.
Table 23 Initiatives at national and regional level linked to EPD Growth

<table>
<thead>
<tr>
<th>France</th>
<th>Germany</th>
<th>USA</th>
<th>Norway</th>
<th>UK</th>
<th>Wider initiatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022 Buy Clean Oregon passes</td>
<td>2021 Buy Clean Colorado passed, requires EPD in 2022</td>
<td>2021 Portland begins requiring EPD for public projects</td>
<td>2019 Statsbygg targets minimum 40% carbon reductions for public construction projects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Building Certification</td>
<td>France</td>
<td>Germany</td>
<td>USA</td>
<td>Norway</td>
<td>UK</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------</td>
<td>---------</td>
<td>-----</td>
<td>--------</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>2012 HQE Performance LCA Experiment 2014 EPD Credit 2017 HQE LCA Renovation</td>
<td>2009 DGNB launched with LCA 2011 BNB launched with LCA</td>
<td>2000 LEED launched 2010 Pilot building LCA credit 2011 Pilot EPD credit 2013 EPD credit 2013 Building LCA credit 2018 International Living Future Institute Zero Carbon Certification launched (ILFI) Living Building challenge (unclear when EC was added to this, but includes some EPD requirements now) 2019 LEED Pilot Procurement of Low Carbon Construction Materials credit</td>
<td>2012 BREEAM NOR launched 2012 Building LCA credit</td>
<td>1990 BREEAM launched 1998 BREEAM Green Guide credit 2011 BREEAM EPD uplift credit 2016 Home Quality Mark, includes LCA and residential LCA benchmarks 2018 BREEAM MAT 01 Building LCA credit 2018 BREEAM MAT02 EPD Credit</td>
</tr>
<tr>
<td>Tools, data, and digitisation</td>
<td>Industry and Government Support</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>France</strong></td>
<td>2011 Industry EPD tools launch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004 inies EPD database</td>
<td>2009 oekobaudat launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007 Elodie launched</td>
<td>2011 BNB launched with LCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 industry EPD tools launch</td>
<td>2014 eLCA tool launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013 inies web-service</td>
<td>2017 IBU.data launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Germany</strong></td>
<td>2009 oekobaudat launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012 Soda4LCA</td>
<td>2014 eLCA tool launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013 Extension of ILCD for EPD published</td>
<td>2017 IBU.data launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>USA</strong></td>
<td>2016 Oregon Dept of Environmental Quality funds concrete EPD Programme</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019 EC3 tool launched</td>
<td>2019 EC3 tool launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016 Oregon Dept of Environmental Quality funds concrete EPD Programme</td>
<td>2019 EC3 tool launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Norway</strong></td>
<td>2005 NORSUS developed excel models for concrete ready-mixed manufactures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012 NORSUS web-based EPD tool</td>
<td>2012 NORSUS first pre-verified EPD generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018 EPD Norge launches EPD.digi</td>
<td>2022 Project to convert EN 15804 EPD to EN ISO 22057 format and develop API to transfer data to BIM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UK</strong></td>
<td>2005 Green Guide launch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012 BRE IMPACT Specification for software implementation</td>
<td>2016 BRE Lina EPD Tool launch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017 IMPACT Update to EN15804</td>
<td>2015 InData launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018 InData launch</td>
<td>2018 InData launch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILCD+EPD</td>
<td>2020 ECO Platform ECO Portal launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022 EN ISO 22057 Digitised EPD for BIM launched</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Wider initiatives**

- 2011 Industry EPD tools launch
- 2009 oekobaudat launched
- 2011 BNB launched with LCA
- 2014 eLCA tool launched
- 2016 Oregon Dept of Environmental Quality funds concrete EPD Programme
- 2019 EC3 tool launched
- 2005 NORSUS developed excel models for concrete ready-mixed manufactures
- 2012 NORSUS web-based EPD tool
- 2018 EPD Norge launches EPD.digi
- 2022 Project to convert EN 15804 EPD to EN ISO 22057 format and develop API to transfer data to BIM
- 2023 EPD Norge Digi+EN ISO 22057 launched
- 1998 Green Guide launch
- 2012 BRE IMPACT Specification for software implementation
- 2016 BRE Lina EPD Tool launch
- 2017 IMPACT Update to EN15804
- 2015 InData launched
- 2018 InData launch
- ILCD+EPD
- 2020 ECO Platform ECO Portal launched
- 2022 EN ISO 22057 Digitised EPD for BIM launched

**Industry and Government Support**

- 2011 Industry EPD tools launch
- 2009 oekobaudat launched
- 2011 BNB launched with LCA
- 2014 eLCA tool launched

**2022 Inflation Reduction Act**

- Provides over $8 billion towards low carbon construction products and $250 million for grants and support for companies producing EPD for construction products.

**No financial support**

**Funding for various research projects and tools**, e.g. BRE Environmental Profiles, ICE database, BRE IMPACT, EccoLAB etc.
Case Study 1: France

The inies database has published annual briefings known as “Baromètre”, on the situation regarding EPD in France since 2013. These documents are the major source of information for this case study (e.g. inies, 2022).

France is the country with the largest number of EPD and has two EPD programmes, both listed within the inies database which is operated by Alliance HQE-GBC, which also runs the HQE building certification scheme. The two EPD programmes are Fiches de Déclaration Environnementale et Sanitaire (FDES) for construction product EPD and Profils Environnemental Produit (PEP) EcoPassport which are EPD for electrical equipment, including building related technical equipment such as air conditioning plant, photovoltaic panels etc. Considering the EPD in inies at the end of 2022, the majority (60%) of EPD listed in inies were manufacturer specific, for products produced in France (60%) or Europe (25%), with the remaining 11% being French collective EPD from trade associations, or European collective EPD (4%), with less than 1% of EPD from companies outside Europe.

In August 2022, there were 343 companies or sector organisations behind the 3190 FDES and 51 companies or sector organisations behind the 599 PEP ECOPassport EPD.

In 2012, the French building sustainability certification scheme, HQE, ran an experiment to understand how life cycle assessment of buildings could be integrated into the scheme (Alliance HQE-GBC, 2022).

France also introduced a Decret which came into force in 2013 (Ministère de l’Égalité des Territoires et du Logement, 2013), which required any manufacturer making an environmental claim in France about a construction product (for example about its carbon footprint or reduced environmental impact) to lodge a copy of an EPD with the Government.

In 2015, the Government announced it would look to pilot embodied carbon assessments of building, and the Energie Positiv Carbone Reduction label (E+C-) Experimentation was published in 2018, this required reduction of embodied and operational carbon alongside an increase in the use of renewable energy generation in buildings (Republique Francaise, 2018). The published methodology for E+C- was based on EN 15978 and used the inies database, with tools for use in the pilot needing approval by the Government.

To enable the pilot, the Government provided données environnementales par défaut (DED) - default datasets - to be used for assessments if collective EPD from industry associations, or specific EPD for the specified manufacturer were not available (Ministère du Logement et de l’Habitat Durable and Ministère de l’Environnement de l’Energie et de la Mer, 2019). The DED carried heavy ‘coefficient de sécurité’ (safety factors), depending on their source. Where there were no collective EPD, or only

Figure 23 Growth of Verified EPD and Generic Data in France
limited manufacturer EPD, DED are used in place of industry average data. DED are produced by the Government on request, and are checked with the relevant industry bodies before publication. The safety factors are determined as below:

- If there is no EPD but generic data in ecoinvent or the European Life Cycle Database, then that data is used with a safety factor of 30%.
- If there is only one manufacturer specific EPD for the product, then the EPD data is used with a safety factor of 100%.
- If there are several manufacturer-specific EPD, then the maximum of the sample, or the mean plus 2 or 3 standard deviations, corresponding to a safety factor of 30% is used.

The use of safety factors was intended to drive the production of both manufacturer specific data and collective EPD from trade associations, which don’t incur safety factors. In 2018 when the E+C experimentation started, there were 320 DED for construction products, and 153 DED for MEP, rising in 2022 to 1009 for construction products, and 486 for MEP as the level of detail covered by DED increased. The number of collective EPD also rose however, from 179 in 2018 to 587 in 2022.

![Inies Database Graph](image)

**Figure 24 Numbers of DED and Collective EPD within the inies database**

The Government also funds the inies EPD database, and this has very low costs for registration of EPD, for example, unlimited EPD can be added each year for an annual payment of €3000, or registration for five years costs €200/EPD for the first 10 EPD down to €125/EPD if more than 100 EPD are submitted – these are much lower than the comparable costs for registration within the International EPD® or IBU programmes for example.

Following a successful pilot, the Government went ahead with a national regulation, Réglementation environnementale des bâtiments neufs (RE2020) (Ministère de la Cohésion des Territoires et des Relations avec les Collectivités Territoriales, 2020) which came into force in 2022 due to COVID delays. The regulation is again based on EN 15978 and requires the use of approved building level tools which follow the national methodology set out in the Arête of 4th August 2021 (Ministère de la Transition Écologique, 2021), and which have been approved by the Government to use the National Database of EPD and generic data, inies.
Case Study 2: Germany

IBU is the main EPD programme in Germany. In addition to the registered EPD available through the programme, IBU has verified EPD tools produced by companies and product sectors for over 10 years. In recent years they have required notification from verified EPD Tool operators of the number of EPD supplied by the tool, and in future, IBU are planning that a copy of each EPD must be supplied to their digital EPD database, IBU.data. In 2022, over 3000 EPD were supplied from these verified tools (S Zwerenz 2022, personal communication, 16 December), compared to the 1300 EPD which were registered with the programme. IBU’s EPD are predominantly for the German market, but it also provides EPD in English, French and other languages, and lists EPD for a number of UK produced products for example.

In addition to IBU, there are two smaller German programmes which started more recently, both operated by certification bodies.

Figure 25 Numbers of EPD in Germany

At the start in 2002, the Arbeitsgemeinschaft Umweltverträgliches Bauprodukt e.V. (Association of Building Product Producers and Distributors (AUB)) started work on an EPD programming, launching it 2004. By 2008, they had established PCR for 14 types of construction product (Braune, Kreißig and Sedlbauer, 2007). The AUB was renamed as the Institut Bau und Umwelt (IBU) in 2008.

In 2009, the German Sustainable Building Council (DGNB)’s voluntary sustainability assessment system DGNB was introduced, requiring life cycle assessment of assessed buildings to contribute around 20% of the credits. Data was drawn from a national database (oekobaudat) of EPD, and generic LCA data for construction products which included ‘uncertainty margins’ of 10%, 20% or 30% for data which had not been verified like EPD, and was based on estimations (Gantner et al., 2018). This drove the production of verified collective EPD and manufacturer EPD within the IBU EPD programme so that data without uplift factors would be available in oekobaudat for use in DGNB assessments.

After the launch of the DGNB scheme in 2009, in 2011, the German Ministry of Building decided to develop its own certification system based on DGNB specifically for the requirements of federal buildings and to label it under its own brand, Bewertungssystem Nachhaltiges Bauen (Evaluation System for Sustainable Building – (BNB)), and use of this scheme, and therefore building life cycle assessment became mandatory for large publicly funded building projects in 2011 (Federal Institute for Research on Building, 2011). Again, this legislation has driven the rise in EPD in Germany, as manufacturers and trade associations provided EPD so that generic data with uplift factors would not need to be used.
Jordan (2021) also notes that in Germany, provision of sectoral EPD were a catalyst for the provision of manufacturer specific EPD, by spreading the cost of EPD creation across companies, and providing a benchmark to give specific EPD proving superior performance a stronger marketing value. It is also likely that producing sectoral EPD increased familiarity with EPD and the process of LCA amongst German manufacturers, another potential driver for growth.

Germany has also been at the forefront of digitisation of EPD. Its national database funded by the Government, oekobaudat, was digitised using XML when it was initiated in 2009, and moved to use International Life Cycle Database (ILCD) format in 2011 (Gantner et al., 2018) when 288 digitised EPD were added to the generic data extending the ILCD format as described by Kusche et al. (2013), later the basis for the ILCD+EPD format proposed by InData (a group parties interested in the digitisation of EPD and generic data) which was a project proposed and led by Tanja Brockmann from the German Ministry (Brockmann, 2022).

From 2021, the Kreislaufwirtschaftsgesetz (KrWG) or Circular Economy Act, stipulates that federal authorities must, for the products that have been used on construction projects, check the quantities which:

- produce less waste with lower emissions,
- are made from recycled waste or recycled materials, or
- are reusable or recoverable.

EPD are one way of providing data for construction products to demonstrate they meet one or more of these requirements.

The flattening of growth seen in Germany from 2017 and the drop in 2019 can potentially be attributed to the amendment of EN 15804 which was published as EN 15804+A2 in 2019, with the IBU PCR to EN 15804+A2 published in 2020. This revision involved some changes, for example to the indicators used in EPD, and also the mandatory provision of Modules C and D in EPD. These changes would potentially mean that EPD published in 2018 or 2019 would need to be revised and republished using the new standard, so many organisations delayed initiating EPD projects or updating EPD. As EPD only have a 5-year validity, some EPD were withdrawn. In practice, CEN allowed a 3-year transition period for EN 15804+A2, and IBU only closed its programme to EN 15804+A1 EPD in June 2022.
Case Study 3: USA

There are several EPD Programmes in the US, most operated by Certification Bodies, with the first being UL Environment which launched in 2010, adopting the IBU PCR and EN 15804, but providing results using the TRACI indicators which are commonly used in the United States for LCA. In 2011, SCS Global and NSF International launched EPD Programmes for construction products using ISO 21930:2007, and ASTM followed in 2012. In 2016, the National Ready Mix Concrete Association launched an EPD Programme specifically for concrete. IERE Earthsure also had an EPD Programme, but this has now closed.

In the United States, the US Green Building Council’s sustainable building certification scheme, Leadership in Energy and Environmental Design (LEED) introduced a pilot credit for projects undertaking a life cycle assessment in 2010. This coincided with the launch of the UL Environment EPD Programme, which drew initially on the Product Category Rules of the IBU EPD Programme in Germany. LEED then brought in a pilot credit for projects using construction products with EPD in 2011. This credit was incorporated as part of a full Materials and Resources credit in LEED v4 which was launched in 2013. LEED v4 also included a permanent credit for undertaking a building life cycle assessment in 2013.

These LEED credits led to a rapid increase in the number of EPD within the UL Environment Programme with overall EPD numbers rising to 170 in 2014 and to nearly 500 by 2016, see Figure 26.

There were then a number of initiatives at State level in the United States which focussed on the provision of EPD for key building materials (M. Lewis, 10 February 2023), for example in 2016, the Department of Environmental Quality in Oregon funded a concrete EPD Programme. State-wide initiatives have tended to focus on public procurement and on key building materials. In 2017, California’s Buy Clean California Act was passed, giving a requirement from 2021 for public projects over $1m to procure structural and reinforcing steel, flat glass and mineral wool insulation products.
that could prove, using EPD, that they met limits for embodied carbon impact (State of California, 2022). The Act actually came into force in July 2022 with tighter limit values set. Similar ‘Buy Clean’ legislation failed to pass in Washington State and Oregon in 2017, but has now been passed in Colorado in 2021, and the same year, New York State passed the Low Embodied Carbon Concrete Leadership Act (LECCLA) covering public procurement of low carbon concrete. Other states are now legislating in similar ways, for example the New Jersey LECCLA was passed in 2023.

In 2017, Minnesota introduced a requirement for public bodies to undertake a whole life carbon assessment for new public projects, but generally building level assessment has not been required in the USA.

In 2019, Marin County California was the first local county in the US to introduce requirements to limit the embodied carbon of concrete into their building code, covering all projects, not just publicly funded project, either through provision of an EPD to demonstrate a low embodied carbon coefficient or by limiting the amount of cement in the concrete, to be verified by batch receipts (Marin County, 2019).

The map in Figure 27 highlighting the location of concrete EPD registered at the start of 2023 in the EC3 tool shows high density of EPD in areas where State and County legislation has been enacted.

On 8th December 2021, President Biden enacted an Executive Order directing the federal government to achieve net-zero emissions from its procurement by 2050 and the order’s measures included a Buy Clean policy to promote the use of construction materials with lower embodied emissions (The President of the United States of America, 2021). This will be enabled through the funding available within the Inflation Reduction Act which was enacted in August 2022 (Senate and House of Representatives of the United States of America, 2022) which has provided funding for programmes encouraging the use of low carbon construction materials including:

- Secretary of Housing and Urban Development ($4bn) (Section 30002)
- Federal Highway Administration ($2b) (section 60506)
- Federal Buildings Fund held by the General Services Administration ($2.15bn) (Section 60503).

![Figure 27 Location of EPD for concrete](source(Building Transparency, 2023))
In addition, the Inflation Reduction Act gives the Environmental Protection Agency funding of $250 million to provide EPD assistance (Section 60112). This programme aims to:

- provide grants to businesses to develop and verify EPD, and to States and non-profit organizations that will support such businesses;
- provide technical assistance to business to develop and verify EPD, and to States and non-profit organizations that will support such businesses, and
- carry out other activities that assist in measuring, reporting, and steadily reducing the quantity of embodied carbon of construction materials and products.

The EPA has also received $100 million to develop a programme to identify low carbon construction materials (Inflation Reduction Act Section 60116) and is currently consulting to determine how low carbon materials will be identified, and how the policy could be implemented in detail (US EPA, 2023).

It is expected that these measures will have a strong effect on the number of EPD in the United States in the coming years.
5.4. The critical mass of data needed to mandate embodied carbon assessment at building level

Introduction

To undertake building level assessments, EN 15978 states that generic data (data that is not manufacturer specific) should be used during the early design stages, and manufacturer specific data such as EPD should be used once particular products have been selected, though generic data can be used if specific data is not available. This means that there should be generic data available that can be used to model all the many different types of construction products.

Estimating the number of different types of construction products which would require generic data is not simple, but the following gives an idea of the scale.

- There are 444 construction product families for which there are harmonised or designated standards according to the 2021 listing of UK Designated Standards.
- There are at least 180 separate construction trade associations in the UK (The Construction Centre, no date), many of which may produce more than one construction product.

The answer, in terms of the number of products which need generic data, is therefore probably somewhere between 200 and 2000. This is because in some cases, different product types could be represented by the same dataset. For example the NBS lists around 30 types of insulation, and the impact of each type (e.g. Flexible glass wool mat insulation, rigid polyurethane (PUR) foam insulation, Expanded polystyrene (EPS) bead insulation) will vary per kg of product due to the different input materials used (as shown in Hill, Norton and Dibdiakova (2018) and discussed in Table 5). However it also lists around 30 types of valves (e.g. differential pressure control valves, flow-measuring valves, and low-temperature thermostatic mixing valves), and it is probably less likely that there will be significant variation per kg of these products, as they are more likely to be made of very similar materials with similar processing, even though each product has a different purpose and therefore a different product classification.

The French EPD programme, inies, and the International EPD Programme are the only EPD programmes in Europe to have over 2000 EPD, but the majority of EPD in both these programmes are manufacturer specific rather than collective EPD which provide generic data; for example only around 600 of the over 4,000 EPD in inies are collective EPD. The International EPD also covers many countries, including Turkey, Australasia, Latin America, so is not in any sense a national EPD Programme. Although the number of EPD is growing, and collective EPD are able to provide generic data for use in a region, there are not sufficient collective EPD in any region to provide generic data to cover all construction products. For this reason, generic databases have been provided which offer embodied carbon or LCA data for construction materials for use in building and infrastructure level life cycle assessment.

Where available, generic datasets will be based on collective EPD for the region, but if these have not been produced, then generic datasets are created for the database to represent the expected impact of the product in the region, using a variety of methods taken from the grey literature, for example:

- UK – BRE IMPACT: for construction products that are internationally traded, use ecoinvent datasets directly; for other products, adapt ecoinvent datasets to represent UK production by adjusting material and energy inputs based on publicly available information and historical product data held by BRE (BRE, 2020).
- Germany – oekobaudat: GaBi datasets with a ‘safety margin’ to encourage the provision of sector and manufacturer specific EPD (Gantner et al., 2018).
- France - inies: If there is no EPD but generic data in ecoinvent or the European Life Cycle Database, then that data is used with a ‘coefficient de sécurité’ of 30% to reflect the uncertainty or lower quality of these datasets compared to a collective EPD. If there is only one manufacturer EPD for the product, then the EPD data is used with a coefficient de sécurité of 100%. If there is more than one EPD, then the maximum of the sample, or mean +2 or +3 Standard Deviations, corresponding to a coefficient de sécurité of 30% is used (Ministère du Logement et de l’Habitat Durable and Ministère de l’Environnement de l’Énergie et de la Mer, 2019).

- UK – ICE Database: reviewing available EPD to provide an indicative embodied carbon figure, sometimes this is the average of available data, other times it accounts for a different consumption mix of sub-materials (Hammond and Jones, 2019).

An analysis of the national databases in European countries which are used in nationally regulated building assessment are provided below in Table 24. The methodology for this is described in 3.3.5. This shows the country for which the database is relevant; the database name (some countries have more than one); how it is accessed and managed; whether some type of adjustment factor is used to reflect the uncertainty of generic data or to encourage provision of EPD; the scope of the data; and how many different types of dataset are included.

Norway has introduced a requirement for public buildings to undertake LCA since 2018, but does not have a national database of generic construction product data.

The largest database in terms of generic data is the Dutch National database, NMD, which was used as part of their building regulation requirement for building LCA in 2012. The NMD had only 800 generic product datasets in 2011, shortly before the building-level LCA regulation came into force in 2012 (van Ewijk, 2011) – this has now grown to nearly 2700 generic datasets. The NMD has recently been providing targeted funds for EPD production to grow the database in certain areas, for example natural building materials through its “Witte Vlekken” (White Spot) programme, and has a target of 10,000 datasets (Stichting Nationale Milieudatabase (Stichting NMD), 2022).

The second largest database in terms of both generic and specific data is inies, the French National database, again used as part of their pilot building LCA regulation in 2018 and for the RE2020 regulation now in force. The inies database had 511 generic datasets and 262 collective EPD at the start of 2018, when the pilot building-level embodied carbon regulation came into force (inies, 2018) and this has grown to nearly 2000 generic datasets at the start of 2023.

Third in size in terms of generic data is oekobaudat, the German National Database, which is used in BNB, the national methodology which assesses building LCA and is mandated for larger publicly funded buildings in Germany. It covers all building elements including MEP. It is also used in the DGNB assessments, which require building LCA to be undertaken as part of a voluntary sustainability assessment for buildings. When the regulation for new public buildings to undertake building-level LCA using BNB came into force in 2011, the oekobaudat initially had 680 generic datasets, this has now only risen slightly to 729.

Product embodied carbon data is described as ‘quite scarce’ (One Click LCA, 2022) for Finland and Sweden, and the Scandinavian databases are considerably smaller. For example, in Sweden where building-level embodied carbon has been regulated since 2022, the Boverket database only contains 170 generic datasets and no EPD, although any EPD to EN 15804 can be used in assessments for the specific products they cover, whilst the Finnish database has only 205 generic datasets. However the scope of the Swedish Klimatdeklaration regulation, which requires use of the database is currently only the external fabric, structure, and internal walls, so this may partly account for the smaller number of generic datasets (The Swedish National Board of Housing Building and Planning, 2018).
Table 24 Quantity and types of generic and specific data in Databases used in National Regulation in Europe at the start of January 2023

<table>
<thead>
<tr>
<th>Country</th>
<th>Database</th>
<th>Funded by</th>
<th>Web Access</th>
<th>Digital access (API)</th>
<th>Used in Regulation</th>
<th>Scope: Cradle to:</th>
<th>Adjustment Factors used?</th>
<th>Collective EPD</th>
<th>Generic datasets</th>
<th>Total generic datasets</th>
<th>Total specific EPD</th>
<th>Total datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>Inies</td>
<td>French Government</td>
<td>Free</td>
<td>Paid</td>
<td>Since 2018</td>
<td>Grave</td>
<td>Yes, up to 100%</td>
<td>596</td>
<td>1403</td>
<td>1999</td>
<td>3989</td>
<td>5988</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>Nationale Milieudatabase (NMD)</td>
<td>Dutch Government</td>
<td>For approved tools only</td>
<td>Since 2012</td>
<td>Grave</td>
<td>Yes, default is 30%</td>
<td>375**</td>
<td>1843</td>
<td>2218</td>
<td>939**</td>
<td>3186</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Oekobaudat</td>
<td>German Government</td>
<td>Free</td>
<td>Free</td>
<td>Since 2011 for public buildings</td>
<td>Grave</td>
<td>Yes, up to 30%</td>
<td>192</td>
<td>537</td>
<td>729</td>
<td>1110</td>
<td>1829</td>
</tr>
<tr>
<td>Denmark</td>
<td>Generic Database for Klima-påvirkningen</td>
<td>Danish Government</td>
<td>Free</td>
<td>No</td>
<td>Since 2023</td>
<td>Grave + Module C&amp;D</td>
<td>Yes, uses oekobaudat</td>
<td>34</td>
<td>416</td>
<td>450</td>
<td>0****</td>
<td>450</td>
</tr>
<tr>
<td>Finland</td>
<td>Rakentamisen päästötietokanta</td>
<td>Finnish Government</td>
<td>Free</td>
<td>No</td>
<td>From 2024</td>
<td>Gate + Module D</td>
<td>Yes, 20%</td>
<td>205 datasets, each with typical and conservative values</td>
<td>205</td>
<td>0****</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>Boverkets klimatdatabas</td>
<td>Swedish Government</td>
<td>Free</td>
<td>Yes</td>
<td>Since 2022</td>
<td>Site</td>
<td>Yes, 25%</td>
<td>170</td>
<td>170</td>
<td>0****</td>
<td>170</td>
<td></td>
</tr>
</tbody>
</table>

** Verified data (but not an EPD) can be added by manufacturers and sectors to the NMD. EPD data here therefore exceeds the number of EPD in the MRPI EPD Programme (349) (Stichting Nationale Milieudatabase (Stichting NMD), 2020).
*** Unverified manufacturer-specific datasets (not EPD) (Categorie 3a)
**** Any EPD using EN 15804 can be used.
The Danish database contains 450 generic datasets, 34 of which are collective EPD, and covers all parts of the building including MEP and finishes. Many of the generic datasets in the Danish database are drawn directly from the German database, oekobaudat.

**Discussion**

Summarising information on the number of generic datasets (collective EPD or generic data) that were included in national databases when regulation came into force gives a varied picture (see Table 25), ranging from 170 datasets in Sweden to 800 in the Netherlands. In Germany, where regulation for public buildings has been in place since 2011, there are still only 729 generic datasets.

**Table 25 Summary of generic dataset availability in countries with regulation when regulation introduced and at the start of 2023**

<table>
<thead>
<tr>
<th>Country with Embodied carbon/ LCA Regulation</th>
<th>Year Regulation came/comes into force</th>
<th>Number of generic datasets before regulation (year)</th>
<th>Number of generic datasets at start of 2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>2011</td>
<td>680 (2009)</td>
<td>729</td>
</tr>
<tr>
<td>Netherlands</td>
<td>2012</td>
<td>800 (2011)</td>
<td>2218</td>
</tr>
<tr>
<td>France</td>
<td>2018</td>
<td>773 (2017)</td>
<td>1999</td>
</tr>
<tr>
<td>Sweden</td>
<td>2022</td>
<td>170 (2022)</td>
<td>170</td>
</tr>
<tr>
<td>Denmark</td>
<td>2023</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Finland</td>
<td>2024</td>
<td>205</td>
<td></td>
</tr>
</tbody>
</table>

It is clearly possible to undertake building LCA with as few as 170 generic datasets in the case of Sweden, though the reduced scope of the current regulation may mean that a smaller number of datasets is required. Denmark, where regulation was introduced for buildings over 1000 m² at the start of 2023, has only 450 generic datasets and the database covers both MEP and finishes. The German, French and Dutch regulations also cover the full building, including MEP and finishes and all these databases had around 700-800 datasets when regulation was initiated. Both France and the Netherlands have provided considerably more generic data since regulation was introduced but the German database has only increased in size very slightly.

**Table 26 EPD Numbers over time in national EPD programmes in countries with embodied carbon regulation**

<table>
<thead>
<tr>
<th>EPD/verified data in national EPD programmes and databases</th>
<th>2011</th>
<th>2016</th>
<th>Jan-18</th>
<th>Jan-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands (MRPI EPD Programme)</td>
<td></td>
<td></td>
<td>43</td>
<td>348</td>
</tr>
<tr>
<td>Netherlands (NMD Database)</td>
<td></td>
<td></td>
<td></td>
<td>1324</td>
</tr>
<tr>
<td>Germany (IBU)</td>
<td>160</td>
<td>1000</td>
<td>1640</td>
<td>1336</td>
</tr>
<tr>
<td>Germany/Austria/Switzerland (oekobaudat) +A1</td>
<td>288</td>
<td></td>
<td></td>
<td>617</td>
</tr>
<tr>
<td>Germany/Austria/Switzerland (oekobaudat) +A2</td>
<td></td>
<td>420</td>
<td></td>
<td></td>
</tr>
<tr>
<td>France (inies)</td>
<td>130</td>
<td>670</td>
<td>1615</td>
<td>5411</td>
</tr>
<tr>
<td>Denmark (EPD Danmark)</td>
<td>0</td>
<td>9</td>
<td>16</td>
<td>284</td>
</tr>
<tr>
<td>Finland (RT EPD)</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>218</td>
</tr>
</tbody>
</table>

In terms of EPD numbers over time shown in Table 26, in the Netherlands, there are still only 348 EPD within the MRPI EPD Programme (mostly manufacturer-specific). However, there are 1324 verified LCA datasets within the National NMD Database which are equivalent to EPD, although only accessible via authorised building LCA tools. In Germany, the numbers of IBU EPD have increased significantly since 2011. The drop in numbers from January 2018 to January 2023 is explained in the case study on Germany above. The IBU programme includes EPD from other countries, and many of these EPD have
not been entered into the oekobaudat, which previously required EPD to be in German for example. There are, however, EPD from Austria and Switzerland included in the oekobaudat which are not in IBU. France has shown a very strong increase in EPD numbers since 2011, discussed in the case above. Both Denmark and Finland have increased the number of EPD significantly since 2018, but each have less than 300 EPD.

Having considered the provision of EPD and generic data more widely, in the next section, we next consider the availability of EPD data for the UK.

5.5. Product-level embodied carbon data in the UK

The UK construction products market

The Construction Products Association in the UK states their industry comprises nearly 24,000 companies covering construction product manufacturers and suppliers. Although there are a number of large multi-nationals (for example, Kingspan, Knauf, Saint-Gobain, Rockwool and Tata Steel) and companies owned by multi-nationals, for example, Aggregate Industries (Holcim), Hanson (HeidelbergCement), and Worcester Bosch (BOSCH), and UK listed companies such as Forterra PLC and Ibstock PLC, many thousands are SMEs (Construction Products Association, 2022).

Table 27 Largest manufacturing sectors associated with the construction products industry in 2021 (source: Office for National Statistics (2022))

<table>
<thead>
<tr>
<th>Construction Product related Manufacturing Industry</th>
<th>£ Millions</th>
<th>% of construction products industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal structures and parts of structures</td>
<td>7,818</td>
<td>11.9%</td>
</tr>
<tr>
<td>Plastic plates, sheets, tubes and profiles</td>
<td>6,432</td>
<td>9.8%</td>
</tr>
<tr>
<td>Builders' ware of plastic</td>
<td>4,774</td>
<td>7.3%</td>
</tr>
<tr>
<td>Other builders' carpentry and joinery</td>
<td>4,521</td>
<td>6.9%</td>
</tr>
<tr>
<td>Paints, varnishes and similar coatings, printing ink and mastics</td>
<td>3,949</td>
<td>6.0%</td>
</tr>
<tr>
<td>Concrete products for construction purposes</td>
<td>2,797</td>
<td>4.3%</td>
</tr>
<tr>
<td>Electricity distribution and control apparatus</td>
<td>2,406</td>
<td>3.7%</td>
</tr>
<tr>
<td>Doors and windows of metal</td>
<td>2,228</td>
<td>3.4%</td>
</tr>
<tr>
<td>Kitchen furniture</td>
<td>2,186</td>
<td>3.3%</td>
</tr>
<tr>
<td>Gravel and sand pits; mining of clays and kaolin</td>
<td>2,028</td>
<td>3.1%</td>
</tr>
<tr>
<td>Ready-mixed concrete</td>
<td>1,682</td>
<td>2.6%</td>
</tr>
<tr>
<td>Sawmilling and planing of wood</td>
<td>1,627</td>
<td>2.5%</td>
</tr>
<tr>
<td>Central heating radiators and boilers (2018*)</td>
<td>1,555</td>
<td>2.4%</td>
</tr>
<tr>
<td>Aluminium production</td>
<td>1,513</td>
<td>2.3%</td>
</tr>
<tr>
<td>Other rubber products</td>
<td>1,493</td>
<td>2.3%</td>
</tr>
<tr>
<td>Flat glass</td>
<td>1,471</td>
<td>2.2%</td>
</tr>
<tr>
<td>Veneer sheets and wood-based panels</td>
<td>1,427</td>
<td>2.2%</td>
</tr>
<tr>
<td>Treatment and coating of metals</td>
<td>1,187</td>
<td>1.8%</td>
</tr>
<tr>
<td>Electric lighting equipment</td>
<td>1,129</td>
<td>1.7%</td>
</tr>
<tr>
<td>Office and shop furniture</td>
<td>1,093</td>
<td>1.7%</td>
</tr>
<tr>
<td>Hollow glass</td>
<td>1,060</td>
<td>1.6%</td>
</tr>
<tr>
<td>Other electronic and electric wires and cables</td>
<td>965</td>
<td>1.5%</td>
</tr>
<tr>
<td>Cement</td>
<td>953</td>
<td>1.5%</td>
</tr>
<tr>
<td>Bricks, tiles and construction products, in baked clay</td>
<td>808</td>
<td>1.2%</td>
</tr>
<tr>
<td>Tubes, pipes, hollow profiles and related fittings, of steel</td>
<td>783</td>
<td>1.2%</td>
</tr>
<tr>
<td>Locks and hinges</td>
<td>695</td>
<td>1.1%</td>
</tr>
<tr>
<td>Remaining products</td>
<td>6,873</td>
<td>10.5%</td>
</tr>
</tbody>
</table>
The UK manufactures a wide range of construction products, but the largest sectors (in terms of value, shown in Table 27) are the manufacture of metal structures, plastics, carpentry and joinery, paints & varnishes and concrete, which account for nearly half of the sector’s value in 2021 although not all of the output from these sectors may be used in construction.

Table 28 Largest UK imports by value of products related to the construction sector in 2021. 5 product groups with the largest net import are also included. (BEIS, 2023; United Nations, 2023)

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Import (£m)</th>
<th>% of UK construction product imports</th>
<th>Main source</th>
<th>Net import (£m)</th>
<th>Net Import Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Wires</td>
<td>2,341</td>
<td>12.6%</td>
<td>Non-EU</td>
<td>1,434</td>
<td>2</td>
</tr>
<tr>
<td>Sawn Wood &gt; 6mm thick</td>
<td>1,541</td>
<td>8.3%</td>
<td>EU</td>
<td>1,487</td>
<td>1</td>
</tr>
<tr>
<td>Air Conditioning Equipment</td>
<td>738</td>
<td>4.0%</td>
<td>EU/non-EU</td>
<td>350</td>
<td>7</td>
</tr>
<tr>
<td>Linoleum Floor Coverings</td>
<td>672</td>
<td>3.6%</td>
<td>EU</td>
<td>367</td>
<td>5</td>
</tr>
<tr>
<td>Central Heating Boilers</td>
<td>577</td>
<td>3.1%</td>
<td>EU</td>
<td>388</td>
<td>4</td>
</tr>
<tr>
<td>Builders Ironmongery</td>
<td>554</td>
<td>3.0%</td>
<td>Non-EU</td>
<td>336</td>
<td>9</td>
</tr>
<tr>
<td>Steel for Fabrication</td>
<td>514</td>
<td>2.8%</td>
<td>EU</td>
<td>353</td>
<td>6</td>
</tr>
<tr>
<td>Paints &amp; Varnishes</td>
<td>472</td>
<td>2.5%</td>
<td>EU</td>
<td>-297</td>
<td>90</td>
</tr>
<tr>
<td>Structural Units (steel)</td>
<td>461</td>
<td>2.5%</td>
<td>EU/non-EU</td>
<td>169</td>
<td>24</td>
</tr>
<tr>
<td>Plugs &amp; Sockets</td>
<td>460</td>
<td>2.5%</td>
<td>EU/non-EU</td>
<td>146</td>
<td>29</td>
</tr>
<tr>
<td>Taps &amp; Valves</td>
<td>452</td>
<td>2.4%</td>
<td>Non-EU</td>
<td>346</td>
<td>8</td>
</tr>
<tr>
<td>Unglazed and glazed Ceramic Tiles</td>
<td>444</td>
<td>2.4%</td>
<td>EU</td>
<td>432</td>
<td>3</td>
</tr>
<tr>
<td>Other Plastic Building Products</td>
<td>394</td>
<td>2.1%</td>
<td>EU</td>
<td>206</td>
<td>19</td>
</tr>
<tr>
<td>Aluminium for Fabrication</td>
<td>362</td>
<td>1.9%</td>
<td>EU</td>
<td>219</td>
<td>17</td>
</tr>
<tr>
<td>Radiators</td>
<td>345</td>
<td>1.9%</td>
<td>Non-EU</td>
<td>325</td>
<td>11</td>
</tr>
<tr>
<td>Portland Cement</td>
<td>336</td>
<td>1.8%</td>
<td>Non-EU</td>
<td>327</td>
<td>10</td>
</tr>
<tr>
<td>Structural Units (aluminium)</td>
<td>332</td>
<td>1.8%</td>
<td>EU</td>
<td>257</td>
<td>13</td>
</tr>
<tr>
<td>Fan Systems</td>
<td>316</td>
<td>1.7%</td>
<td>EU</td>
<td>193</td>
<td>21</td>
</tr>
<tr>
<td>Building Stone: processed</td>
<td>290</td>
<td>1.6%</td>
<td>Non-EU</td>
<td>278</td>
<td>12</td>
</tr>
<tr>
<td>Plastic Pipes</td>
<td>286</td>
<td>1.5%</td>
<td>EU</td>
<td>-59</td>
<td>87</td>
</tr>
<tr>
<td>Fire &amp; Security Alarms</td>
<td>272</td>
<td>1.5%</td>
<td>EU</td>
<td>104</td>
<td>38</td>
</tr>
<tr>
<td>Concrete Reinforcing Bars</td>
<td>268</td>
<td>1.4%</td>
<td>EU</td>
<td>233</td>
<td>15</td>
</tr>
<tr>
<td>Ceramic Sanitaryware</td>
<td>261</td>
<td>1.4%</td>
<td>Non-EU</td>
<td>220</td>
<td>16</td>
</tr>
<tr>
<td>Building Stone: unprocessed</td>
<td>257</td>
<td>1.4%</td>
<td>Non-EU</td>
<td>254</td>
<td>14</td>
</tr>
<tr>
<td>Mastics, Putty</td>
<td>256</td>
<td>1.4%</td>
<td>EU</td>
<td>22</td>
<td>62</td>
</tr>
<tr>
<td>Laminated Wood</td>
<td>214</td>
<td>1.4%</td>
<td>Non-EU</td>
<td>197</td>
<td>20</td>
</tr>
<tr>
<td>Concrete Pipes</td>
<td>213</td>
<td>1.4%</td>
<td>EU</td>
<td>182</td>
<td>22</td>
</tr>
<tr>
<td>Space Heaters</td>
<td>233</td>
<td>1.4%</td>
<td>Non-EU</td>
<td>178</td>
<td>23</td>
</tr>
<tr>
<td>Lifts &amp; Escalators</td>
<td>201</td>
<td>1.4%</td>
<td>EU</td>
<td>165</td>
<td>25</td>
</tr>
<tr>
<td>Plastic Sanitaryware</td>
<td>210</td>
<td>1.4%</td>
<td>Non-EU</td>
<td>162</td>
<td>26</td>
</tr>
</tbody>
</table>

75% by value of all construction products used in the UK are made in the UK (Construction Products Association, 2022), with around 60% of all imports coming from the EU (where Germany, Italy and Spain were the biggest import markets) (BEIS, 2021). For imports from outside the EU, the largest import markets were China and Turkey (BEIS, 2021).

The UK manufactures a wide range of construction products, but the largest sectors (in terms of value, shown in Table 27) are the manufacture of metal structures, plastics, carpentry and joinery, paints &
varnishes and concrete, which account for nearly half of the sector’s value in 2021 although not all of the output from these sectors may be used in construction.

Table 28 shows the 25 largest construction products groups in terms of imports, with their share of total construction product imports, and the major import market – collectively these products groups account for around half of all UK construction product imports. In addition 5 products have been included which are not in the top 25 largest imports, but which are significant in terms of net import (imports minus exports).

The product sector classification for UK Manufacturing and for UK trade are not identical, but there is considerable crossover between the product groups with the greatest value in terms of manufacturing and of imports and net imports. However, considering the product groups which are thought to have the largest carbon impact as discussed in the literature review (Cement and concrete, Metals, Timber, Bricks and ceramics and Glass, see Figure 7 in section 2.3.6) then there are a number of product groups commonly used in construction which are significant in terms of value of UK production, imports or net imports, but do not appear to be significant in terms of carbon impact. These are builders’ ware of plastic, paints and varnishes, electricity distribution and control apparatus, radiators and boilers, electric lighting equipment, and electrical wires and cable.

In the next section, we explore the availability of generic data and EPD for construction materials produced and consumed in the UK.

**EPD and other embodied carbon data for construction products currently available for assessments in the UK**

As noted in the Literature review, the UK was once a leader in EPD and building LCA. In 2010, as part of the Code for Sustainable Homes legislation, the UK required embodied impact assessment of the external and internal walls, windows, roof, and upper floors for all publicly funded residential developments, using the 2009 version of the Green Guide to Specification. If a specification was not listed in the Green Guide (which listed over 1200 specifications), then BRE would provide a Green Guide rating on request. This required a core database of around 300 material datasets (see Table 3), many provided by 19 UK trade associations through EPD projects, or through provision of LCA studies or EPD by international trade associations (Anderson, Shiers and Steele, 2009).

Today, there are several sources of generic data for construction products produced in the UK shown in Table 29. None have been directly funded by UK Government for use as a national database, however, indirectly, UK Government has funded the two largest databases though research funding and funding via arm’s-length bodies. Neither are endorsed by Government, although new public buildings are required to undertake BREEAM assessments which use the BRE IMPACT database if they obtain MAT-1 credits, and the arm’s length bodies such as the Highways Agency, Environment Agency and the Rail Safety and Standards Body use the ICE Database for mandatory assessments of carbon impact.

The BRE IMPACT database was originally funded by BRE and Innovate UK as part of the development of the IMPACT - Computational whole-building life cycle assessment and life cycle costing tool. Further developments of the database have been funded by BRE. The Inventory of Carbon and Energy (ICE) database was originally funded by the Carbon Trust and EPSRC through the Carbon Vision Program as a PhD project at Bath University (Hammond and Jones, 2008). The funding for the latest version came from the Environment Agency, the Rail Safety and Standards Board and Heathrow Airport. The Wood for Good and British Constructional Steelwork Association databases have both been funded by the sector bodies themselves.
Table 29 UK Generic Databases

<table>
<thead>
<tr>
<th>Database</th>
<th>Public Access</th>
<th>Digital access (API)</th>
<th>Scope: Cradle to: Penalty Factors used</th>
<th>EPD</th>
<th>Total generic datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRE IMPACT v5, 2018 (P Hermon, personal communication, 15.3.2023)</td>
<td>No</td>
<td>Paid</td>
<td>Grave</td>
<td>No</td>
<td>No*</td>
</tr>
<tr>
<td>ICE database v3 (Hammond and Jones, 2019)</td>
<td>V3 (2019) Free</td>
<td>No</td>
<td>Gate</td>
<td>No</td>
<td>No**</td>
</tr>
<tr>
<td></td>
<td>V2 (2011) Free</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>ICE database v2 (2011)</td>
<td>Paid</td>
<td>No</td>
<td>Gate</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Wood for Good LCI Database</td>
<td>Free</td>
<td>No</td>
<td>Gate + Module s C&amp;D</td>
<td>No</td>
<td>1 UK Sector</td>
</tr>
<tr>
<td>BCSA End of life database</td>
<td>Free</td>
<td>No</td>
<td>Gate + Module s C&amp;D</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

*Various Trade Association/representative manufacturers’ primary data have been used to inform the BRE IMPACT database.

** Some UK sector and specific EPD have been used to inform the datasets in the ICE Database v3.

The BRE IMPACT database has 269 datasets (P Hermon, personal communication, 15.3.2023) and the ICE database has 605 datasets (Hammond and Jones, 2019), each covering a wide range of construction materials, though both exclude MEP. The BRE IMPACT database has been generated by adapting ecoinvent 3.2 datasets for European construction products to the UK situation using UK electricity grid data, and the adaptation has also been informed by various Trade Association/representative manufacturers’ primary data (BRE, 2018), but does not otherwise reflect UK production. The BRE IMPACT database does include gate to grave data based on UK based scenarios defined in the IMPACT methodology, however neither the methodology nor the database are publicly available and there has never been any peer review or public consultation for the BRE IMPACT database.

In contrast, the ICE database is a freely available database of cradle-to-gate embodied carbon data. Version 3 of the ICE database has been created by averaging UK and a selection of other available EPD for each of ten key product groups to produce 427 datasets. The remainder of the database uses 178 datasets from ICE Database v2 which were generated by review of publicly available LCA and carbon footprinting studies rather than EPD in 2011 (Hammond and Jones, 2019). Mohebbi et al. (2021) has identified the ICE Database as a consistent and reliable source of embodied carbon data that is accepted for use in the UK.

Two other generic databases have been produced by product sectors. The Wood for Good life cycle database provides cradle-to-grave LCIA data for a range of timber products, together with glue and steel connections, to allow timber used in construction to be assessed. The BCSA end of life database provides cradle-to-gate and module C and Module D data for a range of structural brick, timber, steel, and concrete products.

There is likely to be considerable overlap between the BRE IMPACT and ICE databases in terms of materials covered, but as the IMPACT database is not publicly available it is not possible to check this. However, considering all the available databases, there are at least 269 cradle-to-grave generic embodied carbon datasets available for the UK which will provide typical transport and end of life data for the products. There are also around 600 cradle-to-gate datasets which just provide typical manufacturing impact. Given the number of datasets available in other European countries’ national
databases prior to regulation, it would seem that these databases may provide a reasonable starting point for the provision of generic datasets for the UK.

Three things should be noted however:

- Firstly the need to update the 178 datasets from ICE v2 – these are based on much older studies than 2011, using different methodologies, and there are likely now to be many more recent EPD and other generic datasets consistently using EN 15804 meaning there should be sufficient data to update these materials in line with the approach used for ICE v3.
- Secondly the need to provide data for MEP, which is not covered by either database. CIBSE have been looking to address this through their TM65 Guidance on providing embodied carbon data for MEP (Hamot and Baganal George, 2021) and as part of this work have initiated a database to collect relevant embodied carbon data including EPD which may provide a useful source in future for the development of generic data for MEP. As MEP is often imported, the generic data provided in other databases (e.g. in France or Germany) may also be suitable for use in the UK.
- Thirdly, the lack of gate to grave data needs to be addressed. The BRE IMPACT database provides this for all its datasets, but the database not currently publicly available. However, both the updated RICS Professional Statement on Whole Life Carbon assessment in the built environment (RICS, 2023) and the revised PCR for the BRE EN 15804 EPD Programme have been sent for consultation in March 2023 (BRE Global, 2023) and it is hoped that through this process, BRE EN 15804 EPD, the BRE IMPACT database and the RICS default gate to grave scenarios will be harmonised, and made available to ensure that EPD for the UK market can make use of these default specifications. This will provide consistent gate to grave data for use in building LCA and embodied carbon assessment. It is also hoped that the gate to grave data from the BRE IMPACT database will be updated in line with the updated RICS Professional Statement and revised BRE EN 15804 EPD and might be made publicly available in future, particularly given the involvement of BRE in the Built Environment Carbon Database (BEC) project (see 2.3.6).

**EPD data for UK manufacturers**

Using the methodology set out in 3.3.6, there is evidence that the number of EPD for UK manufacturers are growing rapidly. At the start of 2021, the BRE EN 15804 EPD programme, the only Programme in the UK, had just over 250 EPD, but many of these were for companies manufacturing overseas. For various reasons, UK producers have tended to use a range of EPD programmes across Europe. In 2021, taking account of EPD for UK manufactured products listed in all EPD programmes including IBU (Germany), International EPD (Sweden), EPD Norge (Norway), EPD Ireland and manufacturer’s own programmes (e.g. Tata Steel), there were 351 EPD for UK produced products. By the start of 2022 this had grown to over 450 EPD from over 80 manufacturers and 12 Trade Associations, and at the start of 2023, there were 600 EPD for UK produced products from over 110 companies and 5 UK trade associations, covering a broad range of products as shown in Appendix D: EPD for construction products produced in the UK.

In sectors like flooring, coatings and finishes, precast concrete, insulation and suspended ceilings, many UK manufacturers already have EPD for their product ranges, for example there are 11 manufacturers and two European trade associations behind the 123 flooring EPD, and 15 manufacturers and 5 European trade associations behind the 50 EPD for insulation. However in sectors like brick or stone, EPD for UK produced products are a rarity, with just one collective EPD for UK brick, and one manufacturer specific EPD for stone for example.
As for ECO Platform EPD, insulation, wall and floor coverings, gypsum products, paint, precast concrete and ready-mix concrete and mortars and metal products account for the majority of the UK EPD by product type, as shown in Figure 28.

The EPD found for UK manufacturers and Trade Associations are listed in Appendix D: EPD for construction products produced in the UK, broken down into product types. In addition, the listing includes a number of EPD from European Trade Associations and manufacturer bodies which provide average data for products produced and purchased across Europe which may be relevant to the UK. It also includes data from a small number of EPD from European trade associations which are unverified or Life Cycle Assessment studies.

The importance of imported construction products

However, as discussed above, the UK also imports significant quantities of construction products. In the following pages, the product groups which were highlighted as having the largest contribution to GHG emissions in the literature review, Cement and concrete, Metals, Timber, Bricks and ceramics and Glass, have been explored by checking the available embodied carbon data, for example considering the availability of generic data for the product in countries for key import markets, and the availability of manufacturer specific EPD for the key import markets.

This data, together with an overview of UK production and imports, and the availability of an EPD Tools to assist manufacturers in producing EPD, have been assembled together as part of this research, into a series of Embodied Carbon Product Datasheets, using the methodology described in section 3.4. The resulting Embodied Carbon Product Datasheets are provided in Appendix E: Embodied Carbon Product Datasheets for the product groups and sub-groups below:

- Cement and concrete  
  o Cement  
  o Ready-mix concrete and mortar  
  o Precast concrete  
- Metals  
  o Steel structures and structural steel  
  o Reinforcing Steel
• Electrical wiring
  • Brick and ceramics
    o Brick
    o Ceramic tiles
    o Ceramic sanitaryware.
  • Timber
    o Sawn kiln dried softwood
    o Engineered Timber
    o Wood panel products

These product groups have been chosen because they have the largest embodied carbon impact at UK level, as discussed in 2.3.7, and the sub-product groups have been chosen because they are significant in terms of value of UK production (see Table 27) or in terms of net imports (see Table 28).

The datasheets show that for the concrete product group, covering Cement, Ready-mix and Precast concrete, there are both UK collective EPD and low-cost EPD tools available that would allow the main players in the industry to produce specific EPD for their products.

For metals, there are no collective EPD for the UK, but the main UK players have EPD, although for Tata Steel, the EPD cover both UK and Dutch production. There are some collective and specific EPD that cover imported steels, and there are low-cost EPD tools that can be used to produce EPD for specific products. However for electrical wiring, there is limited availability of EPD, though there are lots of generic datasets available in France and Germany and some specific EPD in France.

For bricks, the UK industry had access to an EPD tool, but has only produced one collective EPD. There are collective EPD covering most of the main import markets, (Belgium, Netherlands) and some specific EPD for German imports. Data in the EDGE India database may be suitable for imported brick from India and Pakistan (International Finance Corporation, 2017). There is an EPD for the UK’s only large-scale ceramic tile manufacturer, and collective EPD for Spanish and Italian ceramic tiles, the two largest import markets. For ceramic sanitaryware, like ceramic tiles, most consumption is imported but there are no collective EPD, but a reasonable number of specific EPD for Italy, Germany, and Turkey, but not China (the main source of imports). There is a low-cost EPD tool for brick and ceramic products.

For timber, there is one UK collective EPD for UK produced kiln dried softwood, and generic datasets for UK consumed timber products including engineered timber and wood panel products. There are also collective EPD for kiln dried and engineered timber from Sweden, Germany, North America, and France, and lots of specific EPD from Norway and for wood panel products, from Germany and Ireland. Timber Development UK has access to a low-cost EPD tool for wood and biobased products for its members (Timber Development UK (TDUK), no date).

Looking at these product groups, there appears to be reasonable availability of either collective EPD or generic data covering UK produced and imported products, though there is often a lack of specific EPD for UK production. There are, however, low cost EPD tools available for most of these product groups which would enable manufacturers to produce EPD relatively easily and cheaply, in some cases facilitated by the relevant trade association.

5.6. Is there sufficient data for the UK to mandate embodied carbon assessment?

There is evidence that the number of EPD for UK produced products has been rising steadily at around 125 new EPD each year since 2021, but with only 110 UK companies having around 600 EPD in 2023, coverage is very much lower than the 40% of product portfolios targeted by CO2nstructZero (CO2nstructZero and Construction Leadership Council, 2022), which would require 9,600 of the 24,000
UK manufacturing companies stated by the Construction Products Association to have EPD across their range of products.

Across some sectors, for example, flooring and insulation, there are a broad range of UK manufacturers with EPD, but there are also UK EPD for much less commonly used products such as straw, sheep’s wool, reused steel and reused raised access flooring, which might previously have relied on an assumption of sustainability rather than producing EPD to demonstrate this.

However, the 600 UK EPD compares well with the 617 EPD in the oekobaudat (used for mandatory BNB LCA assessments in Germany), and with the number of EPD in Denmark and Finland which have recently introduced regulation of embodied carbon. Looking back at the number of EPD in Germany and France when regulation was introduced, the UK compares very well, with 288 EPD in oekobaudat in 2011 and 670 EPD in inies in 2016. Given many of the products used in the UK are imported, and may already have EPD, then the situation certainly does not appear to suggest a scarcity that would preclude the introduction of embodied carbon regulation in the UK. There is also ample evidence that the introduction of regulation would stimulate the UK market to produce EPD, as it has done in other countries.

In terms of generic data, the database used in the BRE Green Guide (Anderson, Shiers and Steele, 2009), which was a pre-cursor to the BRE IMPACT database, had around 300 generic datasets, and was able to assess all key elements for publicly funded residential construction as part of the requirements of the Code for Sustainable Homes. And the Greater London Authority has been able to introduce a requirement for embodied carbon assessment for referable schemes, with projects using either the BRE IMPACT or ICE v3 databases and EPD to provide generic data (Mayor of London, 2022).

Considering other countries which have introduced regulation of embodied carbon at building level, then for example, Sweden has required measurement of embodied carbon since the start of 2022 with less than 200 generic datasets available in its national database, and Denmark has required measurement of embodied carbon since the start of 2023, with 450 generic datasets, including those for MEP and finishes. Germany has had around 600-700 generic datasets in the oekobaudat since 2009 when the requirement for BNB was first announced.

It would appear therefore that the existing UK generic databases together offer a sufficient number of datasets to cover most construction materials and allow embodied carbon assessment. However there are gaps, particularly for MEP equipment, which it is hoped the CIBSE MEP Embodied Carbon database and their work on TM65 will address. As much MEP equipment is imported, the generic and specific datasets for MEP equipment, available through the inies database in France and oekobaudat database in Germany for example, both of which are publicly available, may also prove useful in quickly generating relevant generic data.

The other area where there is a lack of data for the UK is in public availability of data for the gate to grave, for example, end of life scenarios and Module D. Although all EPD to EN 15804+A2 now need to provide data for Modules C and D, the scenarios that they use may not be relevant to the UK, or may make use of different assumptions.

The update of the RICS Professional Statement on Whole Life Carbon (RICS, 2023) is intended to provide default transport, wastage and end of life scenarios for different product groups, using the same data as the BRE IMPACT database and the revision of the BRE EPD programme product category rules (BRE Global, 2023). These scenarios will be consulted on before publication. Once they have been published, it should mean that EPD intended for the UK market can use the default end of life scenarios giving consistent data to be used in UK building and infrastructure assessments. It will also mean that these UK scenarios can be incorporated into future CEN Product Standards complying with EN 15804 meaning any EPD going to market in the UK will be able to provide relevant and consistent information.
for end of life scenarios. This will also make it easier to provide average embodied carbon data for these modules for a UK database, aligning with the cradle-to-grave data, or alternatively, the BRE may make the BRE IMPACT database available publicly, or at least its embodied carbon indicators.

It therefore seems likely that relying on the ICE and IMPACT databases, the CIBSE TM65 initiative, and the hopeful signs for a publicly available consistent gate to grave embodied carbon database and the growing resource of EPD, that the UK could consider regulating embodied carbon based on this data, relying on the expected growth of UK EPD once regulation is signposted.

Digitisation is the other factor which is likely to drive data production. Once all EPD can be produced digitally, with API from EPD repositories such as the ECO Portal or BECD allowing direct access by Embodied Carbon tools, then it is more likely that EPD will be used. Digitisation should also make it easier to find EPD. Verified EPD tools will also be able to provide EPD digitally, with initiatives such as Échanges de Données Environnementales Configurées (EDEC) in France allowing manufacturers and building assessors to store EPD produced from verified EPD tools without the need for EPD Registration, and to allow integrated access to building assessment tools. If EPD are provided with parameterised digital data for scenarios such as end of life, then this will be able to be used in tools to provide specific scenarios for different countries, for example meeting the different requirements as part of regulation of embodied carbon assessment.

5.7. Discussion and conclusion

The analysis has recorded an exponential growth in EPD numbers, with over 40,000 EPD to EN 15804 and 90,000 EPD to ISO 21930 now available. The role of automated verified EPD tools in driving numbers is evident in the 25,000 European EPD from these tools to EN 15804, and over 80,000 EPD from verified concrete EPD tools in the US to ISO 21930. There is also a growing interest in EPD to EN 15804 seen outside of Europe and North America, with new EPD programmes in China and Australia, and the International EPD® programme partnering with EPD programmes in Australasia, Turkey, Latin America, South East Asia, Russia and Egypt and offices in China. Certain product groups are dominant in terms of EPD numbers, with seven products (insulation, wall and floor coverings, gypsum products, paint, precast concrete and ready-mix concrete and mortars and metal products) responsible for more than half of each of the ECO Platform programme members EPD.

The literature review identified numerous drivers for growth of EPD, and across the countries studied, there is evidence that many of them have had an effect.

Green public procurement (GPP) has had a clear effect in Germany, where public buildings are required to meet limits in terms of embodied impacts checked with a life cycle assessment, in the USA where the various ‘Buy Clean’ and ‘Low carbon concrete’ legislations at state and county level appear to be driving EPD growth, and in Norway where the Government used GPP to specifically drive the growth in EPD.

Green Building Certification has been successful in driving EPD numbers, particularly in the US where the LEED EPD credit was considered to be responsible for much of the initial growth of the UL Environment EPD programme.

All the programme operators which started early are now amongst the largest programmes, and the later programmes do appear to be slower to grow.

Regulation in France has certainly driven EPD numbers and the number of manufacturer specific datasets in the Netherlands, as has the requirement for public buildings to undertake LCA assessments in Germany. With regulation also comes support for databases and EPD production, discussed below.
Automation of the EPD production process is another factor which has clearly driven data production, with the number of EPD from EPD tools in France, Germany and the US demonstrating this. Initiatives such as Échanges de Données Environnementales Configurées (EDEC) in France allowing manufacturers and building assessors to store EPD produced from verified EPD tools without the need for EPD Registration, and to allow integrated access to building assessment tools, are also clearly successful.

Digitisation of EPD, making it easier for them to be accessed and incorporated into EPD tools and assessments, is also clearly behind some of the success of the French and German programmes with the inies and oekobaudat databases, and Norway has also been leading with EPD digitisation initiatives and the use of EN ISO 22057:2021 which uses data templates to provide EPD and generic data in a format which can be used within BIM. The EC3 tool in the US has also revolutionised the way in which people are able to search for and access the thousands of concrete EPD now available there.

Government support for EPD appears to be influential, with the French, German and Dutch Governments supporting the provision of generic datasets and the upkeep of their national databases, and the German Government actively driving digitisation of EPD through the InData project. In the US, the Inflation Reduction Act is intended to provide $250 million in grants and support for companies to produce EPD and is expected to have significant impact. Other government support includes the White Spot initiative in the Netherlands, providing €2.5k per dataset towards the provision of 190 datasets for products missing from the national database (Stichting Nationale Milieudatabase (Stichting NMD), 2022), the Irish government providing Enterprise funding for companies producing EPD (EPD Ireland, 2020), and the low cost of EPD registration in France.

Reviewing the case studies, the use of safety factors in France and uplift factors in Germany for generic data appear to have driven the production of specific EPD, as well as collective EPD, with the provision of collective EPD also noted to have facilitated the production of manufacturer specific EPD in Germany.

The size of the UK construction product sector is large, and trying to get 40% of the 24,000 companies based here to produce EPD for their portfolios by 2025, as suggested by the CO2nstructZero performance metric (CO2nstructZero and Construction Leadership Council, 2022), seems unlikely and perhaps unnecessary, even if the availability of low-cost EPD tools may make this more feasible. 25% by value of our construction products are imported, and some of our top imports are MEP like wiring, air conditioning equipment, boilers and taps which are among the product groups CIBSE have noted there is a shortage of EPD, hence their CIBSE TM65 guidance to try to address this. Much of this MEP, and other imports, come from the EU and the availability of generic data in the oekobaudat and inies databases for these items may prove useful. Denmark, for example, has used oekobaudat data for much of its generic database.

Most countries which have initiated regulation of embodied carbon or a requirement for building LCA have produced national databases (Norway is the exception). These databases range in size, from 170 and 205 datasets in Sweden and Finland, where regulation is just introduced, to 2000 or so in France and the Netherlands. Germany, France and the Netherlands all had around 700-800 datasets when regulation was introduced, and Germany still has around that number.

Looking back to the use of the Green Guide to Specification in the Code for Sustainable Homes, around 300 datasets were needed to provide data for most residential constructions. The GLA have been able to regulate for the provision of whole life carbon assessments for larger referable products using the BRE IMPACT (269 datasets) or ICE Database (605 datasets) and EPD. It will be important to update the ICEv2 datasets, and to develop more extensive gate to grave scenario data for products however but the proposed alignment of the updated RICS Professional Statement of Whole Life Carbon and the BRE
IMPACT methodology based on the updated BRE EN 15804 PCR seems hopeful that common scenarios can be agreed, and these datasets provided.

UK Manufacturers are producing EPD in increasing numbers, and 600 EPD were found at the start of 2023, provided by over 110 companies and 5 trade associations, and in some sectors, such as flooring and insulation, 26 manufacturers with EPD. However, other sectors, such as brick and stone, have one EPD each. There are also EPD for less commonly used construction products, such as sheep’s wool insulation, reused raised access flooring and straw bales, which some may have been expected to rely on their perceived environmental credentials rather than provide EPD to demonstrate this.

Reviewing the Embodied Carbon Product Datasheets, it seems clear that for many of the key materials, there is suitable data available, and the access for the industry to make use of low-cost EPD tools to provide EPD. Trade bodies such as British Precast, Timber Development UK and the Alliance for Sustainable Building Products have arranged discounted access to One Click LCA EPD tools, and other organisations such as the Mineral Products Association have access to the GCCA EPD tool for cement and concrete.

It therefore seems that the UK is in a reasonable position with regard to both generic data and EPD, with the exception of gate to grave data and the update of the ICE V2 datasets. It is just that the drivers, in terms of green public procurement and regulation of embodied carbon, are not present and driving the market, and some of the barriers, such as cost of registering EPD and a clearly signposted UK database (hopefully to be addressed by the BECD), have not been addressed.

Clear government support and endorsement of EPD, such as provided in Norway through GPP initiatives encouraging EPD; Germany through funding the development of generic datasets for the oekobaudat and digitisation initiatives; France through funding the development of generic datasets for the inies database, its low cost of EPD registration and their endorsement of EPD tools; the Netherlands development of generic datasets and through funding the national database and White Spot scheme to fill data gaps; and Ireland through its Enterprise funding, would all be very helpful in ensuring the UK has a suitable embodied carbon data resource to enable regulation.

In the next chapter, the wide variation of the embodied carbon coefficients of construction products that has been noted in the literature review is explored in greater detail, making use of the large number of EPD that are now available as a resource to do this.
6. Explorations of Variation in EPD data

6.1. Introduction

This chapter responds to the third research question: What are the causes of variation in EPD?

The literature review has highlighted the wide variation in embodied carbon that is found for construction products like cement, insulation, and timber. Although there are papers that say that technological differences are likely to be behind the variations (e.g. Hodková and Lasvaux, 2012; Silvestre et al., 2015; Galindro et al., 2020), in other papers, the underlying causes of variation have not been explored (e.g. Ganassali et al., 2018; Welling and Ryding, 2021; Marsh et al., 2021). However a small number of authors say the variation seems too great to be due to technological and geographical differences alone; they suggest that methodological inconsistency or poor data quality may be responsible (e.g. Moncaster et al., 2018; Waldman, Huang and Simonen, 2020; Crawford and Stephan, 2022). Adding weight to these suggestions, several papers have discussed how many EPD fail to comply with ISO 14025 or are not transparent enough to allow comparison between products (e.g. Gelowitz and McArthur, 2017; Moré, Galindro and Soares, 2022). If this is the case, then it is one of the main limitations to developing policy to measure and reduce embodied emissions. This chapter therefore considers to what extent these concerns are substantiated.

It is therefore necessary to understand whether the variations of impact seen in EPD are due to variability, because if so, then improvements in methodology and compliance will have little effect, and EPD should be considered reliable. If, however, the variation is not caused by variability, but by uncertainty, then improvements in methodology and compliance must be considered before EPD can be considered reliable enough to enable robust embodied carbon assessment.

The number of EPD now available is extensive. Alongside embodied carbon data, these EPD provide details of the types and amounts of energy, and the types of manufacturing processes, inputs and secondary material used. Based on the findings in 2.3.7, this chapter analyses published EPD for some of the most commonly used and impactful construction product groups, including cement and concrete, steel, brick and timber. The methodological approach used for these analyses is described in 3.3.7. Using a typology of variability, the analysis identifies ‘EPD Landscapes’ for products - their range of impacts – and uses these with the information provided on manufacturing processes, inputs and the energy used to check whether the variation seen can be attributed to ‘inherent variations in the real world.’ It therefore aims to understand whether the variation seen in EPD for key construction products can be explained by variability, and can thus be considered a robust and reliable data source.

This chapter is based on a quantitative analysis, the methodology for data collection is described in section 3.3.7 and 3.3.8 and the analysis is described in 3.4.2.

6.2. Typology of variability

Although other authors have looked at variability of specific parameters for particular products, for example Chen et al. (2010) for cement, and AzariJafari, Yahia and Amor (2018) and DeRousseau et al. (2020) for concrete mixes, a typology of variability does not appear to have been used. For this research, as the analysis of EPD progressed, a typology of variability was developed as the causes of variability became clearer. The typology addresses aleatory uncertainty or variability (from innate differences in processes which are unavoidable) rather than epistemic uncertainty which can be reduced through improved processes and methodology. The first level of classification for the typology was into variability related to technology, geography, and time. Further types of variability were then identified, for example for technological variability, differences in input materials,
manufacturing technology, energy sources and product design were found to cause variability in embodied carbon coefficient. The overall typology is described in Figure 29.

Figure 29 Typology of Causes of Variability developed from the analysis

6.3. Types of technological variability

The types of technological variability considered in this section include differences in input materials, manufacturing technology, choice of energy used and the product design. The type of technology and the inputs to a process are often intrinsically linked. Energy demand is also often linked to the choice of technology and can also be influenced by the product design. Different product group EPD have been used to demonstrate the different causes of technological variability.

6.3.1. Variability due to input materials

Cement is an example of a construction material which has very wide variation in reported embodied carbon (see, for example, Pomponi and Moncaster, 2018, and Hammond and Jones, 2019).

Analysing all the available EPD for cements globally found at the end of 2019, the range of GWP per tonne found was from 273 kgCO2e/tonne to 1040 kgCO2e/tonne, with a median of 736 kgCO2e/tonne and a mean of 700 kgCO2/tonne.

Figure 30 shows the range of GWP (A1-A3) for all the available EPD for CEM I, CEM II and CEM III published globally at the end of 2019. This is an EPD Landscape, developed as described in Section 3.3.7. As set out in EN 197-1:2011 (CEN/TC 51, 2011) and described in Table 11, cements are classified into different types based on the amount of clinker (predominantly calcined limestone) and the proportion of different cementitious constituents that are used to replace it, such as limestone or fly ash. For this product group, it is largely just the proportions of the different input materials that vary, although the clinker can also have different impacts. Figure 30 clearly demonstrates that the different types of cements have very different impact, driven by their different inputs, with CEM I (clinker with no more than 5% additional constituents) having the highest impacts, followed by CEM II-A cements (with 80-94% clinker), then CEM II-B cements with 65-79% clinker and CEM III cements have the lowest impact, again with CEM III-A with 35-74% clinker having more impact than CEM III-B cements, which with only 20-34% clinker have the lowest impact seen.

When the range for individual product types is considered, it can be seen to be much smaller than for cements overall, typically less than 200 kgCO2e. The range for ‘average cements’, most of which are averages of national production, is also large, countries produce different proportions of CEM I, CEM II and CEM III for example. Larger ranges are also seen for the overarching product groups CEM II and CEM III for example. In the case of the range for CEM II, this includes CEM II/A with 80-94% clinker and CEM II/B with 65-79% clinker, and various cement replacements including limestone, GGBS or fly ash. CEM III can range from CEM III/A with 36% GGBS to CEM III/C with up to 95% GGBS.
Using different input materials, such as by-products or low impact alternatives (e.g. recycled content), can significantly affect and reduce embodied carbon coefficients. But as discussed in Chapter 3.5, it is important to note that where the use of these alternatives is constrained (e.g. because all the available supply is already used regionally as with GGBS), then although this may show a reduction in impact at product level or building level, there may be no overall reduction in national or global emissions.

6.3.2. Variability due to different manufacturing technology

For steel, a slightly different situation is seen. Here the use of the secondary material, steel scrap, is commonly linked to the technology required, as the blast furnace/basic oxygen furnace (BF/BOF) process normally has a maximum input of around 25-30% scrap (Hall, Zhang and Li, 2021). The electric arc furnace (EAF) process on the other hand, can use entirely scrap as the input apart from a very small proportion of alloying elements, although it can also be used with varying proportions up to 100% of direct reduced iron (DRI), which has no secondary material input. Figure 31 shows the range of embodied carbon coefficient for A1-A3 for all global steel EPD registered in 2020, with either a reported secondary material content over 1 tonne per tonne (so ~100% scrap input and thus using the EAF process technology) or of less than 250 kg/tonne (so thus using either the BF/BOF process technology or the DRI/EAF process). Only a small number of EPD specified the use of direct reduced iron (DRI) when using less than 250 kg secondary material per tonne, and these have been plotted separately on the graph in Figure 31, showing this process has much higher impact than EAF using scrap steel input. This highlights the effect that the use of both secondary material input and process can have on embodied carbon coefficient.

Figure 30 EPD Landscape for CEM I, CEM II and CEM III EPD, showing the GWP range by type. Adapted from analysis presented in Anderson and Moncaster, 2020.
Figure 31 EPD Landscape for steel EPD, showing the range of GWP dependent on recycled content and process. Adapted from analysis presented in Moncaster, Anderson and Mulligan, 2021.

Figure 32 shows the A1-A3 embodied carbon coefficient from steel EPD differentiated by product type. It might appear that product type has considerable influence on impact, but it is in fact, more a reflection on whether BF/BOF or EAF steel is used for each particular product type, for example, coil, light steel and sheet steel, hollow sections and plate are all manufactured almost entirely using BF/BOF, whereas reinforcing steel, open sections and sheet piling are manufactured using either BF/BOF or scrap based EAF according to Swann (2021). Reinforcing steel shows the lowest impacts, due to the common use of the EAF process and most commonly, scrap steel. Structural steel (hollow sections made with BF/BOF and open sections made with a mix of EAF and BF/BOF shows the widest range of impacts because it is commonly made using both processes.

If the supply of the input material driving lower impact technologies is somewhat constrained (e.g. for EAF with scrap steel, the end of life steel recovery rate has been estimated at over 80% (World Steel Association, 2010)), then although moving to higher use of the input material such as scrap steel may show a reduction in impact at product level or building level, there may be no corresponding overall reduction in national or global emissions if other products or buildings as a result use lower quantities of the input material.
6.3.3. Variability due to energy source

The different sources of energy used in materials production are a further cause of variability. CEM I cements generally have similar inputs as they must always contain 95% clinker, and equally have similar manufacturing processes to produce the clinker and blend to CEM I. However, there is still an interquartile range of embodied carbon coefficient from 750-900 kgCO$_2$e/tonne for CEM I as shown in Figure 30. Differences in the types of fuels used, particularly use of waste-derived fuels (reported in EPD with the ‘Use of renewable/non-renewable secondary fuel’ indicators and in Figure 33 with SF-NR and SF-R), and the different adoption of fuels and energy from renewable sources (PERT and SF-R in Figure 33) are both probable causes of this variation in GWP. The carbon intensity of electricity may also be driving the use of renewable energy, shown with the PERT indicator in Figure 33, as CEM I cements from countries such as Switzerland and France with low carbon grid electricity have lower impacts; while those with higher impacts are from Italy and Spain which have historically higher carbon grid electricity.

![Figure 33: CEM I EPD: energy consumption, ECO$_2$ and clinker content, based on analysis previously presented in Anderson and Moncaster, 2020.](image)

The impact of the carbon intensity of the energy used can also be seen in the steel data. For steel products using the Electric Arc Furnace (EAF) with 100% scrap input, there is a clear correlation between embodied carbon coefficient, and the percentage of renewable energy used, as shown in Figure 34. The carbon intensity of grid electricity varies by country (see Figure 38) so in many cases, this can be considered a geographical issue, but manufacturers may also invest in their own generation (for example onsite PV or wind turbines).
Figure 34 suggests that increasing the proportion of renewable energy used reduces the GWP and total primary energy demand for EAF steel, up to around 30% renewable energy. However, the effect is much less pronounced over 30% renewable energy. This raises the question, does increasing the percentage of renewable energy sourced have this effect for all types of construction products; this is further explored for a range of key construction products in Chapter 7, whilst this chapter continues to explore causes of variation.

6.3.4. Variability due to product design

In some cases, it is the design of the product which appears to influence the embodied carbon coefficient. EPD for four different types of clay bricks were analysed.

The analysis covers EPD which were available at the end of 2020 for 37 Ziegel bricks, 18 facing bricks, 5 handmade or twice fired bricks, and 1 reclaimed brick, and Figure 36 shows the analysis of GWP (A1-A3) for the different types of brick. As can be seen, the embodied carbon coefficient of the reclaimed brick is very low, while Ziegel bricks generally have lower GWP than facing bricks, and the handmade bricks and twice fired bricks have the highest GWP.

Reviewing the type and amount of energy provided in the EPD in more detail, as shown in Figure 37, the design of the Ziegel bricks, with a lower density and greater surface area due to the perforations, is likely to have contributed to the lower GWP, as around 25% of the Ziegel bricks have a lower energy demand per tonne than the best facing brick. Ziegel bricks also generally use higher proportions of renewable energy than facing bricks, again reducing their impact relative to facing bricks per tonne. The four Ziegel bricks with the highest proportion of renewable energy had similar energy demand to the handmade or twice fired bricks, but because a high proportion of that energy was renewable, they didn’t have correspondingly high GWP. The handmade and twice fired bricks have a high energy demand, and do not use a high proportion of renewable energy, so their high embodied carbon coefficient is not surprising.
It is clear from this brief example that product design can influence the impact of construction product manufacture, and that it provides significant opportunities to reduce embodied carbon at the product level. But product design can also be used to reduce the mass of product required to provide the required functionality at building level.

6.4. Types of geographical variability

Geographical variability in embodied carbon coefficient could be caused by differences in electricity grids, supply chains and transport distances in different regions and countries, with the variability in carbon impact for grid electricity being one of the most well-known geographical variabilities in GWP shown below (Figure 38).
6.4.1. Variability due to differences in electricity grids

![Figure 38 Carbon intensity of Electricity for the EU27, 2021 (source: European Environment Agency (EAA), 2022)](image)

CARES (a steel certification body) have produced EPD for their members producing reinforcing steel with 100% scrap using a pre-verified EPD tool, which has a single model using the same data sources for upstream data. These EPD therefore use a common methodology and upstream LCI data to provide information about the same technological process. Additionally, CARES audit the manufacturing data provided by their members ensuring minimal chance of any error in the foreground data (Brankley et al., 2017). However, as can be seen in Figure 39 below, there is still considerable variation in both the total amount of energy required to produce 1 tonne of reinforcing steel, and the amount of GWP generated. The EPD with the lowest GWP represents production in France, where electricity has low carbon intensity due to the significant share of nuclear energy.

![Figure 39 GWP and Total Energy Demand for EPD for reinforcing steel (100% scrap) from CARES members](image)

6.4.2. Variability due to differences in typical practices

For average concrete EPD produced by national trade associations, shown in Figure 40, higher impacts per m³ are seen for concretes from the USA and Canada; and those with lower impacts are from France and Germany. The differences here are likely to be related to the typical impact of cement clinker in the country (and as discussed in 6.3.3, the amount of renewable and waste fuels used for cement production) and differences in typical practice regarding use of alternative cementitious materials such as GGBS and PFA in these countries.
Figure 40 GWP of Generic Concrete EPD from national trade associations per m$^3$ by 28-day compressive strength. Adapted from analysis presented in Anderson and Moncaster, 2020.

6.4.3. Variability due to differences in scenarios

Another way in which geography affects impact is the ‘gate to grave’ scenarios for products. There are very different end of life scenarios (Module C and Module D according to EN 15804) for various construction products in different countries, as shown Figure 41 and Figure 42 which provides the different split of end of life routes for construction and demolition waste and for timber. For example, the UK recycles over 90% of construction and demolition waste, whereas in France, Spain, Poland, and Norway, over 20% is still landfilled. The differences for end of life timber are even more extreme: although the EU generally recycles 50% and recovers energy from 50%, some states (e.g. Denmark, Spain, Italy, and Austria recycle between 80-100% of timber, in Finland and Sweden, almost 100% is used for energy recovery, and in the Czech Republic and Malta, nearly 100% is landfilled. (In the UK, according to DEFRA (2021), in 2018 45% of wood wastes were recycled, 11% were used for energy recovery and 41% were incinerated in incinerators without R1 status (see IX Glossary)). These very different end of life routes will have different impacts in Modules C3 and C4, and different benefits in Module D, for example for recycling versus landfill or energy recovery versus incineration. The different approaches to end of life scenarios within EPD for wood panel products and polystyrene insulation are explored below.

Figure 41 EoL routes for mineral Construction and demolition waste for Europe, 2020, source Eurostat (2023); UK, 2018, source DEFRA and Government Statistical Service (2021)
As shown in Figure 41 and Figure 42 above, the recovery of waste from the built environment differs across Europe. A review of EPD for wood panel products and polystyrene insulation was undertaken to consider how gate to grave scenarios were modelled. The methodology for the analysis is described in 3.2.

The analysis identified that in 2019, a significant proportion of polystyrene and wood panel products EPD compliant with EN 15804+A1 (where end of life reporting is not mandatory) already reported Modules C1-C4 and Module D. This differs somewhat from the findings of Stapel et al. (2022) who reviewed nearly 1200 digital EPD from ECO Platform and found nearly 50% only reported Modules A1-A3 (manufacturing) and only 43% reported the product end of life (modules C1-C4).

CEN/TR 16970:2016 (CEN/TC 350, 2016) states in 6.3.8, that

*when different scenarios are developed for information modules C1-C4 the most relevant scenarios are provided as 100% versions. For example, when 20% of a product is recycled, 50% is incinerated and 30% is deposited, scenarios for 100% of 100% of incineration, 100% of recycling and 100% of deposition are declared. This allows the building assessor to choose and calculate the correct scenario on building level as actual waste management practices vary in different member states.*

Four separate classifications of scenarios have been used to classify scenarios for the construction, use and end of life stages and for Module D in EN 15804 EPD as described in detail in the methodology in section 3.3.8:

- ‘100%’ scenarios
- ‘Mixed’ scenarios
- ‘Multiple’ 100% scenarios
- ‘Mixed+100%’ scenarios.

The modules considered for each EPD were C1 (deconstruction and demolition processes), C2 (transport to waste processing), C3 (waste processing), C4 (disposal) and Module D (loads and benefits from recovery).
EPS and XPS polystyrene insulation

20 EPD from nine EPD programmes using EN 15804:2012+A1:2013 were identified and analysed under the product category ‘polystyrene insulation’ and the results are provided in Table 30. Where several EPD for different but very similar specific products from the same manufacturer were produced using the same scenarios, only one was assessed.

10 EPD provided 100% scenarios, four provided two separate 100% scenarios and five EPD provided a ‘mixed’ scenario. There were also some differences in the way in which EPD reporting a 100% scenario for C3 declared module C4 and vice versa. Only 1 EPD did not report any scenarios or impacts for the end of life stage.

3 EPD declared C1 to be zero, with only 1 EPD declaring an impact for demolition. The other EPD did not declare scenarios or impacts for C1.

16 of the 20 EPD declared C2 with quite varied scenarios. Distances included 10 km, 50 km, 200 km, and one Norwegian EPD used 1000 km by road to a recycling plant. For such a lightweight product as polystyrene insulation, it would be expected that the volume capacity might be considered in the transport scenarios, but few EPD mention it: two used a 5% capacity including empty returns, one 18% capacity and one 21%. Fuel consumption for the trucks was reported variously as 0.2 l/km, 0.38 l/km, 25 l/km, 0.173 l/tkm (tonnes.km), 0.4 l/tkm, and 0.026 l/tkm for the large capacity trucks travelling 1000 km. Such varied fuel consumption in the background data, coupled with very different transport distances could lead to very different impacts for C2 (as part of this study however, the reported GWP results were not compared).

There was a wide range of waste treatment and disposal options in the 19 EPD which reported impacts in C3 or C4, including recycling, energy recovery in C3 and incineration with energy recovery and landfill in C4.

14 of the 20 EPD declared Module D showing the benefit of energy and material recovery, though six EPD did not describe the exact energy substitution process(es). Only one described the type of electricity substituted (EU grid mix). For heat, the substituted energy sources were natural gas (3 EPD), oil (2 EPD) and district heating (2 EPD).

Wood panel products: OSB, MDF, particleboard/chipboard and plywood

Twenty-five EPD from five EPD programs were considered within this product group and details of the modules reported and scenarios used were described in Table 31. 4 EPD did not report any end of life scenarios or impacts. 2 EPD used multiple scenarios, 3 EPD used mixed scenarios and the remainder (16) used a 100% scenario. As for polystyrene, very few (5) declared C1. For the 7 EPD which reported C2 (transport to waste processing), scenarios were also varied with distances ranging from 20 to 100 km. Although almost all EPD declaring end of life modelled use of the waste timber for energy, there was a big variation with 8 modelling it as using the waste for energy recovery in C3, 4 modelling incineration in C4, and 8 modelling processing to recover waste as secondary fuels in C3. 2 EPD modelled recycling to substitute virgin woodchip and 1 modelled reuse. 2 EPD modelled landfill and 1 modelled landfill as part of a mixed scenario. As for polystyrene, there was a lack a clarity over the substituted primary processes in Module D, though more EPD mentioned substituting a national or EU average mix.
### Table 30 Scenario data for Polystyrene Insulation EPD. Adapted from analysis presented in Anderson, Rønning and Moncaster, 2019

<table>
<thead>
<tr>
<th>Product</th>
<th>Scenario type</th>
<th>Stated scenario for Module C1</th>
<th>Stated scenario for Module C2 (all road transport)</th>
<th>Stated scenario for Module C3</th>
<th>Stated scenario for Module C4</th>
<th>Stated scenario for Module D</th>
<th>Programme/ Location of Manufacture</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>100%</td>
<td>Collection, no impact</td>
<td>10 km, 5% capacity</td>
<td>Energy recovery</td>
<td>MNR</td>
<td>Substitution exported energy</td>
<td>DK / DK</td>
</tr>
<tr>
<td>EPS</td>
<td>100%</td>
<td>Collection, no impact</td>
<td>10 km, 5% capacity</td>
<td>Energy recovery</td>
<td>MNR</td>
<td>Substitution exported energy</td>
<td>DK / DK</td>
</tr>
<tr>
<td>EPS</td>
<td>100%</td>
<td>Deconstruction</td>
<td>Zero impact</td>
<td>Energy recovery</td>
<td>Zero impact</td>
<td>Substitution exported heat (district heat)</td>
<td>RT / FI</td>
</tr>
<tr>
<td>EPS</td>
<td>mixed</td>
<td>Collection, no impact</td>
<td>10 km</td>
<td>44% recycling, 53% energy recovery</td>
<td>2% landfill</td>
<td>Substitution exported heat + electricity and virgin product</td>
<td>EPD-Norge/ NO, SE</td>
</tr>
<tr>
<td>EPS</td>
<td>multiple 100%</td>
<td>MND</td>
<td>No info</td>
<td>Recycling</td>
<td>related disposal</td>
<td>Substitution of virgin product</td>
<td>EPD Italy/ IT</td>
</tr>
<tr>
<td>EPS</td>
<td>100%</td>
<td>Collection, no impact</td>
<td>25 km</td>
<td>Zero impact</td>
<td>Landfill</td>
<td>Substitution of exported energy</td>
<td>Inies/ FR</td>
</tr>
<tr>
<td>EPS</td>
<td>multiple 100%</td>
<td>MNR</td>
<td>50 km</td>
<td>Recycling</td>
<td>zero impact</td>
<td>Substitution of virgin EPS</td>
<td>IBU / EU</td>
</tr>
<tr>
<td>EPS</td>
<td>100%</td>
<td>MND</td>
<td>MND</td>
<td>Incineration eff.&lt;60%</td>
<td>MND</td>
<td>Substitution exported heat +electricity</td>
<td>IBU / DE</td>
</tr>
<tr>
<td>EPS</td>
<td>MND</td>
<td>MND</td>
<td>MND</td>
<td>MND</td>
<td>MND</td>
<td>EPD Ireland/ IE</td>
<td></td>
</tr>
<tr>
<td>XPS</td>
<td>mixed</td>
<td>INA</td>
<td>INA</td>
<td>50% reaches End of Waste on collection</td>
<td>50% landfill</td>
<td>50% processed to substitute of virgin product</td>
<td>BRE/ PO, CZ</td>
</tr>
<tr>
<td>XPS</td>
<td>mixed</td>
<td>MND</td>
<td>50 km, 21% capacity</td>
<td>MND</td>
<td>10% incineration, 90% landfill</td>
<td>MND</td>
<td>BRE / UK</td>
</tr>
<tr>
<td>XPS</td>
<td>100%</td>
<td>Collection, no impact</td>
<td>50 km</td>
<td>no recycling</td>
<td>Landfill</td>
<td>MND</td>
<td>International EPD/ ES, PT</td>
</tr>
<tr>
<td>XPS</td>
<td>100%</td>
<td>MND</td>
<td>MND</td>
<td>MND</td>
<td>Landfill</td>
<td>MND</td>
<td>International EPD/ TU</td>
</tr>
<tr>
<td>XPS</td>
<td>multiple 100%</td>
<td>MND</td>
<td>no info</td>
<td>MND</td>
<td>Landfill</td>
<td>MND</td>
<td>IBU / EU</td>
</tr>
<tr>
<td>XPS</td>
<td>100%</td>
<td>Collection, no impact</td>
<td>not info</td>
<td>Energy recovery</td>
<td>Zero impact</td>
<td>Substitution exported heat (district heat)</td>
<td>RT / FI, LI, ES</td>
</tr>
<tr>
<td>XPS</td>
<td>multiple 100%</td>
<td>MNR</td>
<td>no info</td>
<td>MND</td>
<td>Landfill</td>
<td>Substitution exported electricity (EU) + heat (natural gas)</td>
<td>IBU / DE</td>
</tr>
<tr>
<td>XPS</td>
<td>multiple 100%</td>
<td>MNR</td>
<td>no info</td>
<td>MND</td>
<td>Landfill</td>
<td>Substitution exported electricity (EU) + heat (natural gas)</td>
<td>IBU / DE</td>
</tr>
<tr>
<td>XPS</td>
<td>mixed</td>
<td>MND</td>
<td>18% capacity, 10 km to ER, 1000 km to recycling</td>
<td>28% recycling, 63% energy recovery</td>
<td>9% landfill</td>
<td>Substitution of virgin polystyrene, exported electricity + heat (oil)</td>
<td>EPD Norge/ NO, SE</td>
</tr>
<tr>
<td>XPS</td>
<td>mixed</td>
<td>MND</td>
<td>10 km</td>
<td>44% recycling, 53% Energy recovery</td>
<td>3% landfill</td>
<td>Substitution of virgin polystyrene, exported electricity + heat (oil)</td>
<td>EPD Norge/ NO</td>
</tr>
<tr>
<td>XPS</td>
<td>100%</td>
<td>Mixed waste collection</td>
<td>200 km</td>
<td>Zero impact</td>
<td>Landfill</td>
<td>MND</td>
<td>Inies/ FR</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Product description</th>
<th>Scenario type</th>
<th>Stated scenario for C1 (all road transport)</th>
<th>Stated scenario for C2</th>
<th>Stated scenario for C3</th>
<th>Stated scenario for C4</th>
<th>Stated scenario for Module D</th>
<th>Programme/ Location of Manufacture</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDF</td>
<td>MND</td>
<td>MND</td>
<td>MND</td>
<td>Shredding + energy recovery</td>
<td>Substitution exported heat (natural gas)</td>
<td>EPD Australasia / Australia</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>multiple 100%</td>
<td>MND</td>
<td>MND</td>
<td>Recycling to wood chip</td>
<td>Substitution (virgin wood chip)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>mixed</td>
<td>Mixed wood waste 85km in NO. % to SE</td>
<td>90% Energy Recovery</td>
<td>2% landfill, 7% incineration</td>
<td>Substitution exported electricity + heat (NO + SE)</td>
<td>EPD Norge /Norway</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>100% not given</td>
<td>85km</td>
<td>Energy recovery</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>EPD Norge /Norway</td>
<td></td>
</tr>
<tr>
<td>MDF*</td>
<td>MND</td>
<td>MND</td>
<td>Chipping to secondary fuel</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>IBU / Germany</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>100% Removal</td>
<td>MND</td>
<td>Secondary fuel use, EU average substitution</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>IBU / Germany</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>100% Removal</td>
<td>MND</td>
<td>Substitution exported electricity</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>IBU / Germany</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>MDF</td>
<td>MND</td>
<td>Substitution exported electricity</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>IBU / Poland</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>100%</td>
<td>MND</td>
<td>Energy recovery</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>International EPD /Spain and Portugal</td>
<td></td>
</tr>
<tr>
<td>OSB</td>
<td>MND</td>
<td>MND</td>
<td>Chipping to secondary fuel</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>IBU / Germany</td>
<td></td>
</tr>
<tr>
<td>OSB</td>
<td>100%</td>
<td>MND</td>
<td>Substitution exported heat &amp; electricity</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>IBU / Poland</td>
<td></td>
</tr>
<tr>
<td>OSB</td>
<td>100%</td>
<td>MND</td>
<td>Only biogenic CO₂ transfer</td>
<td>MND</td>
<td>Substitution exported heat &amp; electricity</td>
<td>IBU / Germany</td>
<td></td>
</tr>
<tr>
<td>Particleboard</td>
<td>mixed</td>
<td>Mixed construction waste 33% 85km (NO), 67% by road and sea (SE)</td>
<td>91% Energy Recovery</td>
<td>2% Landfill 7% incineration</td>
<td>Substitution exported electricity &amp; heat (NO + SE)</td>
<td>EPD Norge /Norway</td>
<td></td>
</tr>
<tr>
<td>Particleboard</td>
<td>100%</td>
<td>MND</td>
<td>Only biogenic CO₂ transfer</td>
<td>MND</td>
<td>Substitution exported heat</td>
<td>IBU / Austria</td>
<td></td>
</tr>
<tr>
<td>Particleboard</td>
<td>100%</td>
<td>MND</td>
<td>Substitution exported heat</td>
<td>MND</td>
<td>Substitution exported heat</td>
<td>IBU / Belgium</td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>100%</td>
<td>Mixed construction waste 85km Only biogenic CO₂ transfer</td>
<td>Energy recovery eff. &lt;60%</td>
<td>MND</td>
<td>Substitution exported electricity + heat</td>
<td>EPD Norge / Norway</td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>mixed</td>
<td>not given</td>
<td>85km Energy recovery</td>
<td>Landfill of ER ash</td>
<td>Substitution exported electricity + heat</td>
<td>EPD Norge / Sweden</td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>multiple 100%</td>
<td>MND</td>
<td>Chipping to secondary fuel</td>
<td>Zero impact</td>
<td>Secondary fuel use, substitution heat (natural gas)</td>
<td>International EPD /Australia</td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Recycling to wood chip</td>
<td>Zero impact</td>
<td>Substitution of virgin woodchip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Reuse</td>
<td>Zero impact</td>
<td>Substitution of virgin product</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Zero impact</td>
<td>Landfill DOCF 0.7%</td>
<td>Substitution exported heat &amp; electricity from landfill gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Landfill DOCF 10%</td>
<td>Substitution exported heat &amp; electricity from landfill gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Substitution exported heat &amp; electricity from landfill gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Zero impact</td>
<td>Landfill DOCF 10%</td>
<td>Substitution exported heat &amp; electricity from landfill gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>MND</td>
<td>MND</td>
<td>Substitution exported heat &amp; electricity from landfill gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood panel</td>
<td>100% not given</td>
<td>100km</td>
<td>Energy Recovery</td>
<td>MND</td>
<td>MND</td>
<td>FDES /France</td>
<td></td>
</tr>
</tbody>
</table>

**Table 31 Scenario data for wood panel product EPD. Adapted from analysis presented in Anderson, Renning and Moncaster, 2019**
Discussion of variability of end of life scenarios

This analysis of end of life scenarios and reporting highlighted the wide variation in end of life routes assumed within EPD. The review raised concerns about possible errors in modelling or reporting of fuel consumption and vehicle capacity, differences in assumptions for transport distances, and the differences in the ‘end of waste state’ used. The ‘end of waste state’ can vary regionally as markets and demand may differ, the secondary material may not be commonly used in some regions and the legal definition of end of waste may also vary. But even for MDF EPD for the German Market, there was not consistency regarding the end of waste state – with one assuming the end of waste is reached before chipping and another assuming it is used as waste in an incinerator without R1 status (see IX Glossary). The analysis showed these differences in scenarios can also lead to differences in impact reported in Module C and Module D.

Although there are geographical differences in scenarios which contribute to variability, the differences and the variation seen in scenario data more likely fit under the definition of uncertainty. The wide uncertainty in scenarios also means that there is a general level of distrust with gate to grave scenario data, with many building LCA tool providers stating in an ISO Workshop led by ISO TC59 SC17 WG3 that they did not use gate to grave data from EPD in their tools (ISO TC59 SC17 WG3, 2017).

Provision of national default scenarios, such as that for the Netherlands (Stichting Bouwkwaliteit, 2014) reduce the effort to produce gate to grave EPD data for that market, as manufacturers generally have limited experience of scenarios beyond delivery of their products to site, and LCA practitioners will not need to individually research and develop representative end of life scenarios. This is also likely to be associated with reduced costs for EPD production, and greater consistency in building level assessments at a national level, particularly where benchmarking or limit values will be set.

Many EPD provide insufficient information on scenarios to allow those using EPD for building LCA to ensure, as suggested by EN 15978 10.2.3,

*Any scenarios incorporated in the EPD and/or other information used for the assessment should be checked for consistency with the scenarios for the building.*

If the type of heat or electricity substituted in Module D is not provided for example, then the module cannot be checked for consistency with building level scenarios for substitution and a new scenario for Module D will have to be modelled.

Very few of the EPD provided more than one 100% scenario for different end of life options, although there were several different end of life routes given across the product groups. EPD providing mixed scenarios did not provide any 100% scenarios for the individual processes despite the text in CEN/TR 16970:2016 6.3.8 recommending this. Complementary PCR (c-PCR) produced by Product TCs to EN 15804 have also failed to recommend this option, although it would help to deal with the different end of life options available in different locations due to variations in legislation, recycling schemes and treatments available. Providing 100% scenarios for recycling, energy recovery, landfill, and incineration (potentially with different end-of-waste states if relevant) gives an understanding of the different impacts of these end of life options and can be used for buildings currently being demolished, wherever they are, to assess the most advantageous options. Where 100% scenarios are reported for re-use and/or recycling in addition to energy recovery, they also enable use of the data for different building level scenarios, such as design for deconstruction, providing encouragement for the circular economy.

6.4.4. Summary of findings about geographical variability

These analyses have demonstrated that geographical differences can have significant influence on the impact of construction products, caused, for example, by different electricity mixes, or different
practices (for example the common use of cement alternatives or different scenarios at end of life). Looking back to the analysis of cements in 6.3.1, the proportion of CEM I, CEM II and CEM III produced in different countries seen in the variation of average cement impact had a geographic aspect, as did the different designs of bricks shown in 6.3.4, with the use of Ziegel bricks being much more common in continental Europe than in the UK. Ziegel bricks are also currently not manufactured in the UK and therefore the impact of transporting them from Europe will need to be considered, whereas facing bricks are available very locally in many parts of the UK.

6.5. Temporal variability

It is well known that the impact of electricity generation has reduced over time as countries look to address climate change and decarbonise their grid (see Figure 43 for the data for EU electricity), so it is clear that processes based on use of grid electricity should show reduced embodied carbon impact over time.

![Figure 43 Carbon intensity (grams CO₂e/kWh) for EU Electricity, source (EAA, 2022)](image)

EN 15804 requires that the most current data shall be used to generate the EPD. However, the life cycle inventory (LCI) data for electricity in common databases such as GaBi and ecoinvent are generally several years behind current practice, for example for the UK, GaBi 2021 and ecoinvent 3.8, both released in 2021, only provided data for the UK electricity grid in 2017 (ecoinvent, 2021; Sphera, 2021), and EPD registered in any given year will often be based on versions of databases from previous years.

Increasing energy costs and concern about climate change have also driven improvements in process efficiency and emissions in the long term, as shown, for example for aluminium (van der Voet, van Oers and Huele, 2014) and UK cement (Mineral Products Association (MPA), 2015). More recent data (Sustainable Concrete Forum, 2021) however suggests that although UK concrete has reduced its carbon intensity (CO₂e/typical m³) by nearly 30% since 1990, it slowed to reduce by only 1.8% between 2015 and 2019, suggesting more serious technical changes will be required to make further reductions.

Figure 44 shows the impact of cement in Cementitious EPD by year of EPD registration and clinker content. Scrivener, John, & Gartner (2018) showed an increase in supplementary cementitious material (SCM) over time for WBCSD CSI members which would be matched by a reduction in the clinker content over time. However there is neither any clear decrease in clinker content for the EPD over time or any clear reduction in GWP over time. For the EPD for concrete which provide this information, the average clinker content reported is 75%.
A review of the effect on the reported GWP of the year of data collection for EPD for steels (differentiated by type) also showed no particular trend, as shown in Figure 45. This may be due to the inclusion of EPD from a wide range of countries with widely different grids, and also the fact that EPD can rely on manufacturing data for several years earlier.

Figure 46 shows the year of Registration for EPD for concretes (differentiated by compressive strength) and GWP, and shows no particular trend over time for concrete impact, although it is clear that there was a strong interest in producing EPD for concrete products in 2016, which coincided with the publication of both the American and Canadian Ready-mix Concrete Association’s collective EPD.

An additional type of temporal variation or uncertainty is as impact assessment approaches improve and update, for example, Stapel et al. (2022) found a roughly 3-5% increase in embodied carbon coefficient in digitised to EPD EN 15804+A2 compared to EN 15804+A1, consistent with the increase in GWP factors for methane and carbon monoxide in (IPCC Working Group III, 2021).
The review of EPD showed temporal aspects related to the year of registration or data collection appeared to have no significant influence on the GWP, however this may reflect similar stagnation of GWP reduction that has been described in the UK concrete and brick industry (Sustainable Concrete Forum, 2021, p. 3; The Brick Development Association, 2022, p. 12). With the decarbonisation of construction product manufacturing which is proposed by industry (ARUP, Giesekam and UK Green Building Council, 2021), embodied carbon coefficients could be expected to reduce by 10% or more over the course of an EPD’s 5 year validity if the decarbonisation was steady. However it may be more likely that decarbonisation will be occur irregularly as technology and investment becomes available, in which case it may be more sensible to produce new EPD after each major decarbonisation intervention, once data is available, even if this is less than 5 years from original registration.

6.6. Variability due to granularity

Granularity was used by Hodková and Lasvaux (2012) to consider how an individual manufacturer’s data sits within the range of values for a group of manufacturers for example. As an EPD becomes more granular (and describes a more specific product), its variance decreases, and its representativeness increases.

EN 15804 requires that a description of the range or variability of the LCIA results is provided, if significant, for average EPD covering several products, but this is rarely done, potentially because no guidance on what level of variability is significant has been provided in the standard. One EPD that has provided information that can be used to assess variability is a cement EPD for Buzzi Unicem in Italy (Buzzi Unicem Spa, 2017), a manufacturer that provides a range of cements across a range of sites. The EPD provides the GWP results for each cement product from each site, together with weighted averages for each product and for each site. Looking at specific products as shown in Figure 47, there is significant variability across sites (for example from 886 to 995kgCO₂e/tonne for CEM I 42.5N and 641-766 kgCO₂e/tonne for CEM II/B-LL).
As the data is all provided within one EPD with the same underlying methodological choices and LCI data, the variability between products and sites cannot be due to differences in methodology or background data, but only due to actual differences in production. Using this data, it is possible to visually illustrate the issue of granularity for product selection.

If we were to take the CEM I cement produced at Vernasca, the EPD gives its impact as 956 kgCO₂e/tonne (shown as the horizontal blue line). This is a little above the average Buzzi Unicem CEM I (923 kgCO₂e/tonne) but within the interquartile range. It is well above the impact of the average cement for the Vernasca site (749 kgCO₂e/tonne) and also its interquartile range (in fact it is the highest impact product at Vernasca). It is also well above the average Buzzi Unicem cement (775 kgCO₂e/tonne). Rather than providing an EPD which provides data for all of its products and sites, Buzzi Unicem could have produced a site specific EPD for the average cement, or perhaps the cement they sell the most; they could have used the averages across all sites to produce product specific EPD (e.g. the average CEM I), or they could have produced a manufacturer average EPD to represent the average Buzzi Unicem cement. All these EPD would each have correctly represented, as a weighted average, the given selection of products and sites. However, each EPD would have had different granularity and representativity.

![Variation in Buzzi Unicem EPD](image)

**Figure 47 EPD Landscape for Buzzi Unicem cement EPD by site (covering all products produced) and by product type (from all production sites). Analysis previously presented in Moncaster, Anderson and Mulligan, 2021.**

It is also possible that variation is introduced where manufacturers choose to produce EPD with different granularity. If one manufacturer chooses to produce an EPD only for the best product with the lowest embodied carbon coefficient per tonne, another an average EPD for their range, and another for all the products in their range, then there will greater variation across the three EPD than if each manufacturer produced the same type of EPD.

The other potential issue related to the granularity of EPD data arises if many manufacturers with poorly performing products decide not to produce specific EPD, but to rely on the average EPD, whilst those with better performing products choose to produce specific EPD. In this case, although the average EPD will be representative of the product group generally, it will be less representative of the products that rely on the average EPD (more of the poorly performing products). To investigate this, it is really necessary to have an EPD which has collected data from across the industry to provide the
average for the sector, and then to see how the specific EPD relate to this in terms of impact. In fact, looking at EPD for concrete from the UK as shown in Figure 48, then the UK generic, which is based on a generic mix and on manufacturing data from 93% of UK concrete producers, appears in fact to be slightly better than the majority of the EPD, and there doesn’t seem to be evidence of manufacturers not producing EPD if they are worse than the average.

![Figure 48](image.png)

*Figure 48 Concrete EPD from UK manufacturers showing their impact in relation to the UK generic concrete*

In fact, if a sample of data is used for a sector average EPD, then an individual manufacturer’s impact may be outside the variation described in the EPD. At a national level, collective EPD may look to represent the impact of both home-produced and imported products which will increase the likely range of values they represent. A generic dataset (not an EPD but a dataset within an LCI database for example) may even be an expert estimate of the impact of the typical product rather than drawing on manufacturer data, further increasing its uncertainty. However each EPD and dataset will only provide a single value for the GWP of the product represented, potentially with a description (which may be qualitative not quantitative) of the variability of the overall data.

The granularity of EPD affects their impact. Sector average EPD with low granularity have a clear role to play in early design, or when specific data is not available. Highly granular specific EPD for individual manufacturer’s products would clearly give the most accurate representation of the building’s impact when products have been specified or installed. But this must be balanced against the difficulties that will occur if so much data is made available, given the difficulties described by the Embodied Carbon Expert Practitioners and discussed in section 4.5, around linking large amounts of product data with embodied carbon models and tools and trying to use it to make comparisons and select products.

6.7. Discussion and conclusion

The literature revealed differences in opinion regarding the variation seen in embodied carbon for construction products, with some suggesting they were due to differences in technology and geography, (e.g. Azarijafari et al. (2021), Hodková and Lasvaux (2012), Lasvaux *et al.* (2015)) which could be considered as due to ‘variability’ as discussed by Huijbregts (1998), and others that they were due to problems with methodology and quality (e.g. Moncaster *et al.* (2018); Waldman, Huang and Simonen (2020); Crawford and Stephan (2022)) which could be considered as due to ‘uncertainty.’ This chapter has considered the variations found in EPD data for key construction materials and considered
whether they can be attributed to variability classified the different causes of variations found in EPD into a typology and looked to understand their significance.

The typology of variation includes types of technological variation (due to differences in inputs materials, technology, energy and product design), types of geographical variation (due to differences in electricity and energy mix) and differences in scenarios, types of temporal variation (such as changes in grid mix or impact assessment methodologies), and variation due to Granularity (i.e. the specificity of the EPD).

Table 32 overleaf describes the different types of variability found in impacts and the range of variability seen for the various examples considered from the analysed EPD. In many cases, the effect will not be purely due to one variable, but potentially a number of variables. The difference in the medians of the range of variability shown has been used to give an indication of the effect. Considering the effect of these types of variability on different products would no doubt provide different ranges. The indicative ranges for the examples should not be seen as being directly relevant to other product groups, nor a likely maximum or minimum range, but they do give an indication as to the scale of variability that could be seen across a product group.

In relation to types of variation caused by technology, the review of EPD also found large differences in embodied carbon coefficient (up to 300% variation) within product groups which can be attributed to differences in technology and input materials, for example, the difference for the BOF and EAF production routes for steel, for different types of cement and concrete, or between facing or Ziegel bricks. Reviewing EPD which have used a common methodology and background data (for example the Buzzi Unicem or CARES EPD produced using an EPD tool, significant variation is still clearly seen across sites (e.g. 15% across CEM I and 20% for CEM II/B-LL in the Buzziem EPD) and across products suggesting these variations are purely caused by technological and geographical differences rather than methodological ones.

The review of EPD also shows that the types of energy used for a particular product also leads to large variations of embodied carbon coefficient, for example the amount of renewable energy used for EAF steel and for facing and Ziegel bricks both vary significantly across the product groups, and have a consequential effect on embodied carbon coefficient (>200%, or even greater (300-1100 kgCO₂e/tonne) for the CARES EPD for reinforcing steel produced from 100% recycled steel).

The analysis also noted that moving to much higher proportions of renewable energy use for EAF steel may not be associated with further reductions in embodied carbon, and this will be explored further in Chapter 8.

Considering the effect of product design, it was clear that this can have a significant effect on the impact of bricks, but also that EPD could be more transparent where differences in product design affect their functionality and the quantity of product required. For example the density and thermal resistance of bricks were often not provided meaning that EPD could not be easily used to correctly compare the environmental impact of two or more products with required insulation in a wall with the same thermal resistance.

The range of variation in impact due to technology highlights the opportunities that exist to reduce impact though use of different processes, different inputs, better efficiencies, and different energy mix for example. It also means that there are good opportunities to procure and increase demand for products with lower impact and thus shift production away from more impactful technologies. However care must be taken when moving to lower impact processes which may be supply constrained (e.g. GGBS, recycled content, renewable electricity), to ensure that this will result in embodied carbon reduction not just at product and building level, but also at a global level.
## Table 32 Typology of variability and indicative effect on impact

<table>
<thead>
<tr>
<th>Type of variability</th>
<th>Sub-type of variability</th>
<th>Example from Chapter 6</th>
<th>Indicative Variation seen in Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological variability</strong></td>
<td>Input Materials</td>
<td>Use of cement replacements in CEM I (&lt;5%) and CEM III/B (66-80%)</td>
<td>300-850 kgCO₂e/tonne (65%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EAF steel (&gt;1 t scrap/tonne) and DRI/EAF steel (0-250kg scrap/tonne)</td>
<td>750-2900 kgCO₂e/tonne (74%)</td>
</tr>
<tr>
<td></td>
<td>Technology and input</td>
<td>BOF steel (0-250 kg/tonne) and DRI/EAF steel (0-250 kg/tonne)</td>
<td>2500 – 3000 kgCO₂e/tonne (17%)</td>
</tr>
<tr>
<td></td>
<td>Technology</td>
<td>Facing bricks and handmade/twice fired facing bricks</td>
<td>150-500 kgCO₂e/tonne (70%)</td>
</tr>
<tr>
<td></td>
<td>Energy Source</td>
<td>CEM I cements</td>
<td>700-930 kgCO₂e/tonne (25%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EAF steels (5% renewable energy and 20% renewable energy)</td>
<td>600 – 1000 kgCO₂e/tonne (40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CARES EAF Steels (100% scrap)</td>
<td>290-1120 kgCO₂e/tonne (74%)</td>
</tr>
<tr>
<td></td>
<td>Product Design</td>
<td>Facing and Ziegel bricks</td>
<td>120-220 kgCO₂e/tonne (45%)</td>
</tr>
<tr>
<td><strong>Geographical variability</strong></td>
<td>Electricity grid</td>
<td>Sweden, EU 27, and Estonia</td>
<td>9, 275 and 946 gCO₂e/kWh. (-97% +344% to EU27)</td>
</tr>
<tr>
<td></td>
<td>Supply chain</td>
<td>Typical French and German concrete and Canadian and US concrete (25Mpa)</td>
<td>180 kgCO₂e/m³ and 300 kgCO₂e/m³ (40% reduction)</td>
</tr>
<tr>
<td></td>
<td>Scenario Data</td>
<td>Landfilling of Mineral Construction &amp; Demolition waste</td>
<td>UK &lt;5%, France 25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incineration of non-hazardous timber waste</td>
<td>EU-27 1%, UK 41%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recycling of non-hazardous timber waste</td>
<td>EU-27 48%, UK 45%, Finland 5%, Italy, and Denmark, &gt;80%</td>
</tr>
<tr>
<td><strong>Temporal variability</strong></td>
<td>Grid electricity improvement</td>
<td>EU, 2015-2020</td>
<td>314-265 gCO₂e/kWh (15% reduction)</td>
</tr>
<tr>
<td></td>
<td>Process improvement</td>
<td>UK concrete, 2015-2019</td>
<td>1.8%</td>
</tr>
<tr>
<td><strong>Granularity</strong></td>
<td>Type of EPD used</td>
<td>Buzzi Unicem average cement by site</td>
<td>780±100 kgCO₂e/tonne</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buzzi Unicem average CEM I by site</td>
<td>940±50 kgCO₂e/tonne</td>
</tr>
</tbody>
</table>
It is also clear from reviewing both the literature and the EPD that variation of embodied carbon coefficient across a particular product group is rarely normally distributed, and the type of distribution and range is a consequence of at least the different types of product, the technologies available, the range of input materials used, and the types of energy used, meaning that the variation in impact seen across each broad product group is likely to be unique. Understanding these causes of variation and the range of variation for each product group will be essential to making use of this data in benchmarking, product selection and eco-design.

Geographical variation was also clear in the EPD analysed. Often the variation appeared to be linked to different energy mixes, different acceptance of the use of alternative input materials or to product designs. As with changes in input materials, moving to use a greater proportion of renewable energy should ensure that the renewable energy is additional, and would need to avoid the ‘double counting’ of benefits that can occur with use of Guarantee of Origin (ISO, 2018, para. 6.4.9.4.4) and also ensure that the change is associated with reduced embodied carbon.

There was also considerable variation in the actual scenarios reported in EPD, and in the transparency with which they describe those scenarios. This limits both the comparability of EPD and their use to provide information for gate to grave scenarios at building level. For example some building LCA tool providers have said that they do not use any gate to grave data from EPD in their tools for these reasons (ISO TC59 SC17 WG3, 2017).

Provision of national scenarios are seen to be useful in reducing effort and cost for manufacturers who may have limited knowledge of scenarios beyond the delivery of their products to site. National scenarios are also useful in ensuring consistency in building level assessments, particularly where benchmarking or limit values will be set.

Very few of the EPD studied provided more than one ‘100% scenario’ and many provided ‘mixed scenarios’ without providing the underlying ‘100% scenarios,’ as suggested in CEN/TR 16970. Again, this limits the use of EPD and means the data is less likely to be used at building level.

Carbon intensity data for electricity shows improvements over time in most European countries, however the review of EPD did not find any trends in embodied carbon coefficients over time and UK industry data for concrete and brick also showed very little change in emissions in recent years (Sustainable Concrete Forum, 2021; The Brick Development Association, 2022). It could be expected however, that as industry’s efforts to decarbonise increase as 2050 draws closer, significant change will be seen. This may require efforts to address this issue if EPD continue to have a validity of 5 years, as this period may encompass significant changes in impact. In future, it should also be possible to review the changing impacts of individual products, product sectors, and even a representative ‘basket of products’ over time, using their EPD to show trends in decarbonisation.

EN 15804 and ISO 21930 have reduced much of the variation that was previously seen in EPD in the 1990’s and 2000’s. Variations due to methodological differences do exist, but are generally of a much smaller magnitude that those which are seen for technological and geographical differences and would not be considered likely to be the major cause of the variations seen in the embodied carbon coefficient of construction products.

However there are clearly areas where there are still different interpretations and a lack of transparency about the method followed in published EPD, particularly for co-product allocation to low value co-products and treatment of waste derived energy. Much greater transparency in reporting the approach to allocation, modelling the use of waste and recovered energy and substitution processes in Module D for example, together with better implementation of the guidance provided in CEN/TR 16970 (CEN/TC 350, 2016).
It is also extremely important that EPD are transparent about the methodological choices they have made regarding allocation, system boundaries at end of life, use of LCI databases etc, particularly where this may be associated with ambiguity or differences in interpretation of the relevant standard, e.g. particularly in regard to the use of economic allocation to low value co-products or the use of waste in energy recovery and co-incineration, the exact position of the end-of-waste state used or the exact substitution processes used in Module D.

The efforts of ECO Platform to bring about greater consistency in EPD is welcomed, and it is hoped that it will continue to lead on this issue, allowing standardisation across EPD programmes to EN 15804 much more quickly than CEN/TC 350 and the Product TCs are able to act.

A number of problems have been seen with EPD, for example in the reporting of recycled content and use secondary material, and in accounting for sequestered biogenic carbon, errors in the reporting of primary energy data were also found during the analysis. Following this review, as EPD programmes have been made aware of the errors, a number of EPD have been corrected.

It is hoped that more guidance will be provided for both practitioners and verifiers to ensure these problems are addressed. As EPD are increasingly digitised, it should become easier in future to check EPD against other similar products to review the plausibility of data, particularly for the indicators outside of embodied carbon where checking the plausibility of results usually has a high focus.

The granularity of EPD clearly affects their impact. Sector average EPD with low granularity have a clear role to play in early design which was a point made by the Embodied Carbon Expert Practitioners (ECEPs), or when specific data is not available. Highly granular specific EPD for individual manufacturer’s products would clearly give the most accurate representation of the building’s impact when products have been specified or installed. But this must be balanced against the difficulties that will occur if so much data is made available, given the difficulties describe by the ECEPs discussed in section 4.5, around linking large amounts of product data with embodied carbon models and tools and trying to use it to make comparisons and select products.

Although variation still remains an issue which must be considered and addressed in product comparisons and building level assessments, the variation seen in impact can very largely be explained by aleatory variability (e.g. by differences in technology and geography), and the influence of epistemic variation such as a lack of methodological rigor, errors or poor-quality data is likely to be small. In fact, the range of variation seen in product impacts in EPD highlights the opportunity manufacturers have to reduce impact through use of improved technologies, input materials and product designs, and different energy strategies. It also emphasises the opportunity that designers have to specify products with lower impact at building level, both moving us more quickly towards a lower carbon future.

In the next chapter, the embodied carbon coefficients of cement and concrete EPD are explored in more detail, and the possible uses of the ‘EPD Landscapes’ describing the range of impact are explored.
7. Analysis of EPD for Cement and Concrete

7.1. Introduction

This chapter responds to the fourth research question: What additional information can an analysis of EPD for a specific product give us?

The International Energy Agency (IEA) and World Business Council for Sustainable Development Cement Sustainability Initiative (WBCSD-CSi) (2018) estimate the greenhouse gases emissions from cement manufacture are already 7% of total global emissions. The greenhouse gas emissions associated with cement come from two main sources (Barcelo et al., 2014):

- GHG emissions from the use of fossil fuels, and
- process emissions of CO$_2$ from the calcination of limestone which yield just of 0.5 kg CO$_2$ per kg clinker$^8$.

When combined with aggregates and water, cement makes concrete, the most used substance in the world after water (Scrivener, John and Gartner, 2017); the IEA also note that cement demand has nearly doubled between 2000 and 2016, mainly due to increased demand in China, and latterly, India (International Energy Agency (IEA), 2018). It is therefore clear that concrete has a major influence on global greenhouse gas emissions.

In the UK, 83% of cement is used in the construction of buildings, mostly as ready-mix concrete with some used in precast concrete and mortars (Shanks et al., 2019), and cement and concrete are responsible for over half of the construction materials related GHG emissions in the UK according to the Net Zero Whole Life Carbon Roadmap (ARUP, Giesekam and UK Green Building Council, 2021). For these reasons, this chapter focusses on an in-depth analysis of published EPD for cements and ready-mix concrete globally at the end of 2019.

The approach to data collection is described in section 3.3.7 and the methodology for the analyses is described in detail in section 3.4.2. Although the number of EPD for cement, and particularly concrete, is known to have increased significantly since then, it is not expected that the results of the analysis seen here would change.

7.2. Overview of EPD for cementitious products generally

102 EPD covering 118 cementitious products were evaluated, including Portland cements, cementitious co-products such as fly ash, and blended cements including cementitious products like ground limestone, were found in various EPD programmes in Europe and elsewhere, as shown in Table 33. The types of cement are described using the classifications provided in EN 197-1:2011, further detail is given in section 3.3.7, Table 11. The Mineral Products Association has also published a useful guide to the classifications (Mortar Industry Association, 2013).

Most cementitious EPD analysed provide data for a single product, though in the International EPD, EPD Norge, EPD Italia and EPD Australasia, some cementitious EPD provided separate data for more than one product. Over 80% of the EPD found used EN 15804:2012+A1:2013, the remainder, in North America, used ISO 21930:2017, which is methodologically very similar. Most EPD provided information

---

$^8$ The IPCC, OECD and IEA (1996) state the amount of CO$_2$ from calcination can be calculated using the assumed limestone fraction of clinker (64.6%) and the relative molecular masses of Calcium Oxide (56g) and CO$_2$ (44g), which gives 0.507 kg CO$_2$ per kg clinker.
on clinker content, and use of secondary fuels, and just over half provided some detail on the constituents of the cement, though many provided a range rather than precise figures.

Table 33: Cementitious EPD by Programme and Country

<table>
<thead>
<tr>
<th>EPD Programmes</th>
<th>Country/Region of Programme*</th>
<th>Cementitious EPD No. product datasets (No. EPD)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 15804+A1 EPD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATILH</td>
<td>France</td>
<td>10</td>
</tr>
<tr>
<td>BCS Okogarantie</td>
<td>Germany</td>
<td>1</td>
</tr>
<tr>
<td>BRE EN 15804 EPD</td>
<td>UK</td>
<td>4</td>
</tr>
<tr>
<td>Cembureau</td>
<td>Europe</td>
<td>3</td>
</tr>
<tr>
<td>DAPcons</td>
<td>Spain</td>
<td>2</td>
</tr>
<tr>
<td>EPD Australasia</td>
<td>Australasia</td>
<td>4 (2)</td>
</tr>
<tr>
<td>EPD Italia</td>
<td>Italy</td>
<td>5 (2)</td>
</tr>
<tr>
<td>EPD Norge</td>
<td>Norway</td>
<td>18 (17)</td>
</tr>
<tr>
<td>Global EPD</td>
<td>Spain</td>
<td>7</td>
</tr>
<tr>
<td>IBU</td>
<td>Germany</td>
<td>26</td>
</tr>
<tr>
<td>International EPD</td>
<td>Sweden</td>
<td>18 (11)</td>
</tr>
<tr>
<td>ITB</td>
<td>Poland</td>
<td>1</td>
</tr>
<tr>
<td>MRPI</td>
<td>Netherlands</td>
<td>3</td>
</tr>
<tr>
<td>Cemsuisse</td>
<td>Switzerland</td>
<td>4</td>
</tr>
<tr>
<td>ISO 21930:2007 EPD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM</td>
<td>USA</td>
<td>4</td>
</tr>
<tr>
<td>CSA</td>
<td>Canada</td>
<td>2</td>
</tr>
<tr>
<td>NRMCA</td>
<td>USA</td>
<td>6 (3)</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>118 (102)</strong></td>
</tr>
</tbody>
</table>

*Programmes can provide EPD for products from other countries

**if more than one product per EPD, number of EPD in brackets

Figure 49 shows the range of Embodied Carbon (taken as the embodied carbon coefficient for Modules A1-A3) for each type of cement. In this analysis, a CEM II/A-L cement would have been included in the analysis as a CEM II cement, a CEM II/A cement and a CEM II/A-L cement; the same approach has been taken across other sub-categories of cements.

As can be seen, the embodied carbon of cement is highest for White cements. White cements omit input materials which may affect the colour of the cement, different fuels are used to prevent contamination of the clinker with ash, the temperature of the kiln is higher, increasing energy consumption and the cement is ground finer than other cements (Schorcht et al., 2013) – these differences account for the high impact of White cements. Calcium aluminosilicate cements have a similar impact to White cements, and are made by calcining a mix of limestone and bauxite, accounting for the higher impact.

CEM I cements with 95% clinker have the next higher impact, with impact reducing as the amount of clinker reduces in CEM II (with CEM II/A (0-20% clinker replacement) having more impact than CEM II/B (20-35% clinker replacement) because of the higher clinker content), then CEM III which has the lowest proportion of clinker (35-65% clinker replacement for CEM III-A, 65-80% clinker replacement for CEM III-B). CEM IV (Pozzolanic cements) have a similar impact to CEM II/B. Cementitious co-products such as fly ash have the lowest embodied carbon.
Manufacturers and/or trade associations in 21 countries have produced EPD for cementitious materials. Figure 50 shows the embodied carbon for the cementitious EPD from each country. The chart shows both national average or collective EPD as separate data points (some of these are for the average cement, others for particular products such as CEM I), and the range of manufacturer specific EPD for a country, which can cover different types of cementitious materials, so should not be seen as being representative of the range of national production. For example, the three Dutch EPD are all for cementitious by-products, hence their low impact. Conversely, the Turkish EPD are all for White Cement or Calcium alumino-sulphate cements, hence their high impacts.

Only a small number of countries have produced more than 5 cementitious EPD – Sweden (14 EPD), Norway (8 EPD), Germany (8 EPD), Italy (7 EPD), USA (6 EPD) and Turkey (5 EPD). The average GWP calculated from all cementitious cement EPD is approximately 600 kgCO₂e/tonne.

There is a wide variation in impact for the average cements in different countries. Looking at Germany, the average German cement EPD gives an impact of just less than 600 kgCO₂e/tonne, this is just less than the 3rd quartile impact for German EPD, so the majority of the 8 German EPD produced have lower than average impact. For the UK, the average UK cement EPD gives an impact of over 800 kgCO₂e/tonne, but again, this is just less than the 3rd quartile impact for the 4 UK Cement EPD. For Italy, in contrast, the average Italian cement has an impact of just less than 800 kgCO₂e/tonne, which is very close to the middle of the distribution of the 7 Italian cementitious EPD.
Figure S0 EPD Landscape for cementitious EPD showing the range of GWP by Country of Producer

Figure S1 EPD Landscape showing GWP excluding calcination v use of fossil fuel (ADP-F) and non-renewable secondary fuel (SR-nr)
For each cement reporting the clinker content, the CO$_2$ from calcination was be calculated (assuming 0.507 kgCO$_2$e/kg clinker (IPCC, OECD & IEA, 1996)) and deducted from the reported GWP indicator, giving the amount of GWP assumed to come from fossil fuel use and from use of non-renewable secondary fuels, and in some cases from the disposal of waste in the cement kiln. Figure 51 shows the CO$_2$e reported in the EPD less the amount calculated to be released from calcination as above. This has then been compared to the use of fossil fuels, reported using the indicator Abiotic Depletion Potential-Fossil (ADP-F), and the use of Secondary Fuels – Non-Renewable (SF-NR). This graph shows a clear correlation ($R^2=0.74$). However, a number of EPD show anomalous results, suggesting a discrepancy in modelling or reporting, which is discussed later.

Figure 52 shows the broad correlation between increasing clinker content (for those EPD reporting it) and increasing embodied carbon coefficient (A1-A3) per tonne. For CEM III (GGBS>40%) and White Cement, GWP correlates closely with clinker content. However for CEM I, CEM II and CEM IV the results are more widely spaced. For CEM I and CEM II cements, the results have been considered in more detail, described later in section 7.3.

![Figure 52 EPD Landscape showing GWP and Clinker Content shown for all Cementitious EPD](image)

**Inconsistencies in the data**

As part of the analysis, a number of inconsistencies or errors in data within the EPD as originally collected were identified. For example, a number of EPD were identified which appeared to have either a very high or very low fossil and SF-NR energy use in relation to their reported GWP. EPD Programmes and/or manufacturers were informed, and some errors have been corrected and the EPD reissued by the EPD Programmes. These errors included reporting PENRT measured in kJ as MJ and GWP measured in grams as kg CO$_2$eq, both resulting in a factor x1000 error. These types of errors could be avoided in future by using the charts in this section as part of the verification of EPD to identify whether the results are plausible.

**7.3. Analysis of EPD by cement class**

An analysis of EPD for CEM I cements was provided in section 6.3.3, in Figure 33, and this should be considered as part of this section.
Analysis of EPD for CEM II cements

CEM II Cements are made with a minimum of 65% OPC with other materials such as fly ash, ground limestone or GGBS. Figure 53 shows the use of energy, the GWP in tonnes CO$_2$e/tonne) and the clinker content for each CEM II cement. CEM II have lower embodied carbon than CEM I (508-789 kg CO$_2$eq/tonne cement), which would be expected due to their lower clinker content. As with CEM I cement EPD (see 6.3.3), the French and Swiss CEM II EPD have not included CO$_2$ emissions from any use of non-renewable secondary fuel. There is no particular correlation between clinker content, energy use or strength and embodied carbon across the range of CEM II EPD.

Analysis of EPD for CEM III, CEM IV and CEM V cements

CEM III cements are made with OPC and between 40% and 90% GGBS. EPD for CEM III cements show a very clear correlation between clinker content and CO$_2$ emissions, as shown in Figure 52, and some correlation between non-renewable energy and CO2 emissions, as shown in Figure 54, although again, there seem to be some anomalous results.

CEM IV are Pozzolanic cements, comprising Portland cement and higher proportion of pozzolana than in a CEM II cement. Pozzolana can be natural, like volcanic ash, or artificial, like fly ash. CEM V are composite cements, comprising Portland cement and combinations of blast furnace slag and pozzolana. There are only small numbers of EPD for these cements, so it is difficult to draw conclusions and there don’t appear to be correlations of GWP with clinker content or energy use.
7.4. Overview of EPD for ready-mix Concrete

The analysis, undertaken at the end of 2019, found 162 separate EPD for ready-mix concrete covering nearly 1000 ready-mix concrete products, as shown in Table 34 overleaf. Some EPD only cover a single product with one mix design and strength, others cover several products with different mix designs and/or strengths. EPD globally were considered and 10 EPD programmes had registered EPD for ready-mix concrete, covering 17 countries of production. Where relevant, any geographical aspects of the findings have been included in the discussion below.

96 EPD used EN 15804 covering 238 ready-mix products, and 66 EPD used ISO 14025 and the North American Carbon Leadership Forum (CLF) PCR which complied with ISO 21930:2007, covering over 750 ready-mix products. The CLF PCR also closely follows EN 15804+A1 so there should be very little difference in outcome for GWP/Embodied carbon results based on the use of standard.

All the EPD provided data per cubic metre. For the purposes of this research, each individual product has been considered as a separate EPD datapoint.

Very few concrete EPD report life cycle stages beyond A1-A3, most were ‘cradle-to-gate’ EPD. Three manufacturer-specific EPD from the UK provided cradle-to-grave data, as does the UK Trade Association IBU EPD, the German trade association IBU EPD, the French Trade Association EPD from inies and the EPD from Australian Manufacturer Holcim. EPD from EPD Norge provide A4 (transport to site) data. Due to the limited data, these life cycle stages were not reviewed.

Table 35 shows the number of products using EN 15804+A1 and ISO 21930 as the PCR. For EN 15804+A1, although they come from one manufacturer specific EPD, Australia has the largest number of products covered using this standard. Norway, with 31 EPD, covers 31 products. In North America, ISO 14025 and the CLF PCR have been used although EN 15804+A1 is starting to be used for concrete, with the USA producing the most EPD (67) and covering the most individual ready-mix products (over 1500).
The ready-mix concretes covered by EPD come in a range of compressive strengths, almost all reported using the 28-day strength. There is great variation in impact reported for any given strength of
concrete, but generally, there is an increase in embodied carbon per m$^3$ as the 28-day strength of the concrete is increased, as shown in Figure 55, although there are some anomalies, for example the high strength concretes with compressive strength between 60-80 MPa have lower impact. The increase in impact with compressive strength would reflect the generally higher cement content for higher strength concretes. However Purnell cautions against the selection of low strength concretes over high strength concretes on the basis of their reduced embodied carbon, highlighting that significantly more of a low strength concrete may be required to fulfil a particular function (Purnell, 2013).

Figure 55 EPD Landscape for concrete EPD showing range of GWP by compressive strength

Figure 56 EPD Landscape for concrete EPD showing range of GWP per unit of structural performance (MPa) by compressive strength
A similar conclusion was drawn by Damineli et al. (2010) who showed that assessing CO$_2$ per m$^3$ and per unit of structural performance (kgCO$_2$/m$^3$/MPa) suggested that C50 concrete was the optimal choice with greater savings in embodied carbon (20–35%) than those achieved by replacing cement with pulverised fuel ash (10–25%) for example. A graph showing the embodied carbon per unit of structural performance (MPa) is shown in Figure 56 for ready-mix concretes with 28-day compressive strength over 10 MPa. As suggested by Damineli et al. (2010), the concretes with lower strength show higher impact using this measure, and the higher strengths of concrete (in this case the concretes with compressive strength of 70-80 MPa perform best in terms of impact per unit of compressive strength.

Figure 57 EPD Landscapes showing GWP (A1-A3) by Compressive Strength, shown for each country

Figure 57 shows how the results are distributed for the different products for each country. France, the UK, Norway, and Germany all have relatively low impact. The French and German EPD are all collective industry averages. Only one UK collective EPD has been produced, this is shown as the coloured region within the general UK Outline. The highest impacts are seen for EPD from Saudi Arabia, Mexico, Panama, and the United States. These high impacts are all from manufacturer specific EPD. The grey and pink shaded regions show the US and Canadian average mixes provided in collective EPD.

Only a few countries (the UK, UAE, and Norway) have produced EPD for concretes with strengths over 60 MPa. Conversely, only the US, Mexico, Italy, and Romania have produced EPD for concretes with strengths of 10 MPa or less. For most countries, there is a clear trend for increased carbon emissions with increased compressive strength, though there are some products which counter this trend, for example some high strength Norwegian and UAE concretes have lower impacts than lower strength concretes from those countries.

The EPD for ready-mix concrete provide a variety of information, mostly for 1 m$^3$ of concrete, though some of the earlier EPD in North America provide results for 1 cubic yard of concrete (these results

---

9 It should be noted that the Norwegian concrete with a 28-day compressive strength of 70 MPa is described in the EPD as strength class B45 and resistance class M40.
have been converted to 1 m$^3$). Almost all provide a measure of compressive strength, normally the 28-day strength. Some provide the type of cement used, the binder intensity, and/or the % of alternative cementitious material (ACM) such as fly ash or slag.

National sector EPD have been produced in a number of countries as follows:

- In Canada, up to 18 defined mixes, plus one industry average mix, have each been assessed for 8 different compressive strengths using Canadian industry average data, providing results for 125 mixes in a single EPD.
- In the US, 8 defined mix designs have each been assessed for 6 different compressive strengths using US industry average data, providing results for 48 mixes in a single EPD.
- In Germany, the average mix for 5 different compressive strengths using German industry average data has been reported in 5 separate EPD.
- In France, 3 compressive strengths have been modelled using an average mix and French industry average data, each reported in a separate EPD.
- For the UK, 1 defined mix design has been assessed for 1 strength using UK industry average data and a representative mix.
- Dubai Municipality has provided an EPD covering 8 producers for a number of defined mixes for 11 different compressive strengths, providing results for 13 mixes in a single EPD; however this does not cover all producers in Dubai.

### 7.5. Analysis of EPD for C30 concrete

A more detailed analysis of the 91 concretes with a 28-day compressive strength of between 28 and 34 MPa has been undertaken, to understand any factors which can be seen to influence impact. This is shown by the six charts in Figure 58, however no clear conclusions can be drawn. Possibly this is because there are not enough EPD, or because the embodied carbon varies in relation with a combination of these factors, for example both binder content and Ordinary Portland Cement (OPC) content together influence the impact of the concrete. Unfortunately, very few EPD reported both binder content and OPC content, so we were unable to consider this possibility.

Within individual EPD which cover a range of different products, or a group of EPD from a single manufacturer, it is possible to see these types of trends. For example, Figure 59 provides the impact of various Holcim Australia Ready-mix concretes from their EPD (Holcim Australia Ready-mix Concrete, 2019) grouped by the type of cement (G-General Blend (no cement replacement), B-Blast furnace slag blend, F-Fly ash blend, and T-Triple blend (fly ash and blast furnace slag)) and the compressive strength. As expected, embodied carbon coefficient increases with compressive strength. The General Blend shows the highest impact for all strengths, followed by the fly ash blends, which generally have lower cement replacement than the blast furnace slag blends. The lowest impact for each strength is shown by the triple blend, which uses both fly ash and blast furnace slag, and has the highest cement replacement.
Figure 58 EPD Landscapes for concretes with a compressive strength around 30 MPa, showing the range of GWP for a variety of differentiators.

Figure 59 EPD Landscape for concretes from Holcim Australia EPD.
7.6. Proposed uses for the ‘EPD Landscapes’

It is clear that the carbon impacts of cement and concrete are very significant. However up until now it has been difficult to compare impacts from different cements and concrete mixes, or understand the range of impacts that are available. Opportunities to use the EPD Landscapes are described in detail below.

For the selection of generic embodied carbon coefficients: During early design stages, EN 15978 recommends using regional generic data for concrete where available. If generic data is not available for a particular region, then using an EPD Landscape created for the product, for example for cement, the EPD Landscape in Figure 57, identify a region with similar technology and use it to pick an appropriate embodied carbon value (from an industry collective EPD if available), or using an EPD Landscape like Figure 55, use the median of the range for the given compressive strength. Ganassali et al. (2018) recommends the median as it is not sensitive to the outliers in a sample composed of a small number of datasets.

At later stages of the design, it is recommended to use specific data, e.g., from manufacturer specific EPD based on the products you have chosen to use in the building (see section on material selection).

In benchmarking: Benchmarks can be provided for a product generally (e.g., cement or concrete) or for a specific product, such as CEM I cement or C30 concrete. Specifying benchmarks at the more specific level will ensure that the products meeting the benchmark are not just lower carbon products, but products which have lower carbon impacts than other products with similar functionality. For concretes, it is important that the functionality is considered in defining the benchmark. Concretes with lower embodied carbon per m$^3$ may have lower compressive strength, and this may lead to a requirement to use more concrete which could have an adverse environmental impact. For situations where compressive strength is relevant, it is recommended to use Carbon Intensity (CO$_2$eq/m$^3$.MPa) as shown in Figure 56 to set benchmarks.

In setting benchmarks, the geographical and related technological situation should also be considered - ideally a regional benchmark should ensure that at least some of the production achieves the benchmark, whilst also stretching producers adopting ‘business as usual’ practices.

In material selection: Cement selection must be considered alongside the functionality of the concrete that is required. Figure 55 shows that that there is great variation in concrete impact reported for any given strength, but that generally, there is an increase in embodied carbon per m$^3$ as the 28-day strength of the concrete is increased. However Purnell (2013) cautions against the selection of low strength concretes over high strength concretes on the basis of their reduced embodied carbon, highlighting that significantly more of a low strength concrete may be required to fulfil a particular function. A similar conclusion was drawn by Damineli et al. (2010).

Many manufacturers are now able to provide EPD for the range of concretes that they produce (see 2.3.2). Therefore, when selecting a concrete, specifiers are recommended to do the following:

- consider the range of embodied carbon coefficients shown in Figure 54 and Figure 55;
- ask local concrete producers if they are able to provide information on the embodied carbon (carbon footprint or EPD) for their concretes;
- look for a producer able to provide a concrete at the lower end of the embodied carbon range for its strength; and
• make sure that any impacts from extended transport distances for a particular supplier do not outweigh the benefits of reduced embodied carbon in production. The transport impacts are provided in Module A4 of EPD.

**In setting reduction targets:** The lower quartile ranges in Figure 49 and Figure 50 for cements and Figure 54 and Figure 55 for concretes show the best performance shown by the best 25% and 50% of products with existing EPD, and therefore what should be achievable in setting long-term reduction targets for the majority of the market. This is also important information for manufacturers who wish to stay competitive in a decarbonizing market.

**In EPD verification:** For cements, an initial check of the EPD against the EPD Landscape in Figure 49 will allow the plausibility of the embodied carbon coefficient to be considered. Figure 50 provides an EPD Landscape showing the range of embodied carbon for EPD by Country of production and by type of cement (CEM I, CEM II etc.), allowing verifiers to further check the plausibility of the GWP for a particular region. Figure 52 can be used to check the plinker content and embodied carbon are within the expected region of the graph, especially for CEM I, II, III and IV cements. Figure 33 and Figure 53 for CEM I and CEM II EPD showing the embodied carbon broken down by CO₂ from calcination and from fuel use, and the primary and secondary fuels use, broken down by renewable and non-renewable sources, could be used to consider the plausibility of data during verification of EPD for CEM I and CEM II cements.

For concrete EPD for verification, Figure 55 could be used to check the plausibility of embodied carbon coefficient for a given compressive strength, and Figure 57, which provides the indicative embodied carbon impacts for different countries and 28-day strengths, could also be used to check that the embodied carbon is in the expected region of the graph.

In conclusion, it is likely various stakeholder groups can be assisted and supported by the EPD Landscapes provided in this chapter:

• For **designers** during the early design stages, the EPD landscapes can enable the choice of appropriate and realistic carbon coefficients, before the design has been fully specified and at a point where the information can have an impact on major decisions on structural materials;

• For **designers and specifiers** during later design stages, the EPD Landscapes will allow comparison of different products, helping them identify those with lower impacts for the same performance requirements.

• For **manufacturers**, the EPD Landscapes will enable them to compare their products with others and encourage them to work towards reducing their impacts; in many cases, even within a given region and specification, there is a considerable range of embodied carbon coefficient for a given type of cement or strength of concrete.

• For **EPD Verifiers**, the EPD Landscapes can be used to check the plausibility of results for individual EPD produced by manufacturers.

### 7.7 Conclusion

While the carbon impacts of cement and concrete remain complex and highly varied, the EPD Landscapes in this chapter and the growing number of countries represented by the EPD, covering Europe, North and South America, the Middle East, India, and Australasia, demonstrate that climate change and the embodied impact of construction materials are now a concern in multiple regions of the world.
This chapter has demonstrated how the analysis of existing EPD for cement and concrete can provide useful information for Designers, Specifiers, Building Assessors, Manufacturers and Verifiers, including for material selection, building LCA, benchmarking, target setting and EPD verification.

The next chapter returns to explore the role of renewable energy in the variation of embodied carbon coefficients which was considered initially in Chapter 6.3.3.
8. Analysis of renewable energy use in EPD

8.1. Introduction

This chapter responds to the fourth research question: What additional information can an analysis of EPD for a specific product give us?

The initial analysis of the role of renewable energy on embodied carbon discussed in 6.3.3 suggested that a detailed exploration of the use of energy, particularly renewable energy, and its impact on embodied carbon across a range of product groups is important.

As carbon impacts are closely correlated to fossil fuel use, this in turn suggests that as industry looks to decarbonise, there will be an increasing pressure on renewable energy resources. Renewable energy has its own associated embodied impacts - for example Asdrubali et al. (2015) in their review of life cycle assessment of renewable electricity production show a range of impacts up to 50 gCO₂e/kWh). Renewable energy also has limited capacity (the IEA forecast that renewables will only be able to provide just over half of electricity generation globally by 2027 (IEA, 2023). We therefore need to use renewable energy resources efficiently in the production of construction products to ensure the transition to net zero.

In Environmental Product Declarations (EPD), the use of energy is described using resource indicators, with Primary Energy indicators describing the total amount of energy from primary sources which has been used to create a product. In EPD, these indicators are split into those reporting renewable primary energy (e.g. from wind, hydro, solar, biomass) and non-renewable energy (e.g. from fossil fuels and nuclear power). The distinction between the two is critical for understanding the impact of products and materials. It should be noted that the calculation approach for the Primary Energy Total indicators (PERT and PENRT) is not defined in any detail in EN 15804, although the approach for the Primary Energy Material indicators (PERM and PENRM) is provided, and the Primary Energy as Energy indicators (PERE and PENRE) are both derived by deducting the respective Primary Energy Material indicator from the Primary Energy Total indicator. For renewable resources, primary energy is normally calculated in EPD using the ‘energy harvested’ cumulative energy demand approach defined in Frischknecht et al. (2015) as this is the approach used in the two major LCI databases, ecoinvent and GaBi.

Ignoring losses from transmission and distribution (T&D), any supply chain impacts for fuels (sometimes known as well to tank (WTT)) and the embodied impact of the infrastructure itself, the renewable primary energy reported for the output of a wind turbine or photovoltaic (PV) installation will be the amount of electricity generated by the turbine or PV. By contrast, for fossil fuel and biomass energy, significantly more fuel is used for generation as the process of converting heat to electricity has significant losses. The thermal efficiency of combined cycle gas turbine generation in the UK is only 48.8% (BEIS, 2020). This means that for a product with an electricity demand of 100 kWh/tonne, if the electricity is generated from natural gas in the UK, the product will have a primary energy demand of over 200 kWh/tonne (100/0.488) excluding the T&D and WTT impacts; however, if the electricity is generated by wind, then the same product will have a primary energy demand of just 100 kWh/tonne. Generally, therefore, use of renewable electricity should reduce the amount of primary energy required. However this isn’t the case for biomass energy, which generally has lower thermal efficiencies (30-34 %) than gas and coal when used for power generation (Magiri-Skouloudi et al., 2019). This would mean the fuel demand for 100 kWh generated from biomass in a power plant (not CHP) would lead to primary energy demand of over 300 kWh/tonne, (100/0.32). Note that the embodied supply chain impacts for biomass fired electricity generation can also be quite high; Raugei and Leccisi (2016) suggests for biomass it could be 86 MJ per 100 MJ generated, compared to 1.6 MJ for hydroelectricity, 5-5.3 MJ for wind and 30 MJ for PV (c-Si). This would mean a primary energy demand around 400 kWh for the delivery of 100 kWh of electricity from a biomass power plant.
Therefore, if production moves from the use of gas fired grid electricity to renewables other than biomass, the primary energy demand of manufactured products would be expected to reduce, and if moving to biomass, to increase. In both cases, the embodied carbon of the product would be expected to reduce however, as renewable energy has much lower GWP per MJ than fossil energy. Nuclear energy has a similarly low GWP per MJ as renewables but has a normal efficiency of 39.9% (BEIS, 2022, tab. 5.10) so 100 kWh electricity would have a primary energy requirement of 250.6 kWh (100/0.399) excluding T&D and WTT impacts.

Evidence from industry supports a potential increase in energy consumption as a consequence of decarbonisation actions. For example, the UK Cement Decarbonisation Strategy (BEIS and Mineral Products Association (MPA), 2017) states some decarbonisation actions such as use of biomass fuels with higher moisture content ‘might make cement manufacture less energy and electrically efficient,’ and the British Geological Society state that carbon capture and storage (CCS), which is one of the major means by which the cement industry will decarbonise, is energy intensive and could increase the fuel needs of a coal-fired electricity plant by 25–40 per cent (British Geological Society, 2021), meaning the decarbonisation of construction product manufacture could lead to greater energy intensity and more pressure on renewable resources. United Nations Economic Commission for Europe (2021) used life cycle assessment to consider the impact of CCS on natural gas combined cycle electricity generation and found whilst climate change reduced by 57%, other impact indicators such as human toxicity, resource use and eutrophication increased by between 19% and 75%.

This chapter analyses published EPD data for key construction materials including cement, structural and reinforcing steel, brick, and structural timber products. It takes the cradle-to-gate life cycle stage (A1-A3) as this is mandatory for all EPD, and for all the products other than timber, it is the most impactful life cycle stage. The analysis considers embodied carbon using the Global Warming Potential (GWP) indicator, the use of renewable energy, non-renewable energy (collectively primary energy) and the use of secondary fuels (both renewable and non-renewable) for each material. It explores the relationship between GWP and total energy demand, the balance of renewable and non-renewable energy demand for different products, and the use of secondary fuels, and considers whether there is any evidence that renewable energy is being used less efficiently than non-renewable energy.

The following sub-types of products were considered as they are the materials most commonly used for structural purposes:

- **Ordinary Portland Cement (CEM I)**
- **Steel** – structural steel and reinforcing steel, made using the blast furnace/basic oxygen furnace (BF/BOF or BOF) route, electric arc furnace (EAF) and direct reduced iron/electric arc furnace (DRI/EAF or DRI) routes
- **Brick** – clay facing brick and Ziegel bricks
- **Structural timber** – Cross laminated timber (CLT), glulam, laminated veneered lumber (LVL) and kiln-dried sawn softwood timber.

Section 3.3.7 describes the approach used to find the EPD and section 3.4.2 and 3.4.3 the methodology for the analysis.

**Geographical issues**

As EPD globally were considered, there were a large number of countries of production included in the EPD studied, as shown in Table 36. This means, for example, that there was considerable variation for example in the embodied carbon coefficient and energy sources for grid electricity used in the countries, for example, Switzerland, Norway and Sweden all have less than 3% of the grid sourced from
fossil fuels, whereas Oman, Belarus and UAE have 97% or more (International Energy Agency (IEA), 2020). The significance of electricity use varies for different products – for EAF steel it is a significant input but for the other products studied, electricity use is not expected to be significant. Additionally, it is possible according to ISO 14067 (ISO, 2018), to make use of on-site renewables, directly connected renewables or the purchase of ‘green electricity’ with tracked Guarantee of Origin to increase the percentage of renewable energy used in comparison to the national grid mix.

Table 36 EPD for structural products considered for the analysis of the role of renewable energy

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Sub-type</th>
<th>EPD</th>
<th>Countries of production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Ordinary Portland Cement (CEM I)</td>
<td>33</td>
<td>CH, DK, ES, EU, FR, IS, IT, JP, LV, NO, NZ, SE, UK</td>
</tr>
<tr>
<td>Steel</td>
<td>Structural steel – BOF</td>
<td>18</td>
<td>AE, AT, AU, BY, CA, CH, DE, DK, ES, EU, FI, FR, HU, IT, JP, KR, LI, LV, LX, MX, NO, NZ, OM, PO, PT, RO, RU, SE, UA, UK, US</td>
</tr>
<tr>
<td></td>
<td>Reinforcing steel – BOF</td>
<td>56</td>
<td>AE, AT, AU, BY, CA, CH, DE, DK, ES, EU, FI, FR, HU, IT, JP, KR, LI, LV, LX, MX, NO, NZ, OM, PO, PT, RO, RU, SE, UA, UK, US</td>
</tr>
<tr>
<td>Brick</td>
<td>Clay facing brick</td>
<td>25</td>
<td>CA, DE, DK, ES, FR, FI, IE, UK, US</td>
</tr>
<tr>
<td></td>
<td>Ziegel brick</td>
<td>38</td>
<td>BE, CZ, DE, ES, FR, IT</td>
</tr>
<tr>
<td>Structural timber</td>
<td>Kiln dried sawn softwood</td>
<td>41</td>
<td>AT, AU, CZ, DE, DK, ES, EU, FI, FR, IT, LA, NO, NZ, SE, UK, US</td>
</tr>
<tr>
<td></td>
<td>CLT</td>
<td>13</td>
<td>AT, AU, CH, DE, ES, IT, LA, NO, SE</td>
</tr>
<tr>
<td></td>
<td>Glulam</td>
<td>12</td>
<td>AT, AU, CH, DE, IT, NO, PO, RU, SE</td>
</tr>
<tr>
<td></td>
<td>LVL</td>
<td>2</td>
<td>FI, PO</td>
</tr>
</tbody>
</table>

Plausibility of data

It should be noted that this level of scrutiny is not normally given to the resource indicators provided in EPD although all EPD results have been verified by an independent expert according to ISO 14025. In some cases, it is possible that the results are erroneous. In such cases where the resource indicators appear to be outliers or not plausible, the EPD programmes have been contacted and requested to make a check. As a result, several notifications of corrections have been provided.

8.2. Renewable energy and EPD for Ordinary Portland Cement (CEM I)

The EPD analysed for CEM I in chapter 7 were also analysed for information on renewable and non-renewable energy use. The average use of renewable energy in the EPD for CEM I cements is 15%, split equally between use of renewable primary energy (as described by the PERT indicator) and renewable secondary fuels (as described by the RSF indicator). Six EPD used more than 25% renewable energy, two each from Sweden (which has a 65% renewable electricity grid), New Zealand (which has an 82% renewable grid) and Latvia (which has a 50% renewable grid). Two EPD had less than 2% renewable energy, from Italy (40% renewable grid) and Israel (5% renewable grid). There is generally considerably more use of waste and secondary fuels derived from waste in the cement industry compared to use of renewables, with non-renewable secondary fuels 16% of energy use on average. The percentage of renewable energy and the GWP (A1-A3) for all CEM I EPD is shown in Figure 60. This shows a slight trend ($R^2=0.47$) to lower GWP as the percentage of renewable energy increases.
As discussed in section 6.3.3, there are significant differences in practice around the reporting of the use of secondary fuel sources – but the use of both renewable and non-renewable secondary fuels should be reported according to EN 15804. Due to this and the high process CO₂ emissions from calcination in cement manufacture, there is not a clear correlation between Total Energy consumption and GWP for CEM I (R²=0.05), as shown in Figure 61. Correlation improves only very slightly when GWP is plotted against Total Non-renewable Energy (R²=0.17).

In Figure 62, when looking at the % of renewable energy, there is a slight reduction in primary energy demand with increasing percentage of renewable energy, but the correlation is not strong (R²=0.127), and there are 4 EPD using less than 4000 MJ/tonne with less than 20% renewable energy, but none above 20% renewable energy.
Figure 63 is an EPD Energy Array, plotting the renewable and non-renewable energy use for EPD for CEM I cements. The average energy consumption per tonne is shown by the black line. The yellow shaded area shows where products use less than 50% of the average energy consumption. The green shaded area shows where products would use more than 50% renewable energy, and the lime shaded area any products that use both less than 50% of average energy and more than 50% renewable energy. The pink shaded area shows the products which use more than the average energy consumption. For CEM I EPD with more than 20% renewable energy use, almost all have below average energy use. Those with the highest energy use (over 5200 MJ/tonne) all have very low use of renewable energy (<10%).

8.3. Renewable energy and EPD for steel

The GWP and the percentage of renewable energy for all steel EPD considered is shown in Figure 64. For both structural and reinforcing steel EPD, the reported use of secondary fuels was insignificant. The use of renewable energy for structural steels was on average 7% of total energy use, for reinforcing steels it was 14%. There were several steels using more than 50% renewable energy; four of these EPD were for production in Norway (over 90% renewable electricity grid), and one each for Denmark (around 80% renewable grid), Finland (around 50% renewable grid electricity) and Japan (which has 19% renewable grid electricity) (International Energy Agency (IEA), 2020). Those with the lowest percentages of renewable energy (less than 2%) were from Qatar, USA, Mexico, Finland, Italy, Romania, South Korea, and Australia. The small number of Direct Reduced Iron (DRI) steels all used small percentages of renewable energy. Of the 30 Basic Oxygen Furnace (BOF) steel EPD, two Canadian EPD used 22% renewable energy, but the others used much lower percentages. For BOF steels, structural steels used around 5% less renewable energy than reinforcing steels. However, for the 67
Electric Arc Furnace (EAF) steel EPD, 10% (all but one reinforcing steels) used over 50% renewable energy.

For all steels, there is a trend for reduced embodied carbon coefficients as the percentage of renewable energy used increases, but the embodied carbon coefficient never seems to reduce beyond around 400 kgCO₂e/tonne, however high the percentage of renewable energy.

Figure 65 first shows total primary energy consumption v GWP. There is a strong correlation between primary energy consumption and GWP for BOF structural steels ($R^2=0.834$), less so for EAF structural steels ($R^2=0.154$) due to several outliers, for example several EAF EPD report extremely low primary energy figures. For reinforcing steels, the correlation between primary energy and embodied carbon was very strong for BOF ($R^2=0.937$) and strong for EAF ($R^2=0.59$).

Looking just at non-renewable primary energy and GWP (the second graph in Figure 65), the correlation is strongest for BOF Reinforcing steels ($R^2=0.94$) and BOF Structural steels ($R^2=0.88$).

Figure 66 shows the relationship between primary energy demand and the percentage of renewable energy used. For BOF structural steels, there is no obvious drop in primary energy demand as renewable energy usage increases ($R^2=0.00006$) but for EAF structural steels, there was a very slight trend reducing primary energy demand with increasing use of renewable energy ($R^2=0.454$). For BOF reinforcing steels, there is little correlation between primary energy and % renewable energy ($R^2=0.03$). For EAF reinforcing steels however, as with EAF structural steels, there is a very slight trend to reducing primary energy demand with increasing use of renewable energy ($R^2 = 0.41$).

Use of renewable and non-renewable energy for all BOF steels and all EAF steels were then plotted on EPD Energy Arrays shown in Figure 67, which have different axis scales, particularly for non-renewable energy. For BOF steel EPD, there are two steels with over 20% renewable energy use, which have a little less than the average energy consumption, and low GWP (the size of the data point). There are also 3 steels with less than half the average energy consumption, but these have less than 10%
renewable energy content, and also have very low GWP. There are also 4 products with double the average energy consumption, which use 10% or more renewable energy, and have very high GWP. For EAF steel EPD, there are a few products with over 50% renewable energy and two with over 33%, all with less than the average energy consumption and low GWP. There is one product with less than half the average energy consumption which less than 10% renewable energy–but this appears to have high GWP and may be incorrectly calculated. Most of the products with higher than average energy consumption use less than 10% renewable energy.

Figure 67 EPD Energy Array for BOF and EAF Steel EPD

Use of renewable and non-renewable energy was then plotted separately on EPD Energy Arrays for structural steels and reinforcing steels, shown in Figure 68. As can be seen, for structural steel, all of the EPD use less than 20% renewable energy and most below 10%. Those with 10-20% renewable energy are mainly those using less than the average total energy demand (shown with the black line).

Figure 68 EPD Energy Array for Structural and Reinforcing Steel EPD

For reinforcing steels, there is a greater distribution than for structural steels, with some EPD having over 50% renewable energy. All of the EPD with over 33% renewable energy have less than 50% of the average energy demand – these are all EAF steels. There are several EPD with high energy demand and using between 10-20% renewable energy – these are all BOF steels.

8.4. Renewable energy and EPD for brick

The two different types of brick considered here have already been described in section 6.3.4.

For bricks with EPD, renewable primary energy accounts for 6.5% of energy use on average, and renewable secondary fuel accounts for nearly 9%, but for several products it is the major energy source. Non-renewable secondary fuel is hardly used. The GWP per tonne and the percentage of all renewable energy for all brick EPD is shown in Figure 69.
For all facing bricks, there is a trend for reduced embodied carbon coefficients as the percentage of renewable energy used increases; but for Ziegel bricks, there is no clear correlation between the two variables.

Figure 70 shows first the relationship between total energy consumption and embodied carbon. For both facing brick and Ziegel brick, there is a trend for increasing embodied carbon with increased energy consumption ($R^2=0.724$ for facing brick and $R^2=0.46$ for Ziegel brick). Looking just at non-renewable energy, the correlation is similar for facing brick ($R^2=0.71$) but higher for Ziegel brick ($R^2=0.63$).

Comparing total energy consumption with the percentage of renewable energy used, Figure 71 shows that though there is no correlation ($R^2=0.03$) for facing bricks, for Ziegel bricks, there is a strong correlation between increasing energy consumption and the percentage of renewable energy used ($R^2=0.628$), in other words, the more renewable energy is used, the greater the total amount of energy that is used.
Figure 71 Total energy v % Renewable Energy for Brick by type

Figure 72 shows the EPD Energy Arrays for the two types of brick. For facing brick, the one EPD with over 50% renewable energy has greater than average energy use. There are a number of EPD with less the average energy consumption (below the black line) and between 20 and 33% renewable energy consumption.

For Ziegel brick, four of the EPD with over 50% renewable energy use have more than double average energy use, one with over 70% renewable energy use having over three times average energy use, though one with just over 50% renewable energy has around average energy use. There are a number of EPD with less than 50% of average energy use (in the yellow shaded area) but only one has more than 20% renewable energy consumption.

8.5. Renewable energy and EPD for structural timber

The use of renewable energy is more common in timber EPD, with averages of around 60% for sawn timber, 55% for CLT and LVL and 64% for Glulam. For sawn timber, two products use significant amounts of renewable secondary fuel, but most use none (the average is less than 3%) and use of non-renewable secondary fuel is insignificant.
Figure 73 shows the relationship between the GWP (excluding sequestered carbon in the product) and the percentage of renewable energy used. A number of products still have negative GWP, implying problems with the reported GWP or reported biogenic carbon content, as products should not be able to have negative GWP excluding sequestered carbon. For sawn timber and CLT, there is a trend for reduced embodied carbon coefficients as the percentage of renewable energy used increases; for glulam and LVL, there is no clear correlation between the two variables.

As timber has renewable energy as feedstock, reported using the indicator PERM, and non-renewable energy used for adhesives included as PENRM, only the resources used for energy have been considered in the analysis, i.e. the indicators PERE, PENRE, RSF and NRSF have been taken to give the total energy used for timber products. The graphs have been split into those showing the results for the product sub-type, sawn timber, and those showing the engineered timber product sub-types, cross laminated timber (CLT), glulam and laminated veneered timber (LVL).

Figure 74 shows the total energy consumption and the reported GWP (including sequestered carbon), and Figure 75 the total non-renewable energy and the reported GWP (including sequestered carbon). There is not a very strong correlation for total energy used and GWP for any of the products due to several outliers (e.g. $R^2=0.008$ for sawn timber, $R^2=0.07$ for CLT).
Figure 75 Total Non-renewable Primary Energy v GWP for Timber EPD

Figure 76 shows the relationship between total energy consumption and the percentage of renewable energy used. For all the products there is no correlation between increased % of renewable energy and total energy used ($R^2=0.0524$ for sawn timber, 0.0966 for CLT and 0.112 for glulam (there are only two LVL EPD). However there are one or two sawn timber, CLT and glulam products with percentage of renewable energy over 80% which have high total energy consumption in comparison to other products in their sub-group.

Figure 76 Total Energy consumption v % Renewable Energy for Timber EPD

When looking at the relationship between renewable and non-renewable energy, shown in the EPD Energy Arrays in Figure 77, 15 of the 19 timber products with energy consumption over the average (shown by the black line) use more than 50% renewable energy. 9 of the 12 products with renewable energy consumption below 33% have below average energy consumption.

Figure 77 EPD Energy Array for Timber EPD

But for both products groups, the greatest number of products are seen in the green shaded areas of the Array, with both below average energy consumption and more than 50% renewable energy.
consumption. There are also a few sawn timber, CLT and glulam products with less than half the average energy consumption and more than 50% renewable energy consumption (the lime green shaded area).

8.6. Proposed uses of the ‘EPD Energy Arrays’

To support the transition to net zero, specifiers must not only select products which have reduced embodied carbon but also look to find products that achieve this using energy, and particularly renewable energy efficiently. Especially for timber and bricks, where evidence was found that increased use of renewable energy is associated with higher energy consumption, specifiers are recommended to address this firstly by demanding environmental product declarations (EPD) for the products they consider so they can review their environmental performance, particularly with regard to embodied carbon in view of the need to achieve net zero. After initially selecting products with lower embodied carbon for their chosen specification (where products have a common declared unit and are functionally equivalent as the comparison rules in EN 15804 require (CEN/TC 350, 2019b), they should identify the location of the products on the relevant EPD Energy Arrays (Figure 63 for CEM I cement, Figure 67 and Figure 68 for steel, Figure 72 for brick and Figure 77 for timber). The red shaded area in Figure 78 indicates the area of EPD Energy Arrays where products would have above average energy use. The yellow shaded area indicates where products would have less than half the average energy use and the pale green shaded area where products would have at least 33% renewable energy use and below average energy use; the resulting lime green shaded area where the green and yellow overlap is where products would have half the average energy use and more than 33% renewable energy use – these products are likely to be the most effective in moving to low carbon energy and minimising pressure on renewable resources. Where possible, it is recommended that whilst also considering the embodied carbon coefficient, products with low energy demand and higher proportions of renewable energy located in the green and yellow shaded areas of the EPD Energy Array are selected rather than products in the red shaded area.

![Illustrative EPD Energy Array](image.png)

*Figure 78 Illustrative EPD Energy Array*
8.7. Summary and Discussion

In Figure 79, the GWP (excluding sequestration for timber) and total energy consumption for all the EPD have been plotted on a single chart. The overall trend of increasing GWP with increasing energy consumption across the products groups is clear, but for CEM I and timber products, there was no obvious relationship between the total energy consumption and the GWP. This is likely to be due to the high use of renewable energy for timber which significantly influences the energy consumption without influencing the GWP, and the CO$_2$ emitted from calcination of cement, which significantly influences the GWP without being influenced by energy use. We also see that the CEM I EPD all have increased GWP relative to the trend for most product groups, because of the CO$_2$ from calcination, and all the timber EPD and some of the Ziegel brick EPD have lower GWP relative to the trend, because of their significant use of renewable energy.

Perhaps unsurprisingly, all the steel and brick products show a correlated relationship between increasing energy consumption and increasing GWP, though this correlation is weakest for Facing Brick.

Figure 80 provides an overview of the use of renewable and non-renewable energy for all the product groups. The product groups are each clustered to some extent, with the products which use the greatest amount of non-renewable energy per tonne (BOF and EAF Steels) having lower use of renewable energy. The timber products and Ziegel bricks have the greatest use of renewable energy and lower non-renewable energy consumption per tonne than the steels. Facing brick and CEM I both occupy a similar location on the chart in terms of use of renewable and non-renewable energy, using a similar amount of non-renewable energy to timber products, but much lower amounts of renewable energy.
Figure 81 provides a summary of the use of renewable energy as a percentage of total energy consumption from the EPD for the various product groups. For all products except the timber products, the median values (shown by the horizontal line in the blue bar) are lower than the average values (shown by an X). This suggests a small number of EPD with a high percentage of renewable energy use may be skewing the average for most products, whereas for engineered timber, it is a small number of EPD with a low percentage of renewable energy use that are skewing the average. (See 3.4.2 for an explanation of box and whisper graphs, and definitions of average and median values).

For BOF steel, use of renewable energy was generally low (median 5.5%, average 7% and maximum of 22%), likely as a result of the substantial barriers to decarbonising BOF steel production such as those highlighted by Griffin and Hammond (2019). DRI steel and structural steel generally used similarly low levels of renewable energy. For EAF steels, average use of renewable energy was 14%, median 7.3% with a maximum of 65%, and very little use of renewable secondary fuels (RSF).

The average use for renewable energy is similar for CEM I cement and facing brick, with renewable energy accounted for 15% of energy used on average (median 14.2% for CEM I and 11.5% for facing brick), and a maximum of 36% for CEM I and 52% for facing bricks, with 50% of the renewable energy coming from renewable secondary fuels (RSF) for cement and nearly 60% for bricks. Use of non-renewable secondary fuels is on average just more than all renewable energy for CEM I (16% of energy use). The cement industry in the UK has been using NRSF, and RSFs such as meat and bone meal, processed sewage pellets, and waste paper and wood for many years (Mineral Products Association (MPA), 2008). UK brick manufacturers were using 11% secondary material input in a similar time period (Smith, 2011) and some UK brick manufacturers have been capturing the landfill gas created from landfills within their clay quarries to generate electricity, e.g. (Ibstock, 2015).

For all timber products, on average at least 50% of energy use came from renewable sources, with 64% for glulam, but very little was from RSF. Saw mills, engineered timber and wood panel producers have internally recycled their own wood waste as a fuel for many years, often using combined heat and power (CHP) to provide both heat and power, and sourcing the remainder of their heat demand from timber biofuel, for example in 2009, the European timber industry reported it sourced up to 75% of its energy from wood (CEI-Bois, 2009).
Figure 82 summarises the effect on GWP for the various product groups as the percentage of renewable energy increases. The thicker the line, the higher the correlation.

![Graph showing GWP decrease as renewable energy increases](image1)

**Figure 82 Change in GWP as Percentage of renewable energy used increases (weight of line represents the strength of correlation)**

The analyses showed for CEM I, EAF steel, and the engineered timber products, there is a trend for reduced GWP as the percentage of renewable energy increases – potentially this is due to the use of renewable electricity or renewable fuels burnt with higher efficiencies, with better delivered to primary ratios. For Ziegel brick, there is an increase in GWP for EPD with a higher percentage of renewable energy though this has a relatively low correlation. Potentially this is due to the use of renewable fuels with a higher delivered to primary energy ratio. The results for BOF steel, Facing brick and Sawn timber showed no correlation between GWP and percentage of renewable energy use.

For CEM I, no EPD had over 40% renewable energy. It is not clear whether the reduction in GWP seen for lower percentages of renewable energy would continue for EPD with increased renewable energy use, or whether GWP would stay relatively constant, as appeared to be the case for renewable energy use above 20%.

![Graph showing total energy consumption increase as renewable energy increases](image2)

**Figure 83 Changes in total energy consumption as the percentage of renewable energy increases (weight of line represents the strength of correlation)**

Figure 83 provides a summary of the trends in total energy consumption from EPD as the percentage of renewable energy increases. For EAF steels and CEM I cement, there was a trend to reduced energy consumption with increasing percentage of renewable energy use, with the correlation stronger for EAF steels, although the reduction was smaller. But both the brick and engineered timber products showed an increase in energy consumption with increasing percentage of renewable energy used –
the correlation was strongest for Ziegel bricks, but lower for the other products. For BOF steels and kiln dried timber, there was no obvious relationship between total energy consumption and renewable energy use.

It is concerning that both brick and engineered timber show increased energy consumption with increased use of renewable energy, suggesting that renewable energy is being used with less efficiency. To decarbonise, both these industries are going to need to move to significantly greater use of renewable energy which will, of itself, increase the demand for renewable energy. If, in addition, there is also an increased demand because of the less efficient use of renewable energy then renewable energy capacity will need to further increase.

The timber industry already uses significant amounts of timber for energy and those in the brick industry using more renewable energy use significant amounts of waste derived renewable secondary fuel. Because energy derived from wood is seen as ‘carbon neutral,’ and because waste derived energy doesn’t have the same financial cost as fossil fuels, there is perhaps a perception that there is no need to consider the efficiency with which these energy sources are used. In fact, although low carbon, wood derived fuel is not carbon neutral, DEFRA’s greenhouse gas conversion factor for wood chip is 6.5 g CO$_2$e/MJ, and for wood pellet is 14.7 gCO$_2$e/MJ compared to 66 g CO$_2$e/MJ for natural gas (BEIS and DEFRA, 2021).

8.8. Conclusion

This chapter has evaluated the use of renewable and non-renewable energy in the manufacture of key construction materials through the analysis of EPD published in the last five years. It has identified relationships between embodied carbon, as the GWP indicator and embodied energy, as the total primary and secondary energy consumption, and with renewable and non-renewable energy use.

As industry transitions to net zero over the next 30 years, it will be important to check both that products have low embodied carbon, but also that they use low carbon sources of energy such as renewables and nuclear energy efficiently, so that industry does not put excessive demand on their capacity as this will hinder the transition. This study thereby provides a mechanism for identifying those products which efficiently use both embodied energy and renewable energy in particular, whilst reducing embodied carbon emissions. In the future, it should also provide a useful resource for benchmarking the progress that the construction materials industry has made towards decarbonisation.
9. Conclusion

9.1. Summary

This thesis provides a detailed analysis of the increasingly large amount of data on embodied carbon impacts of construction products provided in EPD and generic datasets. In doing so it addresses current concerns about the availability and uncertainty of such data, both of which have been suggested as barriers to embodied carbon assessment of buildings and construction projects. As the embodied impacts of construction are a significant proportion of global greenhouse gas emissions, these are critical concerns which need addressing. While acknowledging a number of sources of data, the predominant focus of the research is on Environmental Product Declarations (EPD), a means of communicating standardised and verified environmental information for construction products.

Through a detailed literature review, including ‘grey’ literature as well as standard academic articles, a series of research questions related to EPD were posed. These covered how EPD are used in industry practice, the extent of available published EPD (at time of analysis), the variability of embodied carbon coefficients within product groups and the causes of this variability, and a deeper level of analysis looking at additional information which can be found from an ‘EPD Landscape’ and an ‘EPD Energy Array’, novel methods which are proposed to visualise gathered EPD data.

Through the interviews with some of the UK’s most experienced embodied carbon practitioners, it is clear that embodied carbon data for construction products is key to their role. Generic data and collective EPD are essential early in the design process, and manufacturer specific EPD become extremely useful as projects progress. The complexity of embodied carbon assessment, and the fact that there are rarely simple answers, means that embodied carbon data of both types is essential to check that real reductions are being achieved when mitigation strategies are applied.

Concerns about the robustness of EPD data due to its variation have been expressed in some of the academic literature, which has cited that this could be due to epistemic factors such as inaccuracy, lack of standardisation, or poor quality data, although there are many other studies that have suggested that aleatory factors such as technical or geographical differences could be behind the variability seen. A typology of variability is therefore proposed, using EPD analysis to demonstrate the different causes of variation. This is intended to explain the many aleatory factors behind the wide variation in product impacts – it helps understand the causes and reveals whether there is a real difference between products. The analysis demonstrates that the variation seen in EPD data, rather than being caused by epistemic factors, can be attributed largely to variability caused by technical, geographical and temporal differences, and to the different granularity of the data. This variability cannot be reduced through improved methodology or better practice, but is inherent to the differences between manufacturers, factories, production lines and products, and the choices available in terms of different raw materials and energy sources. Therefore the wide variability in impact emphasises the opportunity manufacturers have to reduce impact through use of improved technologies, input materials and product designs, and different energy strategies, and that designers have to procure products with lower impact at building level, both moving us more quickly towards a lower carbon future. In short, the aleatory variability found across EPD serves to highlight the opportunity that both manufacturers and designers have to reduce embodied carbon emissions.

EPD Landscapes are provided for a number of key construction products offering a pragmatic solution to understanding data, the range of impact and what “good might look like”. Whilst these show for cement and concrete that impacts remain complex and highly variable, the growing number of countries producing EPD across Europe, North and South America, the Middle East, India, and Australasia, demonstrate that climate change and the embodied carbon of construction materials are now a concern in multiple regions of the world. The EPD Landscapes for cement and concrete
demonstrate how such an analysis of EPD can provide useful information for designers, specifiers, building assessors, manufacturers and EPD verifiers, including for material selection, building LCA, benchmarking, target setting and EPD verification. It is hoped that these stakeholders will access and use this information to now reduce impacts.

The final chapter, Chapter 8, offers a further example of the benefit of analysing EPD, in the form of EPD Energy Arrays. In reviewing the use of renewable energy, there are concerns that it may be used more inefficiently than non-renewable energy, with some evidence of overall energy intensity increasing as the percentage of renewable energy increases. To ensure industry does not hinder the transition to Net Zero by putting further pressure on valuable renewable energy resources whilst reducing embodied carbon emissions, the EPD Energy Landscapes provide a mechanism for identifying those products which demonstrate an efficient use of embodied energy, and in particular, renewable energy. In the future, they should also provide a useful resource for benchmarking the progress that the construction materials industry has made towards decarbonisation.

In conclusion, EPD are widely used, and are considered by industry to be robust and the most appropriate data to use once products have been specified. Globally, the number of EPD are growing exponentially, driven for the most part by the growth in automation of EPD production using verified EPD Tools, by regulation of embodied carbon at building level and by green public procurement. The EPD Landscapes and EPD Energy Arrays developed within this thesis provide tools to enable the necessary transition towards a lower carbon future. Further detailed conclusions are given at the end of each of the analysis chapters 4 to 8.

The contribution to knowledge achieved by this thesis is to combine the previously poorly connected knowledge in this field in industry and academia with a major and innovative analysis of EPD data, providing new knowledge of direct relevance for multiple stakeholders looking to reduce the embodied carbon of buildings and products, and speeding the transition to net zero.

9.2. Additional commentary on UK situation

The UK Government appears nervous of supporting EPD and embodied carbon assessment based on an apparent concern with a lack of standardisation and the uncertainty of product data. Given the widespread use of EN 15804 for EPD and EN 15978 and the RICS Professional Statement in product and building level assessments in the UK and elsewhere, the concern about standardisation seems unfounded, though perhaps it has been overly influenced by the academic literature and its recognition of the lack of standardisation in academic studies which, as discussed in the literature review, rarely use the ISO standards for LCA, let alone the CEN/TC 350 standards.

DLUHC have recently said, ‘there are questions about whether there is the critical mass of EPD needed’ for whole life carbon assessments (DLUHC, 2022). Reviewing other countries which have regulated embodied carbon, it seems that the UK is in a reasonable position, with around 600 EPD for UK produced construction products and at least 600 cradle to gate generic embodied carbon datasets. This is not far from the 700-800 generic datasets that were available in the Netherlands, Germany and France when regulation came into force, and significantly more than the 200 generic datasets and a similar number of EPD in Finland and Sweden which have just started regulation. Some of the ICE Database generic datasets would benefit from being updated, and generic gate to grave data for all datasets should be provided and made freely available. It is hoped that the BECD will provide a central resource of appropriate embodied carbon data for the UK, delivering a user-friendly interface to find and compare data, and to make the data seamlessly available through API with building LCA and BIM tools in the UK.

At present however, the UK has reached this point with almost no direct Government funding for embodied carbon data since the initial PhD project behind the ICE database in 2008. The 600 EPD and
600 generic embodied carbon datasets currently available would be sufficient for regulation. However it is clear that the success of databases in other countries is made much easier by the support offered by Government, and the $250 million for EPD support available in the US will be considered enviously by many considering developing EPD in the UK. Government support for the development the BECD, update of generic datasets and provision of generic gate to grave data, and for the provision of EPD would be very welcome.
9.3. Suggestions for future research

1. How best to incorporate increasing quantities of data into design decisions

EPD are recognised as being verified and reliable, but the time needed to link EPD to materials in BIM models and to find EPD easily is a challenge that needs to be addressed quickly, as the amount of EPD is rising exponentially.

Over 130,000 EPD were available at the start of 2023, and automated EPD tools are having a dramatic effect on increasing this number – over 80,000 of these were EPD for concretes produced using verified EPD tools in the US, driven by the surge in Buy Clean and Low Carbon Concrete legislation being passed by states and counties there. With $250 million pledged through the Inflation Reduction Act to support the provision of EPD over the next couple of years, the number of EPD in the US are likely to rise ever higher.

A number of other drivers exist in Europe and elsewhere, including Green Public Procurement which has been used successfully in Norway and Germany, and EPD Credits in Green Building Certification such as BREEAM’s MAT 02 credit. Meanwhile regulation of building level embodied carbon appears to be behind the large number of EPD in France and Germany, and the over 1800 verified manufacturer specific datasets in the Dutch National Database. The publication of specific EPD are encouraged by Government funding of national databases, and the use of safety or uplift factors for generic data (which therefore penalises generic and encourages specific data), while industry is becoming increasingly familiar with EPD processes.

CO2nstructZero and the Construction Leadership Council (2022) have set a target for 40% of construction product portfolios to have EPD by 2025, and 100% by 2030 – meaning potentially 10,000 companies with at least one, and possible hundreds of EPD each, plus the EPD for the products that the UK imports. Meanwhile digitisation of EPD data is developing rapidly, for example through the standardisation of the InData ILCD+EPD format, BS EN ISO 22057 and the EC3 tool. However, until tool providers can solve the “flawless exchange” between EPD and BIM, there is a limit to how many EPD of these EPD could be easily found and used in assessments. The effective incorporation of this within BIM, and the impact of doing so, is an important area of research.

2. Investigation of wider impacts of material strategies

Material related strategies such as use of recycled content and use of cement replacements can show significant reductions at the asset level, but due to constraints in availability (of metal scrap, GGBS and PFA etc), may have no effect globally, or may even increase impact through increased transport as these materials are sourced from further afield. EPD and asset level LCA do not seem to be able to address this problem. An important area for future research is, how can we ensure that embodied carbon reduction strategies do not result in greater impacts?

3. A number of specific issues for embodied carbon assessment

There are a number of issues for embodied carbon assessment which could be researched to analyse the impacts of different potential decisions currently being discussed in industry and policy groups. These include:

- Should we take into account the future decarbonisation of embodied and operational impacts, and if so, what decarbonisation scenario should be used for materials, and should the focus change from carbon to other indicators (e.g. energy rather than carbon from 2025)?
• Module D – reused and recycled materials show no benefit at end of life in Module D if they are recovered, as they have no net output flow of recovered material. How can EPD better address the circular economy and inform building design in a positive way.

• End of life impacts for timber – how do EPD compare and how does the temporal assessment of radiative forcing vary from EPD Module C and D? How can we relate EPD information to the impacts of demolishing buildings now?

4. What is the impact of assessment on embodied carbon emissions?

Perhaps one of the most important remaining questions is, how much will the embodied carbon of construction reduce in real terms as a result of undertaking assessments and using EPD? As interest in embodied carbon across the Architecture, Engineering and Construction (AEC) industry in the UK and elsewhere starts to grow, there is still little understanding of the relationship between the data provided through EPD, their use in embodied carbon tools and the behaviour of the AEC industry. What is the evidence that measuring embodied carbon encourages people to reduce embodied carbon?
10. References


Building Transparency (2022b) EC3 - Digitized EPDs in EC3, by Category. Available at: https://buildingtransparency.org/ec3 (Accessed: 8 February 2022).


Buzzi Unicem Spa (2017) EPD for Buzzi Unicem Cement EPD Italy 0025. Available at: https://www.buzziunicem.it/documents/90625/431292/Dichiarazione+ambientale+di+prodotto+-++Cementi.pdf/ce98b3d4-ded0-ad09-b57c-cd46192d45bc.


Cabinet Office et al. (2022) Whole Life Carbon Assessment - Briefing Note for Environmental Audit Committee What percentage of public projects have undertaken whole life carbon assessments? London. Available at: https://committees.parliament.uk/work/1147/sustainability-of-the-built-environment/publications/.


ecoinvent (2021) ‘Market for electricity, low voltage, GB - ecoinvent v3.8’. ecoinvent. Available at: https://v38.ecoquery.ecoinvent.org/Details/UPR/1ca1bd16-ed38-4ebf-b4f1-4ac046550b41/8b738e0-f89e-4627-8679-433616064e82.


social opportunities (EV0490), The Warwick Research Archive Portal (WRAP), (February). Available at: https://wrap.warwick.ac.uk/152270/.


IEA (2023) Renewables 2022: Analysis and forecast to 2027.


ISO TC59 SC17 WG3 (2021) prEN FDIS 22057:2021 Sustainability in buildings and civil engineering works – Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM).


LETI (2020) LETI. Available at: https://www.leti.uk/about (Accessed: 1 January 2020).

LETI, WLCN and Institution of Structural Engineers (2021) Embodied Carbon Target Alignment. London. Available at: https://www.leti.uk/_files/ugd/252d09_25fc266f7fe44a24b55c0e95a92a3878.pdf.


Life Level(s) (2020) Life Level(s). Available at: https://lifelevels.eu/.


Metsims (no date) LCA Database. Available at: www.lcadatabase.com.


Moncaster, A. M. *et al.* (2023) *Understanding the impact of individual, industry & political decisions on transitions towards environmental sustainability*. Uster. Available at: https://oro.open.ac.uk/87046/.


Moncaster, A. M. (2015) ‘Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries’, *Int J Life Cycle...


Richardson, S. (2017) Embodied Carbon Assessment: Decision Making under Uncertainty: Case studies of UK supermarket construction. Reading University. Available at:


Skanska UK PLC (2021) ‘Skanska sustainable procurement’, pp. 1–31. Available at:


Sphera (2021) ‘Electricity grid mix; AC, technology mix; consumption mix, to consumer; <1kV (en)’.


Stanhope PLC (2023) *Environmental, Social and Governance Strategy (Esg).* Available at: https://assets.ctfassets.net/ghkmu4mofbog/EGADzI1Btuv3h6UJGzYlB/39e046c5a10b1339fde4fb0da5a7e32c/STANHOPE_-_ESG_Strategy_2023__Low_res.pdf.


Stichting Bouwkwaliteit (2014) *Assessment Method Environmental Performance Construction and Civil Engineering Works (GWW).*


Stocker, T. F. *et al.* (2013) *Climate change 2013 the physical science basis: Working Group I contribution to the fifth assessment report of the intergovernmental panel on climate change.* doi: 10.1017/CBO9781107415324.


Symons, K. E. (2022) ‘New methodology charts course to reducing embodied carbon in buildings’,


The Swedish National Board of Housing Building and planning (2018) Klimatdeklaration av byggnader.


UK Green Building Council (2020) ‘Building the Case for Net Zero: A feasibility study into the design, delivery and cost of new net zero carbon buildings’, (September). Available at:


United Nations (2023) *UN Comtrade Database*. Available at: https://comtradeplus.un.org/.


Wood for Good (2017) *BREG EN EPD 000124 Dried Planed or Machined Sawn Timber Used as*
Structural Timber. Watford.


Appendix A: Environmental Product Declarations (EPD)

Introduction

What are EPD? EPD provide a standard way of declaring the impacts of manufacturing and using products through Life Cycle Assessment (LCA). In Europe, EN 15804 provides the overarching set of Product Category Rules (PCR) to ensure consistent reporting of environmental impact information for all construction products. This Annexe describes the information provided in EPD compliant with EN 15804:2012+A1:2013 and EN 15804+A2.

Information provided by an EPD

All EN 15804 EPD are required to provide the same core information. This annex aims to describe the types of data, and how it can be used. On the last two pages of the annex, two EPD from different programmes are shown so you can see how the different information is displayed.

1. **Product and Company data:** EPD will give the product name, the company that owns the EPD. It will often provide technical information about the product so you can check the product meets your specification.

2. **Manufacturing Data:** EPD provide description of the product and how it is manufactured, and explaining what it is made of – the product content. They also provide a process diagram which will often show the ‘system boundaries’ – which processes are included in the Life Cycle Assessment (LCA) model behind the EPD, which is particularly relevant if the product uses recycled content. If not, the system boundaries should be described with text.

3. **Product Category Rule Information:** Each EPD will list the Core PCR used (EN 15804 in Europe, ISO 21930 or EN 15804 outside Europe). EN 15804+A1 and EN 15804+A2 provide slightly different information, so it is important to know which standard has been used. The EPD Programme will also have its own Product Category Rules, and often sub-category rules covering a product group like concrete, timber or bricks which will be detailed on the EPD. These may link to a European Product Standard which are complementary to EN 15804, for example, EN 16908:2017+A1:2022 for Cement and building lime.

4. **EPD Data:** Each EPD has a registration number, and dates of validity (normally 5 years from registration).

5. **Verification Data:** EPD are independently verified by an expert in life cycle assessment with knowledge of the type of product. The EPD will give details of the Verifier and explain if they are internal or external to the manufacturers’ organisation.

6. **LCA data:** The EPD should also list the LCA consultant or any EPD tool which has been used. It will also provide the source of the LCA data which has been used and its date, and the year of data collection for the manufacturing process. It should describe any data quality issues, and will explain how allocation and cut-off have been considered - allocation explains how the LCA has dealt with any processes which produce two or more products, and cut-off explains if any processes have been excluded from the assessment.

7. **Declared Unit:** EPD always need to tell you what the declared or functional unit it. This is the quantity of the product that has been assessed – so results are given per declared unit – e.g. per tonne of cement, per cubic metre of concrete or timber, per square metre of flooring or plasterboard for example. Declared units are normally chosen because they are the way that products are purchased and specified, and mean that the EPD data can be used straightforwardly at building level by multiplying the impact per declared unit by the quantity of the product used in the building. Some EPD use a ‘functional unit’ which has a quantity and one of more functions that the product provides – for
example insulation often has a functional unit of 1 m² with a thermal resistance of 3 W/m²K. Some products may use a mass based declared unit rather than another which is the way that the product is specified – for example stone wool insulation products’ impacts per m² will vary with density and thickness, but the impact per kg will be the same, so a per kg declared unit will make the EPD more useful.

8. **Mass of the declared unit**: EPD always need to give you the mass of the declared unit – this is very important if a non-mass based declared or functional unit has been used. It can be used to calculate impacts for transport and other scenarios. EPD may also provide scaling information, so that you can scale the results of for one product to other similar products.

9. **Composition of the product**: EPD should give you an idea of the composition of the product and as a minimum, list any substances that are on the European Chemicals Agency’s ‘Candidate List of Substances of Very High Concern for authorisation.’

10. **Biogenic Carbon Content**: It is good practice in EPD to EN 15804+A1 to provide the biogenic carbon content of biobased products. This is normally given in kg CO₂ – reflecting the amount of CO₂ that has been sequestered to provide the carbon. 12 kg biogenic carbon = 44 kg CO₂. In **EPD to EN 15804+A2**, it is a requirement to report the amount of biogenic carbon sequestered in the product in kg Carbon (kgC), if it is more than 5% of the product mass. The same requirement applies to packaging. The conversion between CO₂ and Carbon is 12 kg Carbon = 44 kg CO₂.

11. **Life cycle stages**: Each stage has a number of modules corresponding to an aspect of that stage. The stages comprise the product stage (A1-A3); construction stage (A4-transport, A5-installation); use stage (B1-B7), end of life stage (C1-C4) that includes disposal and waste recovery and a module showing the benefits of waste recovery in the next product system (Module D). It is mandatory in EN 15804+A1 to provide the data for the product stage A1-A3 or ‘cradle-to-gate.’ These cover all processes including material extraction until the product is ready to leave the factory gate. Where recovered waste material or energy is used, the impacts of generating the waste are not included. In **EPD to EN 15804+A2**, it is now mandatory to provide Modules A1-A3 and Modules C and D for all products, with a few excepts such as cement or wood preservative, where only Modules A1-A3 are required.

12. **Modules Assessed**: Each EPD normally provides a table (see example from a BRE EPD below) which shows which modules have been assessed.

<table>
<thead>
<tr>
<th>Product</th>
<th>Construction</th>
<th>Use stage</th>
<th>End-of-life</th>
<th>Benefits and loads beyond the system boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>A5</td>
</tr>
<tr>
<td>Raw material supply</td>
<td>Transport</td>
<td>Manufacturing</td>
<td>Transport to site</td>
<td>Transportation, Installation</td>
</tr>
<tr>
<td>Use</td>
<td>Maintenance</td>
<td>Repair</td>
<td>Replacement</td>
<td>Operation of energy use</td>
</tr>
<tr>
<td>B6</td>
<td>B7</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
</tr>
<tr>
<td>Transport</td>
<td>Waste disposal</td>
<td>Release, Recovery and Recyclability</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13. **Scenario Descriptions**: If the EPD provides any impacts beyond the factory gate, then the EPD needs to describe the basis of assessment – the scenario - for each module. This information allows you to check whether the scenario is appropriate for your building. Information about the scenarios is described below.

14. **A4 Transport**: If A4 is reported, the EPD will need to explain what journey has been assessed. This might be the typical journey from the factory to a building site or 100 km by road. It might be a simple trip, or a combination of road and sea. It should explain what type of vehicle(s) have been used, the
distance in each vehicle, the fuel consumption, and the capacity utilisation (how full the vehicle is (including return journeys). It should explain if the data is from the company’s records (for example if the company owns its own delivery vehicles, or requires its haulage contractor to provide this information; or it may be default figures. Knowing how far the factory is from your site, it can be possible to use the A4 scenario data to calculate the exact distance.

15. **A5 Construction**: if A5 is declared, this should tell you the wastage rate used, what happens to the waste (recycling etc.), and any impact for construction (say pumping for ready-mix concrete). Again, if your contractor can give you specific data for product wastage from their sites then you can adapt this data.

16. **B1 Emissions**: B1 covers emissions for products, for example volatile organic compounds from solvent based paints or off gassing of blowing agents from thermal insulation. If B1 is reported, then this should explain what is emitted, where it is emitted (e.g. into indoor air), how much is emitted, how long it is emitted for, together with the standard used to measure it. Carbonation (the reaction of free lime in concrete, lime mortars etc. with CO₂ in the atmosphere to form carbonates) should also be described here if it occurs before the end of life of the building.

17. **Reference Service Life (RSL)**: Any EPD providing modules B2-B5 will need to provide the Reference Service Life – how long the product is expected to last in the building, together with the reference conditions that support that service life: for example any design application requirements, how it should be installed and maintained, the indoor or outdoor exposure, and usage conditions (e.g. how much use a floor will get). The reference service life should be adapted for the building if required. For example, if you are installing the product with a different exposure, or will not be maintaining it, then the given Reference Service Life will not be appropriate.

18. **B2 and B3 Maintenance and Repair**: this will describe any maintenance and repair processes needed over the reference service life, how often they are required and what materials and resources are needed.

19. **B4 and B5 Replacement and Refurbishment**: this will describe any major processes needed over the reference service life. Normally the replacement of the whole product would occur at the end of the service life, so would not be included in an EPD.

20. **B6 and B7 Energy and water in use**: if the product uses energy or water in use, then this section should give information on the amount and type of energy in B6 and water in B7. EPD should provide this information even if it hasn’t been modelled in the EPD.

21. **C1-C4 End of life**: These modules cover the end of life of the product from the point it is no longer used in the building. They are mandatory for almost all EPD to EN 15804+A2.

22. **C1 Dismantling**: This module shows the impacts of demolition or deconstruction. If the waste reaches the end of waste state when it is collected on site, then this will be the only end of life module with an impact.

23. **C2 Transport**: This module shows the impact of transporting the waste to waste processing and final disposal.

24. **C3 Waste processing**: this module shows the impact of any waste processing to recover the waste to a secondary material or secondary fuel. If the waste is incinerated with energy recovery in a plant with R1 status (see Glossary), then the impacts are included in C3.

25. **C4 Waste disposal**: this module shows the impact of any disposal processes such as landfill or incineration with no energy recovery, or with energy recovery in a plant without R1 status (see Glossary).
26. **Module D**: If material or energy is recovered in any modules A4-A5, B2-B5, C1, C3 or C4, then Module D will show the benefits of the net output of recovered material or energy that is used in the next product system. It will include any impact of further processing until the output substitutes a virgin material or energy source – which is included as an avoided impact in Module D.

27. **Indicator Results**: EPD results are normally only given to 3 significant figures. Some EPD use scientific notation to show the results.

<table>
<thead>
<tr>
<th>Actual Number</th>
<th>3 significant figures</th>
<th>Scientific Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13274</td>
<td>0.133</td>
<td>1.33E-01 or 1.33*10^{-1}</td>
</tr>
<tr>
<td>1343.23</td>
<td>1340</td>
<td>1.34E+03 or 1.34*10^{3}</td>
</tr>
<tr>
<td>1.3813</td>
<td>1.38</td>
<td>1.38E+00 or 1.38*10^{0}</td>
</tr>
</tbody>
</table>

28. **Mandatory Environmental Impact Indicators**: EN 15804+A1 currently provides 7 impact indicators for the product and EN 15804+A2 provides 10 mandatory core impact indicators.

29. **Global Warming Potential (GWP)** relates to greenhouse gases and global warming and includes emissions and removals of both fossil and biogenic carbon. In EN 15804+A1 it is given as the total of all removals and emissions in each module – this is the embodied carbon, and is a mandatory indicator.

In EN 15804+A2, it is reported separately for biogenic carbon, fossil carbon, and carbon from land use and land use change, and then as a total of the three sub-indicators. The total is the embodied carbon and is a mandatory indicator. Biogenic carbon and land use carbon must always be reported in the total, and must be reported if they are more than 5% of the total GWP.


31. **Acidification Potential** relates to acidification of soil or water and its impact. Mandatory in EN 15804+A1 and EN 15804+A2 but the units differ and cannot be compared.

32. **Eutrophication Potential** how over-fertilisation causes excessive growth of biomass. The units and scope of the indicators below vary and cannot be compared.
   b. **Eutrophication Potential – Aquatic freshwater** - Indicator covering only impacts on freshwater. Mandatory in EN 15804+A2.
   c. **Eutrophication Potential – Aquatic marine** - Indicator covering only impacts on the ocean. Mandatory in EN 15804+A2.

33. **Photochemical Ozone Creation Potential** impacts of ozone and other oxidants in the lower atmosphere. Mandatory in EN 15804+A1 and EN 15804+A2 but the units differ and cannot be compared.

34. **Abiotic Depletion Potential – elements** the impact of elements, minerals and energy consumed. Mandatory in EN 15804+A1 and EN 15804+A2 but the scope of the indicators differ and cannot be compared.

35. **Abiotic Depletion Potential – fossil** the impact of consuming fossil resources (e.g. oil, coal gas). Mandatory in EN 15804+A1 and EN 15804+A2 but the units differ and cannot be compared.

36. **Water (user) deprivation potential Eutrophication Potential – Aquatic fresh water** - Indicator covering scarcity and water consumption. Mandatory in EN 15804+A2.
37. **OPTIONAL ENVIRONMENTAL IMPACT INDICATORS**: EN 15804+A2 provides 6 optional impact indicators which must be assessed but do not have to be reported in the EPD.

38. **Particulate matter** – indicator describing the incidence of disease arising from particulate emissions. Optional in EN 15804+A2.


42. **Human toxicity, non-cancer effects** – indicator describing emissions causing other effects on humans. Optional in EN 15804+A2.

43. **Land use related impacts / Soil quality** **Human toxicity, cancer effects** – indicator describing the effects of agriculture on soil quality and land use. Optional in EN 15804+A2.

44. **DISCLAIMERS**: The reporting of the indicators Nos. 34., 35., 36., 39., 40., 41., and 42. in EPD to EN 15804+A2 requires the use of disclaimers in the EPD.

45. **RESOURCE USE INDICATORS**: EPD also provide indicators for primary and secondary energy, freshwater consumption; secondary material use. These indicators are mandatory in both EN 15804+A1 and EN 15804+A2

46. **Primary Energy Renewable Energy** the amount of renewable resources used to produce energy.

47. **Primary Energy Renewable Material** the amount of renewable resources used within the product (e.g. timber in the product). Measured as the net calorific value of the renewable input.

48. **Primary Energy Renewable Total** the total amount of renewable resources used.

49. **Primary Energy Non-Renewable Energy** the amount of non-renewable resources used to produce energy.

50. **Primary Energy Non-Renewable Material** the amount of non-renewable resources used with the product (e.g. oil used in plastics). Measured as the net calorific value of the non-renewable input.

51. **Primary Energy Non-Renewable Energy** the total amount of non-renewable resources used.

52. **Secondary Material** the mass of inputs to the process which are derived from waste. This is not always the same as the recycled content, as all the secondary material input does not always end up in the product.

53. **Renewable Secondary Fuel** the amount of fuel used that is derived from waste made of renewable resources, e.g. paper, cotton textiles, cooking oil etc.

54. **Non-Renewable Secondary Fuel** the amount of fuel used that is derived from waste made of non-renewable resources, e.g. plastics, engine oil etc.

55. **Net Use of Fresh Water** the amount of fresh water consumed.

56. **WASTE DISPOSAL INDICATORS**: EPD provide indicators showing the amount of waste disposed of from each module. These indicators are mandatory in both EN 15804+A1 and EN 15804+A2.

57. **Hazardous Waste Disposed** the mass of hazardous waste that is sent to final disposal.

58. **Non-hazardous Waste Disposed** the mass of non-hazardous waste that is sent to final disposal.

59. **Radioactive Waste Disposed** the mass of radioactive waste from nuclear power that is created.
60. **Other Output Flows**: EPD provide indicators showing material and energy that is recovered from each module.

61. **Components for Reuse** the mass of end of life material which is reused.

62. **Material for Recycling** the mass of secondary material created by recycling waste.

63. **Material for Energy Recovery** the mass of secondary fuel created by processing waste.

64. **Exported Energy** the amount of energy (often separated into electricity and heat) that is recovered from combustion of waste, for example in Energy from Waste plants (C3) or in waste incinerators (C4) or of landfill gas (C4).

65. **Interpretation**: Some EPD provide an explanation of the results, for example which input or process causes the biggest impacts.

66. **References**: EPD will normally provide details of the standards and PCR used for the assessment, any standards used to provide technical information and other relevant documents, for example certification to ISO 14001, and the LCA tool and database used.

67. **Other information**: EPD will normally give the name and contact details for the EPD Programme and the LCA Practitioner who undertook the Life Cycle Assessment used in the EPD.

**Using the Data from an EPD**

**Energy Data**: The total amount of energy (feedstock and energy) used to manufacture a product is the sum, for A1-A3, of PERT, PENRT, RSF and NRSF. The total amount of feedstock energy is the sum of PERM and PENRM. The total amount of energy used as energy is the sum of PERE, PENRE, RSF and NRSF.

ADPF is also a measure of energy – covering energy from fossil sources. For EPD to EN 15804+A1 it differs from PENRT as it does not include nuclear energy which is considered based on the ADPE of uranium. Thus in EPD to EN 15804+A1, the amount of energy from nuclear sources is PENRE minus ADPF.

For EPD to EN 15804+A2, ADPF includes both fossil and nuclear energy, but may differ from PENRT as it uses standardised calorific values rather than specific ones.

**Biogenic Carbon**: For timber products, the amount of biogenic carbon sequestered within the product can be calculated according to EN 16449 by considering the dry mass of timber in the product - if the EPD gives the timber content and the moisture content (X%) then the dry mass = timber mass @ X% /(100%+X%). Biogenic carbon = dry mass * 0.5 *44/12.

For other biobased products, the dry mass of the biomass and the carbon content are needed. The [Phyllis database](https://phyllis.nl) provides indicative moisture content and carbon content for a wide variety of biobased materials.

Carbon can be converted to CO$_2$ by multiplying by 44/12.

Biogenic carbon figures given in the EPD can be checked in this way too.

---

Appendix B: Questionnaire for Interviews

1 INTERVIEWEE

- Interviewee’s role and experience in the construction industry?
  - PROBES: Years worked, other roles, and level of expertise

2 EMBODIED CARBON

- When did you become aware, or familiar with Embodied Carbon. What about Whole Life Carbon, Upfront Carbon, and Building Life cycle Assessment?
- What do you know about them?
  - PROBES: what do you know about their Significance, the Standards used, ways of Measuring/Assessing, Whether and how you can reduce them?
- Were you taught about Embodied Carbon at university? How much, which course, how long?

3 EMBODIED CARBON AND BUILDING LCA TOOLS

- Do you have experience of using any relevant tools (Green Guide, embodied carbon tools, building LCA tools). (no experience, looked at it, consultant used it, used it once, used it several times, very familiar).
  - PROBES: Green Guide, Rapier/EccoLAB, H\B:ERT, Tally, ies IMPACT, eTool, oneclickLCA.
- What are the typical type of projects where you used these tools?
  - PROBES: large/small (£ & m²), housing, commercial, infrastructure?
- Who asks for embodied carbon or LCA assessments?

4 FOR A SPECIFIC PROJECT: Now focussing on a specific project where you remember a specific tool was used

- What tool was used
- What type of project was it, how big (£, m²)
- How long ago was this (year)
- What/who motivated them to use consider embodied impacts?
  - PROBES: client, BREEAM credits, office policy, regulation, etc
  - ACTORS – DRIVERS – who else involved
- Why/how did the tool get chosen?
  - PROBES: Cost, time, training, ease of use, experience, recommendation, BREEAM requirement etc?
- Who was involved in choosing the tool?
- Was it a particular type of tool in terms of compliance? E.g. RICS Professional Statement, EN 15978, BRE IMPACT compliant etc?
- What did you use the tool to measure?
  - PROBES: Embodied carbon, upfront carbon, whole life carbon, LCA?
  - How much of the building – structure, structure, and fabric, etc
- During which RIBA Design Stages was the tool used?
- Who actually used the tool (e.g. an embodied carbon consultant, the architect etc.)?
  - PROBES – why was this? Did it work well? How much interaction with them?
- Who else was involved undertaking the assessment?
  - PROBES: e.g. in providing information on areas, information on detailed specifications, (note interpreting and using results are covered later on)

5 FOCUS ON CONCRETE (for example for floor structure or foundations) in the tool

- Do you remember concrete featuring in the assessment?
- How was concrete considered in the tool?
  - PROBES: Mix designs and strengths, standard concrete, standard specifications?
- How much product data was considered using the tool and how useful was this?
- How do they remember feeling about the options that were available – not enough, too many? Realistic, unrealistic? Transparent or black box?
- What options were available (e.g. mix, thickness, design, reinforcement etc)
● Was company specific data available in the tool or requested from suppliers?
● Could company specific/project specific data be used in the tool if provided?
● What data for concrete was initially chosen in the tool?
● What data for concrete was actually used in the final assessment?
● What type and specification of concrete was actually used in the building?
● Was the design of the concrete structure changed to reduce carbon?
● What type of concrete and specification is typically used on this sort of project?
● Limits of availability of GGBS and PFA.

6 FOCUS ON THE TOOL RESULTS

● What do you remember of the assessment and the results (AT DIFFERENT STAGES IF RELEVANT)?)
  ○ PROBES: Was the impact ‘good’ or ‘bad’ and how this was worked out. What were the significant ‘hot spots’ or causes of impact? Did anything surprise you?
● How easy was it to use the tool at different points in the design?
● How easy was it to understand the outputs from the tool?
● How many indicator results do you remember there were?
  ○ PROBES: ECO2, EN 15978, Ecopoints etc). Which did they consider relevant?
● How many life cycle stages were assessed?
  ○ PROBES: Cradle-to-Gate, Upfront Carbon, Use Stage, End of Life, Module D? Which of these were considered most relevant?
● Was the whole building assessed?
  ○ PROBES: What did they ignore? E.g. Foundations, building services, balconies, parking etc? How did they feel about what was ignored?
● Who else was involved in using the assessment?
  ○ PROBES: in reviewing results? In making decisions based on the results

7 CHANGING THE SPECIFIC PROJECT DESIGN

● How did they use the results?
  ○ PROBES: what changes (if any) in the design were considered whilst using or as a result of using the tool? Materials changes? Product changes?
● Who was involved in those decisions?
● Whether any changes were actually made?
● Why changes did or didn’t happen?

8 LEARNING FROM THE TOOL

● Do you ever consider embodied carbon for a building without using a tool?
  ○ PROBES: what do you consider? What do you change? Has any tool influenced you in this?
● What is the role of intuition in considering embodied carbon?
● What would you say you have learnt from using the tool?
  ○ PROBES: quick wins, top tips, good materials
Appendix C: Statistical Terms

An overview of the statistical terms used in the literature and in the research described in the thesis is provided below.

**Arithmetical mean (or mean):** the sum of a collection of numbers divided by the count of numbers in the collection. It is not a robust statistic, meaning that it is heavily influenced by outliers (values that are very much larger or smaller than most of the values).

\[ \mu = \frac{1}{n} \sum x_i \]

\( \mu \) = arithmetic mean
\( n \) = number of values in the population
\( x_i \) = each value from the population

**Variance:** Variance is a measure of dispersion, meaning it is a measure of how far a set of numbers is spread out from their mean value.

\[ V = \frac{\sum(x_i - \mu)^2}{n} \]

\( V \) = Variance
\( \mu \) = arithmetic mean
\( n \) = number of values in the population
\( x_i \) = each value from the population

**Standard deviation:** The standard deviation of a random variable, sample, statistical population, data set, or probability distribution is the square root of its variance. A useful property of the standard deviation is that, unlike the variance, it is expressed in the same unit as the data.

\[ \sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{n}} \]

\( \sigma \) = Standard deviation
\( \mu \) = arithmetic mean
\( n \) = number of values in the population
\( x_i \) = each value from the population

**Coefficient of variation** using the method of Laner et al. (2015) Assuming uncertainties are described by normal distributions, the coefficient of variation (CoV) is the ratio between the standard deviation \( \sigma \) and mean \( \mu \) of each data point \( i \), with the true value expected to fall within \( 2\sigma \) of the mean 95% of the time.

\[ CoV = \frac{\sigma}{\mu} \]

\( CoV \) = Coefficient of variation
\( \sigma \) = Standard deviation
\( \mu \) = arithmetic mean

**Median:** any value such that at least half of the population is less than or equal to the proposed median and at least half is greater than or equal to the proposed median. The median is not skewed by a small proportion of extremely large or small values, and can therefore provide a better representation of a ‘typical’ value.
Minimum and maximum values: the extremes of the variation – can very easily be distorted by outliers. The minimum and maximum can also be expressed as a percentage relative to the mean, e.g. minimum = 5, mean = 10, maximum = 12, min = -50%, max = +20%.

Interquartile range: the range from maximum of the 25% of values above the median to the minimum of the 25% of values below the median.
The following table sets out the EPD for construction products produced in the UK, as described in 3.3.6.

**Table 37 EPD covering UK Production**

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Collective EPD</th>
<th>EPD Owner and number of EPD*</th>
<th>EPD Programme</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aggregates</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aggregate Industries – 3 EPD for aggregates</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCO Technology – 1 EPD for manufactured limestone aggregate</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td><strong>Bitumen and Waterproofing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GCP Applied Technologies - 2 EPD for waterproof membranes</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td><strong>Cement and Lime</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anhydritec - 2 EPD for anhydrite binders</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DB Group - 1 EPD for binder</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lafarge Cement – 1 EPD for cement</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>UK</strong> Mineral Products Association (MPA) - 1 EPD for cement</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> Cembureau – 3 EPD for European average cements</td>
<td>Cembureau</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> European Lime Association – LC1* for quick lime and for hydrated lime</td>
<td>ELA</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> Calcium Carbonate Association Europe – 3 EPD for Dry ground calcium</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Ceramic products</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>UK</strong> Brick Development Association – 1 EPD for average UK produced brick</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Coatings and finishes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AkzoNobel Decorative Paints – 32 EPD for Dulux paints</td>
<td>MRPI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>akzoNobel International Paint – 2 EPD for International Intumescent paints</td>
<td>MRPI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AM Technology – 1 EPD for Airlite paint</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Armourcoat Ltd – 7 EPD for coatings</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clayworks – 1 EPD for clay plaster</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crown Paints - 2 EPD for paint</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fosroc UK – 1 EPD for render</td>
<td>EPD Hub</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Johnsons Tiles - 1 EPD for ceramic wall tiles</td>
<td>EPD Hub</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jotun Paints UK – 7 EPD for coatings, 3 EPD for Steelmaster intumescent paint</td>
<td>EPD Norge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and 1 EPD for Barrier 90 steel primer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> PPG Architectural Coatings – 23 EPD for Johnstone’s paints</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sika - 16 EPD for coatings and finishes</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Global</strong> ICDLI – Laminate Association – 2 EPD for high pressure laminates</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Global</strong> IGI - The Global Wallcoverings Association – 5 EPD for wall coverings</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Concretes (ready-mix and mortar)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hoben Concrete – 1 EPD for Bagwork product</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CPI Mortars Ltd – 1 EPD for masonry mortar</td>
<td>EPD Hub, International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>UK</strong> Hanson UK – 13 EPD for ready-mix concrete</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>London Concrete Pumping - 3 EPD for ready-mix concrete</td>
<td>EPD Hub</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> British Ready-Mixed Concrete Association (BMRCA) – 1 EPD for ready- mix</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>concrete</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Construction Chemicals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> European Federation of Concrete Admixtures Associations (EFCA) – 6 EPD</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for concrete admixtures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> FEICA - Association of the European Adhesive and Sealant Industry –</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21 template EPD for reactive resin products (10), dispersion-based products</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2) and for modified mineral mortars (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Flooring</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alтро – 16 EPD for flooring products</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Amticо - 11 EPD for flooring products</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burmatex – 20 EPD for carpet tiles</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gradus Ltd - 8 EPD for carpet sheet and tiles</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heckmondwike FB - 5 EPD for carpet tiles</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interface – 37 EPD for modular carpet tiles (1 tufting factory in Northern</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ireland)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mannington Mills - 1 EPD for resilient floor tile</td>
<td>UL Environment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Milliken Industrials - 18 EPD for carpet tiles</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paragon Carpet Tiles - A Division of National Floorcoverings Ltd - 3 EPD</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for carpet tiles</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rawson Carpet Solutions - 2 EPD for carpets and carpet tiles</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shaw Contract – 2 EPD for flooring</td>
<td>International EPD*</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> European Resilient Flooring Manufacturers (ERFMI) – 10 EPD for PVC</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5), LVT (2), Rubber, Linoleum and Cork resilient flooring products</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>EU</strong> Gemeinschaft umweltfreundlicher Teppichboden e.V. (GuT) – 30 EPD</td>
<td>IBU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for carpet tiles</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Drainage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PolyPipe Civils &amp; Green Urbanisation - 1 EPD for geocellular sub-base</td>
<td>EPD hub</td>
<td></td>
</tr>
<tr>
<td></td>
<td>replacement system</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Electrical</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Backbone Connect - 1 EPD for fibre cable and base unit</td>
<td>BRE</td>
<td></td>
</tr>
<tr>
<td>Product Type</td>
<td>Collective EPD</td>
<td>EPD Owner and number of EPD*</td>
<td>EPD Programme</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------</td>
<td>-------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td><strong>Furniture</strong></td>
<td>Foster and Partners – 1 EPD for a chair</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td>Glass</td>
<td>Pyrogard - 1 EPD for safety glass</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td>Insulated panels</td>
<td>Kingspan – 6 EPD for Quadcore insulated panels</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Euroclad – 1 EPD for insulated wall cladding</td>
<td></td>
<td>Tata Steel</td>
</tr>
<tr>
<td></td>
<td>Europanel – 1 EPD for insulated wall cladding</td>
<td></td>
<td>Tata Steel</td>
</tr>
<tr>
<td></td>
<td>SAB – 2 EPD for insulated wall panels</td>
<td></td>
<td>Tata Steel</td>
</tr>
<tr>
<td></td>
<td>CA Building Products – 1 EPD for insulated steel roofing</td>
<td></td>
<td>Tata Steel</td>
</tr>
<tr>
<td>EU</td>
<td>PPA-Europe - European Association for Panels and Profiles – 2 EPD for steel sandwich panels, 2 EPD for profiled metal sheet</td>
<td></td>
<td>IBU</td>
</tr>
<tr>
<td><strong>Insulation</strong></td>
<td>Building Innovation – 3 EPD for insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Ecotherm – 5 EPD for insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Eden Renewable Innovation Ltd – 2 EPD for Thermafleece insulation</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Jablite Ltd - 2 EPD for EPS insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>IGO Insulations Ltd – 1 EPD for insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Interfloor – 1 EPD for acoustic insulation</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Kingspan Insulation – 18 EPD for insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Knauf Insulation – 2 EPD for stone wool insulation</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>MW Insulation – 1 EPD for Supaphen phenolic insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>School of Natural Building - 1 EPD for straw as insulation</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Polyfoam XPS - 2 EPD for XPS insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Rockwool – 1 EPD for an insulation product</td>
<td></td>
<td>EPD Ireland</td>
</tr>
<tr>
<td></td>
<td>Saint-Gobain ISOVER UK Ltd - 8 EPD for glass wool acoustic insulation</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Superglass Insulation – 2 EPD for glass wool insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Xtratherm – 1 EPD for PIR insulation, 1 EPD for phenolic insulation</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Extruded Polystyrene Insulation Board Association (EXIBA) - 1 EPD for extruded polystyrene (XPS) with halogen free blowing agent</td>
<td></td>
<td>IBU</td>
</tr>
<tr>
<td>EU</td>
<td>European Manufacturers of Expanded Polystyrene (EUMEPS) – 7 EPD for expanded polystyrene insulation products</td>
<td></td>
<td>IBU</td>
</tr>
<tr>
<td>EU</td>
<td>PU Europe – 1 EPD for PU spray insulation</td>
<td></td>
<td>IBU</td>
</tr>
<tr>
<td>EU</td>
<td>European Cellulose Insulation Association (ECIA) – 1 EPD for loose fill cellulose insulation</td>
<td></td>
<td>RT EPD</td>
</tr>
<tr>
<td>EU</td>
<td>European Cellulose Insulation Association (ECIA) – 3 EPD for cellulose insulation</td>
<td></td>
<td>Ines</td>
</tr>
<tr>
<td>EU</td>
<td>Eurima – 3 EPD for mineral wool insulation</td>
<td></td>
<td>Eurima</td>
</tr>
<tr>
<td>Hardware and Locks</td>
<td>ARGE- Consortia of the Associations of the European Lock and Hardware Industry – 14 template EPD for hardware products, which can be used by any member of ARGE</td>
<td></td>
<td>IBU</td>
</tr>
<tr>
<td>EU</td>
<td>Assa Abloy UK - 1 EPD for a Union cylinder lock</td>
<td></td>
<td>IBU</td>
</tr>
<tr>
<td>Lighting</td>
<td>Dialight – 9 EPD for lighting products</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Whitecroft - 2 EPD for lighting</td>
<td></td>
<td>EPD Hub</td>
</tr>
<tr>
<td></td>
<td>Novus48 - 1 EPD for lighting system</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Blue Chip – 1 EPD for metal balcony</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>British Gypsum Saint Gobain – 1 EPD for Gypsum metal framing for plasterboard</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>British Steel – 1 EPD for a steel railing</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>CCL International - 2 EPD for anchors and 1 EPD for duct</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Celsa Steel - 2 EPD for steel rod and bar, and 2 EPD for steel section</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>European Metal Recycling - 1 EPD for reusable steel</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>EOS Framing Ltd - EPD for light gauge steel frame</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Gripple - 1 EPD for a bracket</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Hydro aluminium UK Ltd - 1 EPD for aluminium extrusion billet</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>Hy-tex – 1 EPD for steel reinforcement</td>
<td></td>
<td>International EPD*</td>
</tr>
<tr>
<td></td>
<td>IG Masonry Support – 7 EPD for masonry supports and lintels</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Liberty Steel – 1 EPD for reinforcing steel from scrap</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>Midland Lead – 1 EPD for cast lead sheet</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>MiTek Industries Limited - 1 EPD for metal fastenings</td>
<td></td>
<td>BRE</td>
</tr>
<tr>
<td></td>
<td>SAB – 1 EPD for structural decking</td>
<td></td>
<td>Tata Steel</td>
</tr>
<tr>
<td></td>
<td>Sapphire Balconies - 1 EPD for balcony anchor</td>
<td></td>
<td>EPD Hub</td>
</tr>
<tr>
<td></td>
<td>Thames Reinforcements – 2 EPD for fabricated steel reinforcement</td>
<td></td>
<td>RT EPD</td>
</tr>
<tr>
<td></td>
<td>Tata Steel – 17 EPD for steel products</td>
<td></td>
<td>Tata Steel</td>
</tr>
<tr>
<td></td>
<td>Voestalpine Metsec plc - 2 EPD for steel framing systems</td>
<td></td>
<td>EPD Hub</td>
</tr>
<tr>
<td>Global</td>
<td>UK CARES – 1 EPD for average steel reinforcement production by CARES members globally</td>
<td></td>
<td>BRE EPD</td>
</tr>
<tr>
<td>EU</td>
<td>European General Galvanizers Association (EGGA) – 1 EPD for hot dip galvanising of steel products</td>
<td></td>
<td>International EPD</td>
</tr>
<tr>
<td>EU</td>
<td>European Copper Institute – 3 EPD for copper pipe and 1 EPD for copper sheet</td>
<td></td>
<td>Ines</td>
</tr>
<tr>
<td>Product Type</td>
<td>Collective EPD</td>
<td>EPD Owner and number of EPD</td>
<td>EPD Programme</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>----------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>EU</td>
<td>PPA-Europe - European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Saint Gobain PAM UK – 2 EPD for cast iron rainwater products</td>
<td>IBU</td>
</tr>
<tr>
<td><strong>Municipal street products</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Allfar – 1 EPD for acoustic boards</td>
<td>BRE</td>
</tr>
<tr>
<td><strong>Panel products</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Falcon Panel Products - 1 EPD for Resysta profile</td>
<td>BRE</td>
</tr>
<tr>
<td>Plasterboards</td>
<td></td>
<td>See Ltd – 1 EPD for laminated panels</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>British Gypsum Saint Gobain – 7 EPD for Gyproc plasterboards, 3 EPD for Glastron products</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Elex – 1 EPD for GTEC plasterboard</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Knauf UK – 8 EPD for plasterboards</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td><strong>Eurogypsum</strong> – unverified LCA for plasterboard**</td>
<td>Eurogypsum</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>British Gypsum Saint Gobain – 7 EPD for Thistle plasters</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Environment – 1 EPD for composite decking, cladding, and fencing product</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td><strong>Plastics Europe</strong> – LCI* or EPD for up to 70 plastic products and intermediate products</td>
<td>Plastics Europe</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td><strong>The European Plastic Pipe and Fittings Association (TEPPFA)</strong> – 21 unverified EPD for plastic pipe products**</td>
<td>TEPPFA</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Brett Landscaping and Building Products - 6 EPD for landscaping products</td>
<td>EPD Hub</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Durisol – 1 EPD for insulated block</td>
<td>EPD Hub</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Lignacite Ltd - 10 EPD for various concrete blocks</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Mannok Building Products – 1 EPD for precast hollowcore flooring, 1 EPD for 3 types of autoclaved aerated blocks, 1 EPD for 6 types of concrete roof tiles</td>
<td>EPD Ireland</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Marshalls - 1 EPD for perforated dense facing bricks</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Moore Concrete Products Ltd - 6 EPD for precast concrete products</td>
<td>EPD Ireland</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Shay Murtagh - 3 EPD for prestressed concrete</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Sicut Enterprises Ltd - 4 EPD for composite sleepers</td>
<td>MRPI</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Tobermore Concrete Products Ltd - 13 EPD for concrete blocks</td>
<td>EPD Ireland</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td><strong>British Precast – 1 EPD for T-Beam</strong></td>
<td>IBU</td>
</tr>
<tr>
<td><strong>Precast concrete</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Prefabricated units</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Optima Products – 3 EPD for Adaptable meeting rooms and walls</td>
<td>International EPD*</td>
</tr>
<tr>
<td><strong>Protection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Protec International - 3 EPD for Protec sheets</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Bathgate Flooring Ltd – 5 EPD for raised access flooring</td>
<td>EPD Hub</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Isaac H Grainger and Son – 1 EPD for raised access flooring</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Kingspan Access Floors – 11 EPD for raised access flooring</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>London Raised Floors – 1 EPD for raised access flooring</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>BMF Installation &amp; Services Ltd – 1 EPD for recycled raised access flooring</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Addagrip Terraco – 1 EPD for resin bound surfacing</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Portland Stone Firms - 1 EPD for Portland stone</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Armstrong World Industries – 29 EPD for ceiling products</td>
<td>IBU</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>JBG Soft Furnishings Ltd – 1 EPD for a suspended ceiling system</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>SAS International - 48 EPD for suspended ceiling systems</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>James Jones &amp; Sons – 1 EPD for JJI Joists</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Norbord Europe – 2 EPD for MDF and OSB</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Pasquill Saint Gobain – 1 EPD for a timber roof truss</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Russwood – 10 EPD for various cladding products</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Vastern – 1 EPD for 3 thermally treated timber products</td>
<td>International EPD*</td>
</tr>
<tr>
<td><strong>Resin bound surfacing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Wood for Good – 1 EPD for UK grown and produced kiln dried sawn timber</td>
<td>BRE</td>
</tr>
<tr>
<td><strong>Stone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Tefelt - 1 EPD for underlay</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Brett Martin Daylight Systems –6 EPD for rooflights</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Hambleside Danelaw - 3 EPD for rooflights</td>
<td>BRE</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>European Waterproofing Association – 3 EPD for bitumen roof sheets, lightweight underlay, and shingles</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Optima Products Ltd – 7 EPD for aluminium glazed doors</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Optima - 14 EPD for partition products</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>RP Products - 5 EPD for aluminium partitions</td>
<td>International EPD*</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td>Selo - 1 EPD for riser door</td>
<td>IBU</td>
</tr>
<tr>
<td>EU</td>
<td>European Association for Panels and Profiles – 2 EPD for profiled metal sheet</td>
<td><strong>European PVC Window Profiles and Related Building Products Association (EPPA)</strong> – 2 EPD for double and triple glazed PVC windows</td>
<td>IBU</td>
</tr>
</tbody>
</table>

*(EPD in bold are Collective EPD from a UK or international trade association)*
Appendix E: Embodied Carbon Product Datasheets

Embodied Carbon Product Datasheets have been developed for the following product groups and sub-groups below, using the methodology described in 3.3.6 and 3.4.4.

- **Cement and concrete**
  - Cement
  - Ready-mix concrete and mortar
  - Precast concrete

- **Metals**
  - Steel structures and structural steel
  - Reinforcing Steel
  - Electrical wiring

- **Brick and ceramics**
  - Brick
  - Ceramic tiles
  - Ceramic sanitaryware.

- **Timber**
  - Sawn kiln dried softwood
  - Engineered Timber
  - Wood panel products
# Embodied Carbon Product Datasheet for UK Cement

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Cement and Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Cement</strong></td>
</tr>
<tr>
<td>UK sector Value in 2021</td>
<td>£ 953 m</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>9,330 ktonnes</td>
</tr>
<tr>
<td>UK imports (2020)</td>
<td>£100,321,000 (~11% of cement by mass)</td>
</tr>
<tr>
<td>Top 30 UK construction product imports?</td>
<td>Yes (0.6% of UK construction product imports)</td>
</tr>
<tr>
<td>Sources for imports (2020)</td>
<td>EU (IE, FR, ES, DE, IT...) Non-EU (TU)</td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>Mineral Products Association (MPA) - 1 EPD for UK average cement Mineral Products Association (MPA) - 1 EPD for average CEM I cement</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td>The MPA have access to the GCCA verified EPD tool and can provide EPD for any cement and plant to MPA members who cover 100% of UK cement production.</td>
</tr>
<tr>
<td>Other pre-verified EPD tools</td>
<td>One Click LCA preverified EPD tool for cementitious products</td>
</tr>
<tr>
<td>EPD for UK Manufactured Products</td>
<td>Anhydritec - 2 EPD for anhydrite binders DB Group - 1 EPD for binder Lafarge Cement – 1 EPD for cement</td>
</tr>
<tr>
<td>Availability of specific EPD and embodied carbon data</td>
<td>see above. UK cement producers covering 100% of UK cement production can produce product specific EPD using GCCA verified EPD tool.</td>
</tr>
<tr>
<td>Collective EPD for imports (EU)</td>
<td>Cembureau – 3 EPD for European average CEM I, CEM II and CEM III cements Collective EPD for national production of cement in Ireland, France, Spain, Germany, Italy, Switzerland, Austria</td>
</tr>
<tr>
<td>Specific EPD (EU) from key import markets</td>
<td>7 specific EPD for cement in EPD Ireland 3 specific EPD for cement in GlobalEPD 154 specific EPD for cement from Holcim Germany</td>
</tr>
<tr>
<td>Collective EPD for imports (non-EU)</td>
<td>US Cement</td>
</tr>
<tr>
<td>Specific EPD non-EU from key import markets</td>
<td>7 specific cements from EPD Turkey</td>
</tr>
<tr>
<td>Other generic data</td>
<td>9 German generic cement datasets in oekobaudat</td>
</tr>
<tr>
<td>Datasheet developed by</td>
<td>Jane Anderson</td>
</tr>
<tr>
<td>Valid at</td>
<td>March 2023</td>
</tr>
</tbody>
</table>
### Embodied Carbon Product Datasheet for UK ready-mix concrete and mortar

<table>
<thead>
<tr>
<th><strong>Product Group</strong></th>
<th>Cement and Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td>Ready-mix concrete and mortar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>UK Product Sub-Group value in 2021</strong></th>
<th>£ 2,011 m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UK production in 2021</strong></td>
<td>25,829 ktonnes</td>
</tr>
<tr>
<td><strong>UK imports in 2021</strong></td>
<td>Not significant</td>
</tr>
<tr>
<td><strong>Top 30 UK construction product imports?</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Source of imports</strong></td>
<td>n/a</td>
</tr>
<tr>
<td><strong>UK Collective EPD</strong></td>
<td>British Ready-Mixed Concrete Association (BMRCA) – 1 EPD for ready-mix concrete</td>
</tr>
<tr>
<td><strong>UK Sector access to pre-verified EPD tools</strong></td>
<td>The GCCA Verified Concrete EPD tool is available to GCCA members, which include Breedon, Cemex, CRH, Holcim (Aggregate Industries) and Heidelberg Cement (Hanson).</td>
</tr>
<tr>
<td><strong>Other pre-verified EPD tools</strong></td>
<td>OneClickLCA pre-verified cementitious products EPD tool</td>
</tr>
<tr>
<td><strong>UK generic data (not EPD)</strong></td>
<td>Inventory of Carbon and Energy Database, v3: Datasets for numerous concrete and mortar mixes. BRE IMPACT Database</td>
</tr>
</tbody>
</table>
| **EPD for UK Manufactured Products**   | CPI Mortars Ltd – 1 EPD for masonry mortar  
Hanson UK – 13 EPD for ready-mix concrete  
London Concrete Pumping – 3 EPD for ready-mix concrete  
Hoben Concrete – 1 EPD for Bagwork product |
<p>| <strong>Availability of specific EPD and embodied carbon data</strong> | Tarmac, Hanson, Aggregate Industries, CEMEX have all had access to their own verified EPD Tools and have been able to provide EPD and embodied carbon data on demand for any mix or site. |
| <strong>Collective EPD for imports (EU)</strong>    | n/a |
| <strong>Specific EPD (EU) from key import markets</strong> | n/a |
| <strong>Collective EPD for imports (non-EU)</strong> | n/a |
| <strong>Specific EPD non-EU from key import markets</strong> | n/a |
| <strong>Other generic data</strong>                 | n/a |
| <strong>Datasheet developed by</strong>             | Jane Anderson |
| <strong>Valid at</strong>                           | March 2023 |</p>
<table>
<thead>
<tr>
<th>Product Group</th>
<th>Cement and Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Sub-Group</td>
<td>Precast Concrete</td>
</tr>
<tr>
<td>UK Value in 2021</td>
<td>£ 2,790 m</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>34,138 ktonnes</td>
</tr>
<tr>
<td>UK imports in 2021</td>
<td>Not significant</td>
</tr>
<tr>
<td>Top 30 UK construction product imports?</td>
<td>No</td>
</tr>
<tr>
<td>Source of imports</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**UK Collective EPD**

| UK Collective EPD | British Precast – 1 EPD for T-Beam | British Precast - Architectural and Structural – 1 EPD for structural concrete (ground beam), 1 EPD for architectural cladding, 1 EPD for brick-faced cladding |

**UK Sector access to pre-verified EPD tools**

| UK Sector access to pre-verified EPD tools | British Precast have had a verified EPD tool and have provided more collective EPD (now expired). The EPD tool allowed any British Precast member to provide low cost EPD on demand. |

**Pre-verified EPD tools**

| Pre-verified EPD tools | GCCA verified EPD Tool for cement and concrete OneClickLCA pre-verified cementitious products EPD tool |

**UK generic data (not EPD)**

| UK generic data (not EPD) | Inventory of Carbon and Energy Database, v3: Datasets for 6 precast concrete products. BRE IMPACT Database. |

**EPD for UK Manufactured Products**

| EPD for UK Manufactured Products | Brett Landscaping and Building Products - 6 EPD for landscaping products Durisol – 1 EPD for insulated concrete block Lignacite Ltd - 10 EPD for various concrete blocks Mannok Building Products – 1 EPD for precast hollowcore flooring, 1 EPD for 3 types of autoclaved aerated blocks, 1 EPD for 6 types of concrete roof tiles Marshalls - 1 EPD for perforated dense facing bricks Moore Concrete Products Ltd - 6 EPD for precast concrete products Shay Murtagh - 3 EPD for prestressed concrete Sicut Enterprises Ltd - 4 EPD for composite sleepers Tobermore Concrete Products Ltd - 13 EPD for concrete blocks |

**Availability of specific EPD and embodied carbon data**

| Availability of specific EPD and embodied carbon data | Marshalls have had a verified carbon footprint tool able to provide embodied carbon data for any product. |

**Collective EPD for imports (EU)**

| Collective EPD for imports (EU) | n/a |

**Specific EPD (EU) from key import markets**

| Specific EPD (EU) from key import markets | n/a |

**Collective EPD for imports (non-EU)**

| Collective EPD for imports (non-EU) | n/a |

**Specific EPD non-EU from key import markets**

| Specific EPD non-EU from key import markets | n/a |

**Other generic data**

| Other generic data | n/a |

**Datasheet developed by:**

| Datasheet developed by | Jane Anderson |

**Valid at**

| Valid at | March 2023 |
# Embodied Carbon Product Datasheet for UK Structural Steel

<table>
<thead>
<tr>
<th><strong>Product Group</strong></th>
<th><strong>Metals</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Steel Structures and structural steel</strong></td>
</tr>
<tr>
<td><strong>UK Value in 2021</strong></td>
<td>£615.4m</td>
</tr>
<tr>
<td><strong>UK production in 2021</strong></td>
<td>299.8 ktonnes</td>
</tr>
<tr>
<td><strong>UK imports in 2021</strong></td>
<td>£270.7m (structural units (steel)) (44% of production)</td>
</tr>
<tr>
<td><strong>Top 30 UK construction product imports?</strong></td>
<td>Y (1.7%) EU, Non-EU</td>
</tr>
<tr>
<td><strong>Source of imports</strong></td>
<td></td>
</tr>
<tr>
<td><strong>UK Collective EPD</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>UK Sector access to pre-verified EPD tools</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Pre-verified EPD tools</strong></td>
<td>CARES EPD tool, OneClickLCA metal-based product EPD generator</td>
</tr>
<tr>
<td><strong>UK generic data (not EPD)</strong></td>
<td>ICE Database v3: datasets for various steels, e.g. hot rolled section, plate, pipe, tube with various recycled contents, BRE Impact Database</td>
</tr>
</tbody>
</table>
| **EPD for UK Manufactured Products** | British Steel – 1 EPD for a steel rail and sections  
Blue Chyp – 1 EPD for metal balcony  
British Gypsum Saint Gobain – 1 EPD for Gypframe metal framing for plasterboard  
Celsa Steel - 2 EPD for steel section  
European Metal Recycling - 1 EPD for reusable steel  
EOS Framing Ltd - EPD for light gauge steel frame  
SAB – 1 EPD for structural decking  
Tata Steel – 17 EPD for steel products produced in the UK and the Netherlands  
Voestalpine Metssec plc - 2 EPD for steel framing systems |
| **Availability of specific EPD and embodied carbon data** | Tata Steel have access to LCA software to produce their own EPD. |
| **Collective EPD for imports (EU)** | 4 EPD for BauforumStahl members  
1 Spanish collective EPD  
Numerous French collective EPD |
| **Specific EPD (EU) from key import markets** | 6 specific EPD from Global EPD in Spain  
Numerous specific EPD from France  
72 Specific EPD from IBU in Germany |
| **Collective EPD for imports (non-EU)** | |
| **Specific EPD non-EU from key import markets** | 1 EPD from UAE (CARES)  
1 EPD from Turkey (CARES) |
| **Other generic data** | |
| **Datasheet developed by:** | Jane Anderson |
| **Valid at** | March 2023 |
### Embodied Carbon Product Datasheet for UK Reinforcing Steel

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Reinforcing Steel</strong></td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>No</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td>CARES EPD Tool</td>
</tr>
<tr>
<td>Pre-verified EPD tools</td>
<td>CARES EPD tool</td>
</tr>
<tr>
<td></td>
<td>OneClickLCA metal-based product EPD generator</td>
</tr>
<tr>
<td>UK generic data (not EPD)</td>
<td>ICE Database v3: datasets for rebar and wire rod with various recycled content</td>
</tr>
<tr>
<td></td>
<td>BRE Impact Database</td>
</tr>
<tr>
<td><strong>EPD for UK Manufactured Products</strong></td>
<td><strong>Celsa Steel - 2 EPD for steel rod and bar</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Hy-ten – 1 EPD for steel reinforcement</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Liberty Steel – 1 EPD for reinforcing steel from scrap</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Thames Reinforcements – 2 EPD for fabricated steel reinforcement</strong></td>
</tr>
<tr>
<td><strong>Availability of specific EPD and embodied carbon data</strong></td>
<td>CARES have a verified EPD tool which has been used to product specific EPD for all their members.</td>
</tr>
<tr>
<td><strong>UK Value in 2021</strong></td>
<td>£160.3m</td>
</tr>
<tr>
<td><strong>UK production in 2021</strong></td>
<td>186.6 ktonnes</td>
</tr>
<tr>
<td><strong>UK imports (2020)</strong></td>
<td>£126.5m (79% of production)</td>
</tr>
<tr>
<td><strong>Top 30 UK construction product imports?</strong></td>
<td>Y (0.8%), EU</td>
</tr>
<tr>
<td><strong>Collective EPD for imports (EU)</strong></td>
<td><strong>CARES – 1 EPD for average steel reinforcement production by CARES members globally</strong></td>
</tr>
<tr>
<td></td>
<td>2 Spanish collective EPD</td>
</tr>
<tr>
<td></td>
<td>Numerous French collective EPD</td>
</tr>
<tr>
<td><strong>Specific EPD (EU) from key import markets</strong></td>
<td>5 specific EPD for various CARES members (PT/ES/DE/FR)</td>
</tr>
<tr>
<td></td>
<td>17 specific EPD from Global EPD in Spain</td>
</tr>
<tr>
<td></td>
<td>6 EPD from IBU in Germany</td>
</tr>
<tr>
<td><strong>Collective EPD for imports (non-EU)</strong></td>
<td>19 specific EPD for various CARES members (e.g. TU, UAE, Saudi Arabia)</td>
</tr>
<tr>
<td><strong>Specific EPD non-EU from key import markets</strong></td>
<td>4 specific EPD from Singapore</td>
</tr>
<tr>
<td><strong>Other generic data</strong></td>
<td>1 German generic dataset in oekobaudat</td>
</tr>
<tr>
<td><strong>Datasheet developed by:</strong></td>
<td>Jane Anderson</td>
</tr>
<tr>
<td><strong>Valid at</strong></td>
<td>March 2023</td>
</tr>
</tbody>
</table>
## Embodied Carbon Product Datasheet for UK electrical wiring

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Electrical wiring</strong></td>
</tr>
<tr>
<td>UK Value in 2021</td>
<td>£898.8m</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>n/a</td>
</tr>
<tr>
<td>UK imports (2020)</td>
<td>£916m (102% of production)</td>
</tr>
<tr>
<td>Top 30 UK construction product imports?</td>
<td>Y (5.8% construction product imports), non-EU</td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>No</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td>No</td>
</tr>
<tr>
<td>UK generic data (not EPD)</td>
<td>none</td>
</tr>
<tr>
<td>EPD for UK Manufactured Products</td>
<td>Backbone connect – 1 EPD for Backbone Connected Building Base Unit and 1m of Fibre Cable</td>
</tr>
<tr>
<td>Availability of specific EPD and embodied carbon data</td>
<td>n/a</td>
</tr>
<tr>
<td>Collective EPD for imports (EU)</td>
<td>International Copper Alliance – LCA for copper 2 French collective EPD for wiring and cables</td>
</tr>
<tr>
<td>Specific EPD (EU) from key import markets</td>
<td>33 specific French EPD for cables and wires</td>
</tr>
<tr>
<td>Collective EPD for imports (non-EU)</td>
<td>International Copper Alliance – LCA for copper</td>
</tr>
<tr>
<td>Specific EPD non-EU from key import markets</td>
<td>27 EPD for Superior Essex cables (US)</td>
</tr>
<tr>
<td>Other generic data</td>
<td>50 Default French Datasets for wiring and cables 3 German generic datasets for wires in oekobaudat</td>
</tr>
<tr>
<td>Pre-verified EPD tools</td>
<td>OneClickLCA metal-based product EPD generator</td>
</tr>
<tr>
<td>Datasheet developed by:</td>
<td>Jane Anderson</td>
</tr>
<tr>
<td>Valid at</td>
<td>March 2023</td>
</tr>
<tr>
<td><strong>Product group</strong></td>
<td><strong>Brick and ceramics</strong></td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Brick</strong></td>
</tr>
<tr>
<td><strong>UK Value in 2021</strong></td>
<td>£665.5m</td>
</tr>
<tr>
<td><strong>UK production in 2021</strong></td>
<td>1,989,877 m³</td>
</tr>
<tr>
<td><strong>UK imports (2020)</strong></td>
<td>~£160m (1.3 ktonnes) (~25% of UK production) (BE, NL, DE, PK, TU, IN)</td>
</tr>
<tr>
<td><strong>Top 30 UK construction product imports?</strong></td>
<td>Y</td>
</tr>
<tr>
<td><strong>UK Collective EPD</strong></td>
<td>Brick Development Association – 1 EPD for average UK produced brick</td>
</tr>
<tr>
<td><strong>UK Sector access to pre-verified EPD tools</strong></td>
<td>BRE Lina tool</td>
</tr>
<tr>
<td><strong>Pre-verified EPD tools</strong></td>
<td>OneClickLCA Ceramic and clay-based product pre-verified EPD tool</td>
</tr>
<tr>
<td><strong>UK generic data (not EPD)</strong></td>
<td>ICE Database v3 -3 datasets for brick BRE IMPACT database</td>
</tr>
<tr>
<td><strong>EPD for UK Manufactured Products</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Collective EPD for imports (EU)</strong></td>
<td>1 Collective EPD for Belgian facing brick 1 Collective EPD for Belgian clay block 1 Collective EPD for Dutch facing brick</td>
</tr>
<tr>
<td><strong>Specific EPD (EU) from key import markets</strong></td>
<td>1 specific EPD for Breedon Brick (Ireland) 81 specific Danish EPD from EPDDanmark 7 specific German EPD from IBU</td>
</tr>
<tr>
<td><strong>Collective EPD for imports (non-EU)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Specific EPD non-EU from key import markets</strong></td>
<td>1 specific EPD for Turkish brick</td>
</tr>
<tr>
<td><strong>Other generic data</strong></td>
<td>EDGE Database for Indian brick manufacture</td>
</tr>
<tr>
<td><strong>Datasheet developed by:</strong></td>
<td>Jane Anderson</td>
</tr>
<tr>
<td><strong>Valid at</strong></td>
<td>March 2023</td>
</tr>
</tbody>
</table>
# Embodied Carbon Product Datasheet for UK Ceramic tiles

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Brick and ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Sub-Group</td>
<td>Ceramic tiles</td>
</tr>
</tbody>
</table>

| UK Value in 2021       | £41.9m (ceramic tiles generally) |
| UK production in 2021  | n/a (“~4 million m²”) |
| UK imports (2020)      | £312m (unglazed) (ES, IT, TU, IN) |
| Top 30 UK construction product imports? | Y (2.0% of UK construction product imports) from EU |

| UK Collective EPD      | No |
| UK Sector access to pre-verified EPD tools | No |

| Pre-verified EPD tools | OneClickLCA Ceramic and clay-based product pre-verified EPD tool |
| UK generic data (not EPD) | ICE Database v2 |

| EPD for UK Manufactured Products | Johnson Tiles – 1 EPD for ceramic tiles (‘the UK’s only large-scale manufacturer of ceramic tiles’) |
| Collective EPD for imports (EU) | 1 EPD from the Spanish Association of Tile and Ceramic Flooring Manufacturers  |
|                                 | 1 EPD from the Italian Confindustria Ceramica |

| Specific EPD (EU) from key import markets | 40 specific Spanish EPD from GlobalEPD  |
|                                           | 18 specific Italian EPD from EPDItaly |
|                                           | 13 specific EPD from International EPD® (ES/TU/Saudi Arabia) |

| Collective EPD for imports (non-EU) | 13 specific EPD from EPDItaly |
| Specific EPD non-EU from key import markets | 13 specific EPD from EPDItaly |

| Other generic data |       |
|                   |       |

| Datasheet developed by: | Jane Anderson |
| Valid at               | March 2023  |
### Embodied Carbon Product Datasheet for UK Ceramic tiles sanitaryware

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Brick and ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Ceramic sanitaryware</strong></td>
</tr>
<tr>
<td>UK Value in 2021</td>
<td>£16.2m</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>97,500 items</td>
</tr>
<tr>
<td>UK imports (2020)</td>
<td>£154m (China, IT, DE, TU) (960% of UK production)</td>
</tr>
<tr>
<td>Top 30 UK construction product imports?</td>
<td>Yes (1.0% of UK construction product imports)</td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>No</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td></td>
</tr>
<tr>
<td>Pre-verified EPD tools</td>
<td>OneClickLCA Ceramic and clay-based product pre-verified EPD tool</td>
</tr>
<tr>
<td>UK generic data (not EPD)</td>
<td>ICE Database v2</td>
</tr>
<tr>
<td><strong>EPD for UK Manufactured Products</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Collective EPD for imports (EU)</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Specific EPD (EU) from key import markets | 5 specific German EPD from IBU  
3 specific Italian EPD from EPD Italia  
3 specific Turkish EPD from EPD Turkey  
2 specific Spanish EPD from DAPCons  
1 specific German EPD from International EPD® |
| Collective EPD for imports (non-EU) | |
| Specific EPD non-EU from key import markets | 3 specific Turkish EPD from EPDTurkey |
| Other generic data | 1 dataset for Germany in Oekobaudat |
| Datasheet developed by: | Jane Anderson |
| Valid at | March 2023 |
### Embodied Carbon Product Datasheet for UK sawn kiln dried softwood

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Timber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Sub-Group</td>
<td>Sawn kiln dried softwood</td>
</tr>
<tr>
<td><strong>UK Value in 2021</strong></td>
<td>£840m</td>
</tr>
<tr>
<td><strong>UK production in 2021</strong></td>
<td>3.2 million m$^3$</td>
</tr>
<tr>
<td><strong>UK imports (2020)</strong></td>
<td>£790.3 m (94% of UK production) (SE, LT, FI, RU)</td>
</tr>
<tr>
<td><strong>Top 30 UK construction product imports?</strong></td>
<td>Y (5.0% of construction product imports).</td>
</tr>
<tr>
<td><strong>UK Collective EPD</strong></td>
<td><strong>Wood for Good – 1 EPD for UK grown and produced kiln dried sawn timber</strong></td>
</tr>
<tr>
<td><strong>UK Sector access to pre-verified EPD tools</strong></td>
<td>Yes TDUK has access to One Click LCA preverified EPD tool for wood and plant-fibre based products</td>
</tr>
<tr>
<td><strong>Pre-verified EPD tools</strong></td>
<td>DEBois and DEBoisdefrance for France, GreenDelta EasyEPD for Germany</td>
</tr>
<tr>
<td><strong>UK generic data (not EPD)</strong></td>
<td>Wood for Good - 4 LCIA datasets for UK consumed timber</td>
</tr>
<tr>
<td><strong>ICE Database V3:</strong></td>
<td>Pasquill Saint Gobain – 1 EPD for a timber roof truss</td>
</tr>
<tr>
<td></td>
<td>Russwood - 10 EPD for various cladding products</td>
</tr>
<tr>
<td></td>
<td>Vastern – 1 EPD for 3 thermally treated timber products</td>
</tr>
<tr>
<td><strong>Availability of specific EPD and embodied carbon data</strong></td>
<td>TDUK has access to One Click LCA preverified EPD tool for its members</td>
</tr>
<tr>
<td><strong>Collective EPD for imports (EU)</strong></td>
<td>1 Collective EPD for Swedish kiln-dried softwood</td>
</tr>
<tr>
<td></td>
<td>1 Collective EPD for German kiln dried softwood</td>
</tr>
<tr>
<td></td>
<td>Numerous collective EPD for French kiln dried softwood and carpentry</td>
</tr>
<tr>
<td><strong>Specific EPD (EU) from key import markets</strong></td>
<td>&gt;40 EPD from EPD Norge in Norway</td>
</tr>
<tr>
<td></td>
<td>2 EPD from Germany</td>
</tr>
<tr>
<td><strong>Collective EPD for imports (non-EU)</strong></td>
<td>1 collective EPD for North American softwood lumber</td>
</tr>
<tr>
<td></td>
<td>1 collective EPD for US Redwood lumber</td>
</tr>
<tr>
<td><strong>Specific EPD non-EU from key import markets</strong></td>
<td>1 German generic dataset in oekobaudat</td>
</tr>
<tr>
<td><strong>Datasheet developed by:</strong></td>
<td>Jane Anderson</td>
</tr>
<tr>
<td><strong>Valid at</strong></td>
<td>March 2023</td>
</tr>
</tbody>
</table>
## Embodied Carbon Product Datasheet for UK Engineered Timber

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Timber</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Engineered Timber (e.g. Glulam, LVL, CLT)</strong></td>
</tr>
<tr>
<td>UK Value in 2021</td>
<td>£116m</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>161,262 m³ (plywood and laminated wood)</td>
</tr>
<tr>
<td>UK imports (2020)</td>
<td>£276.4m (238% of UK production)</td>
</tr>
<tr>
<td>Top 30 UK construction product imports?</td>
<td>Y (1.7% of construction product imports)</td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>n/a</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td>Yes TDUK has access to One Click LCA preverified EPD tool for wood and plant-fibre based products</td>
</tr>
</tbody>
</table>
| Pre-verified EPD tools | One Click LCA preverified EPD tool for wood and plant-fibre based products  
DEBois and DEBoisdefrance for France  
GreenDelta EasyEPD for Germany |
| UK generic data (not EPD) | Wood for Good - 4 LCIA datasets for UK consumed engineered timber  
ICE Database V3: datasets for 5 engineered timber products |
| EPD for UK Manufactured Products | James Jones & Sons – 1 EPD for JJI Joists |
| Availability of specific EPD and embodied carbon data | TDUK has access to One Click LCA preverified EPD tool for its members |
| Collective EPD for imports (EU) | German collective EPD  
1 French collective EPD |
| Specific EPD (EU) from key import markets | 4 specific EPD from inies in France  
22 specific EPD from IBU in Germany  
2 specific EPD from Sweden  
>40 EPD from EPD Norge in Norway |
| Collective EPD for imports (non-EU) | 1 collective EPD for North American Glulam EPD  
1 collective EPD for Quebec Glulam EPD |
| Specific EPD non-EU from key import markets | 14 specific EPD from North America |
| Other generic data | 5 German generic datasets in oekobaudat |
| Datasheet developed by | Jane Anderson |
| Valid at | March 2023 |
### Embodied Carbon Product Datasheet for UK Wood panel products

<table>
<thead>
<tr>
<th>Product Group</th>
<th>Timber</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Sub-Group</strong></td>
<td><strong>Wood panel products</strong></td>
</tr>
<tr>
<td>UK Value in 2021</td>
<td>£1,070m</td>
</tr>
<tr>
<td>UK production in 2021</td>
<td>n/a</td>
</tr>
<tr>
<td>UK imports (2021)</td>
<td>£123 m (DE, IE, LT)</td>
</tr>
<tr>
<td>Top 30 UK construction product imports?</td>
<td>N</td>
</tr>
<tr>
<td>UK Collective EPD</td>
<td>No</td>
</tr>
<tr>
<td>Pre-verified EPD tools</td>
<td>One Click LCA preverified EPD tool for wood and plant-fibre based products&lt;br&gt;DEBois and DEBoisdefrance for France&lt;br&gt;GreenDelta EasyEPD for Germany</td>
</tr>
<tr>
<td>UK generic data (not EPD)</td>
<td>Wood for Good – 4 for UK consumed wood panel products&lt;br&gt;ICE Database V3: datasets for 6 wood panel products</td>
</tr>
<tr>
<td>EPD for UK Manufactured Products</td>
<td>Norbord Europe – 1 EPD for MDF&lt;br&gt;Norbord Europe – 1 EPD for OSB</td>
</tr>
<tr>
<td>Availability of specific EPD and embodied carbon data</td>
<td>TDUK has access to One Click LCA preverified EPD tool for its members</td>
</tr>
<tr>
<td>UK Sector access to pre-verified EPD tools</td>
<td>Yes TDUK has access to One Click LCA preverified EPD tool</td>
</tr>
<tr>
<td>Collective EPD for imports (EU)</td>
<td>4 German collective EPD</td>
</tr>
<tr>
<td>Specific EPD (EU) from key import markets</td>
<td>19 specific EPD from IBU in Germany&lt;br&gt;11 specific Irish EPD from EPD Ireland</td>
</tr>
<tr>
<td>Collective EPD for imports (non-EU)</td>
<td>n/a</td>
</tr>
<tr>
<td>Specific EPD non-EU from key import markets</td>
<td>n/a</td>
</tr>
<tr>
<td>Other generic data</td>
<td>5 German generic datasets in oekobaudat</td>
</tr>
<tr>
<td>Datasheet developed by:</td>
<td>Jane Anderson</td>
</tr>
<tr>
<td>Valid at</td>
<td>March 2023</td>
</tr>
</tbody>
</table>