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Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies

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ABSTRACT

This paper publishes the results from a major five year International Energy Agency research project which investigated the reduction of embodied energy and greenhouse gas emissions over the whole life ('cradle to grave') of buildings. Annex 57 collated and analysed over 80 detailed quantitative and qualitative building case studies from the participating nations.

For many years the multiple variations in methodological approach of case studies to assess the whole life embodied impacts of buildings have presented a major challenge for politicians and other decision makers. Any real change in design and construction practice has also proved elusive. This paper describes a modified research synthesis and meta analysis as a novel and valid method for drawing meaningful conclusions from large sets of significantly diverse studies.

The quantitative analyses consider embodied impacts of the product stage, replacement, and end of life stages, of new and refurbished buildings, and of different building assemblies and construction materials. The product stage is shown to dominate in most cases, with the median value around two thirds of the whole life embodied impacts, with replacements the next highest with a median figure of around 25%; however replacements in five studies were over 50% of the whole life impacts. It should be noted that several life cycle stages are still missing from these studies.

The case studies included eleven refurbishment projects, in which energy efficient measures and low carbon technologies were retrofitted to existing buildings; for these projects the median product stage impact was found to be just under half that for the new build projects. While further research is required to compare the operational energy use in the new and refurbished buildings, this suggests that such energy refurbishments have a significantly lower impact than new buildings. Several other studies considered the impacts from technical equipment and internal fixtures and fittings, both frequently excluded, and demonstrated that they can be responsible for up to 45% of the whole life embodied greenhouse gases and up to 48% of the whole life embodied energy.

Finally, the paper combines the analysis of the quantitative case studies with that of qualitative studies, to explore the impact of contextual factors at both policy and project level in significantly reducing the embodied environmental impacts of buildings. The case studies have shown that planning authorities, major clients, developers, and individual designers, can all play an important role in reducing embodied impacts through encouraging innovation.

The paper concludes with recommendations for policy makers, designers and LCA modelers which will support and effect real reductions in the whole life embodied impacts of buildings.

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1. Introduction

Across most countries regulations are now in place to reduce the environmental impacts of buildings from heating, cooling and lighting. The resultant reductions in these 'operational' impacts however have led to both a proportional, and an actual, increase in the 'embodied' impacts (Malmqvist et al., 2018). These are the impacts from individual materials and components which arise through the whole life of the building, including from their manufacture, transport and construction activities (during the 'product' life cycle stage), their refurbishment and replacement during the 'in use' life cycle stage, and their demolition and waste processing during the 'end of life' life cycle stage (see Fig. 1). All life cycle stages referred to from hereon in (A1-A3, B4 C3-4) use the EN 15978 nomenclature (CEN, 2012b) as shown in Fig. 1.

Research into the embodied impacts of buildings is increasing (Pomponi and Moncaster, 2016), with academics developing numerous detailed case studies of individual buildings from the earliest studies (Cole and Kernan, 1996; Peuportier, 2001; Chen et al., 2001; Adalberth et al., 2001) to more recent times (Monahan and Powell, 2011; Wallhagen et al., 2011; Larsson et al., 2017; Lasvaux et al., 2017; Wiik et al., 2018).

However, the large number of studies also creates a problem for policy makers and designers, in that apparently similar case studies often display a huge spread of results. This was first demonstrated by Sartori and Hestnes (2007) through an analysis of 60 cases from 9 countries. More recent reviews (see for example Ibn Mohammed, 2013; Pomponi and Moncaster, 2016; Dixit, 2017; Anand and Amor, 2017; Hossain and Ng, 2018; Rasmussen et al., 2018) have identified multiple reasons for this spread, including variations in methodology, and inherent design variations between different building types. Moncaster et al. (2018) discern three broad categories of methodological variation as temporal, spatial and physical. An additional problem is that many published LCA studies fail to include sufficient information about their methodology, making valid comparison of the data with other cases difficult (Optis and Wild, 2010; Moncaster and Song, 2012; Dixit et al., 2012; Frischknecht et al., 2015; Pomponi and Moncaster, 2016). The assessment methods used also differ; while in Europe the majority of studies use a process-based LCA, in other regions of the world input-output (I-O) methods, or hybrids of the two, are in common use (Säynäjoki et al., 2017; Crawford et al., 2018a; Pomponi and Lenzen, 2018). The latter commonly give much higher results than the process-based or 'bottom up' assessments used across Europe, due to the wider system boundaries (Crawford et al., 2018b).

Several authors note that recurrent embodied impacts during the building lifetime, and end of life impacts, are often either omitted or based on limited information (Aktas and Bilec, 2012; Soust-Verdaguer et al., 2016; Pomponi et al., 2018; Dixit, 2019). Understanding the impact of these later life cycle stages is important for many reasons, including making appropriate design choices for material durability, and for understanding the role of maintenance and management of buildings. More detailed information is also key when making decisions as to whether to demolish and rebuild, or refurbish existing buildings, an important

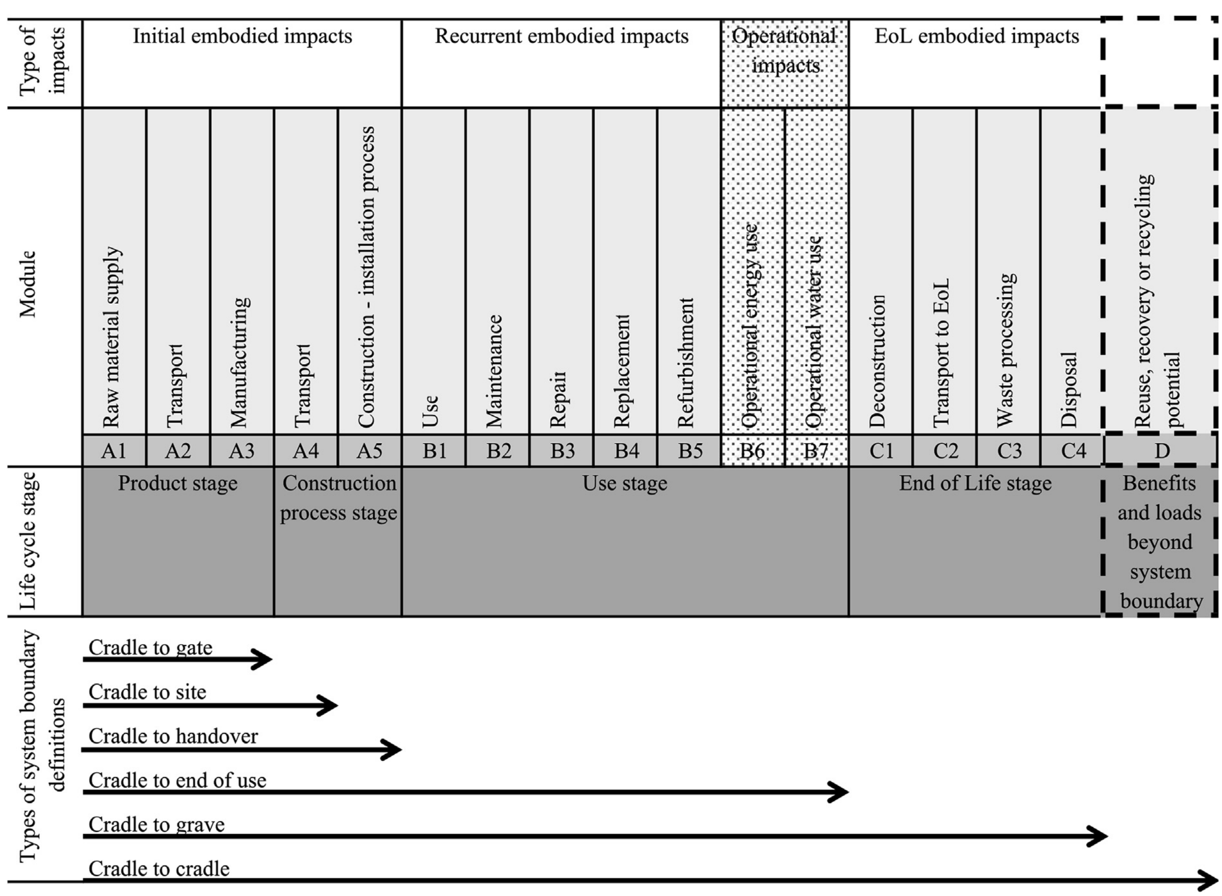

Fig. 1. System boundaries definitions in relation to the life cycle stages of a building (adapted from Balouktsi, & Lützkendorf, 2016).

concern for redevelopment of urban 'brownfield' sites in highly built up regions such as Europe (Beccali et al., 2013; Brown et al., 2014; Rasmussen and Birgisdottir, 2016; Moncaster et al., 2018a; Schwartz et al., 2018).

Additional uncertainties in the underlying data for LCA case studies on buildings are due to variability in the coefficients used for the main construction materials (Hoxha et al., 2017; Moncaster et al., 2018) which can make comparisons between studies difficult. For timber in particular there is considerable debate about whether to include the sequestration (storage) of carbon (Brandão et al., 2013; Hauschild et al, 2013; Symons et al., 2013) with this remaining a major variation between different databases and studies. This makes it difficult to draw clear conclusions from the many studies, for instance, which consider the use of timber as a structural material (Upton et al., 2008; Salazar, 2009; Vukotic et al., 2010; Lupíšek et al., 2015; Larsson et al., 2017; Ramage et al., 2018). There are also alternative approaches to modelling open-loop recyclable metals such as steel which will significantly affect results (Frischknecht, 2010; Gala et al., 2015).

This limited and variable information has meant that advice on how to reduce embodied impacts of buildings have until recently been dismissed by both policy makers and by industry practitioners. The European TC350 standards on 'Sustainability of construction works' were published in 2011 and 2012 in an attempt to harmonise disparate approaches across Europe (CEN, 2011; CEN, 2012), and are currently being updated. However more than five years after their publication Säynäjoki et al. (2017a) suggested that the published research in this area was still inadequate for informing policy. Without the 'stick' of policy and regulation, industry therefore still has limited experience of measuring or reducing embodied impacts (Rekola et al., 2012; Giesekam et al., 2015; Orr et al., 2019), and considerable variation in industry calculations remain (Fouché and Crawford, 2015; De Wolf et al., 2017; Pomponi et al., 2018; Francart et al., 2019).

However there are signs of change at both policy level and within industry practice. Increasing coverage of environmental product declarations (EPD) at component level (Passer et al., 2015), their development within the forthcoming version of EN15804, and evidence that the inclusion of embodied impacts into building regulations, is starting to happen (Lützkendorf, 2017). The Netherlands is the first country to introduce a requirement into its building regulations to measure the embodied impact of materials (Scholten and van Ewijk, 2013), and several other countries are now making the first steps towards this end including France (French Ministry of Environment, Energy and the Sea & French Ministry of Sustainable Housing, 2017), Sweden (Boverket, 2018), Norway (Standard Norge, 2018), Denmark (The Danish Government, 2018; InnoBYG, 2018) and Finland (Kuittinen and le Roux, 2017). Meanwhile recent studies have developed guidance on embodied impact assessment for building designers. The existence of an accepted methodology within Europe has been followed by advice on how to adapt this to the early design stage (Moncaster and Symons, 2013; RICS, 2017; Marsh et al., 2018), and details of design and construction strategies and approaches to reduce embodied impacts from buildings are provided by Häkkinen et al. (2015), Kreiner et al. (2015) and Malmqvist et al. (2018) among others. These include: substitution of materials with lower carbon – often plant-based – alternatives; use of recycled materials; use of light-weight structures; optimization of building form; extension of the building life; re-use of existing structures; and reduction of construction and demolition impacts.

This paper presents a research synthesis and meta analysis of cases of the assessment of embodied impacts of buildings, from across multiple countries and regions. The purpose of the paper is to demonstrate the use of a specific approach to utilize the large number of valuable but disparate studies which are being undertaken. The paper uses the collection and analysis of over 80 information-rich purposefully sampled case studies to identify the breadth of approaches and methodological choices that are commonly taken within the current body of research, to quantify their impact on results, and to draw generalisable lessons from those results. To the technical perspective provided by the majority quantitative LCA studies of buildings the paper also adds a novel socio-technical perspective, which considers the effects of the contexts within which design decisions are made through qualitative case studies. It thereby bridges current insight into the calculation of embodied energy and greenhouse gases with studies into how contextual settings can support their reduction in practice. The paper uses this informed insight to provide detailed advice, supported by a significant new body of evidence, for policy makers, designers and LCA modelers looking to minimise embodied impacts from buildings.

2. Materials and methods

This paper publishes the research synthesis and meta analysis of over 80 qualitative and quantitative case studies collected and collated by the International Energy Agency Energy in Buildings and Communities program (IEA EBC) Annex 57 project (Birgisdottir et al., 2017).

Research synthesis and meta analysis have been used for many years, across multiple disciplines but with a particular focus in the areas of education and health, in order 'to produce new knowledge by making explicit connections and tensions between individual study reports that were not visible before' (Suri, 2011). The seminal work by Cooper (1982) identified five stages in the research process: problem formulation; data collection; data evaluation; data analysis and interpretation (the meta analysis); and public presentation. By 2009 he had added two additional stages: data collection had been split into searching the literature, and gathering data from studies, and the analysis stage had been split into analyzing and integrating, and interpretation (Cooper, 2009).

This process was adjusted to allow for the integration of the work of the case study subtask group within the larger Annex 57 project, and for the complexity of the subject area. First, the problem formulation stage (1) combined the early work and discussions of the whole Annex with the research focus of ST4 on the development of design and construction strategies for reducing embodied impacts of buildings. The data required was identified as a body of studies from different researchers in different countries, following different methodologies and conducted for different purposes, which would offer perspectives on a number of issues of interest determined by preceding literature review (see Malmqvist et al., 2014). The issues were: 'Strategies for reduced embodied EEG [embodied energy and greenhouse gases]; significance of different factors over the full life cycle; impacts of calculation method and system boundaries; reduction strategies, significant factors and calculation of EEG for building sector at national level; and integration of embodied EEG calculations in decision making process' (Birgisdottir et al., 2016, p.16)

Such 'purposeful sampling' can identify cases which are 'information-rich … those from which one can learn a great deal about issues of central importance to the purpose of the inquiry' (Patton, 2002). This method differs from the systematic literature reviews (for example, Pomponi and Moncaster, 2016; Dixit, 2019), and avoids some of the limitations. These include most notably publication biases (Rothstein et al., 2006), which for a systematic review could potentially magnify the initial errors. Publication bias in turn is caused by a long list of other biases, including the accepted norms within a field of research, and any pre-existing relationships between authors, reviewers, publishers and readers (Lee et al., 2013). The other key limitation of literature review, systematic or otherwise, for LCA studies is the limited information about the system boundaries that is often published, as mentioned in the previous section. Additional limitations are due to the primary data from individual building case studies, which are often either a combination of convenience sampling, in which the researcher happens to have access to a particular case or cases (for example Monahan and Powell, 2011), and 'extreme' sampling, in which the building is an exemplar in a particular field (for example Larsson et al., 2017). The purposeful sampling followed in this article, in which cases were requested to answer particular issues, and in which direct access to the authors allowed additional information to be requested, are still necessarily subject to some of the same issues. The cases were requested from Annex 57 participants, and therefore could be seen to be biased towards a particular 'community of practice' (Wenger, 2000). Nevertheless Annex 57 had over twenty participants, each national experts in this field, from sixteen countries; therefore the use of case studies personal to them would both ensure their quality and provide access to the richness of the original research data.

The split second stage of Cooper's (2009) process were the collection of the data (the cases) and the collection of literature. The collection process for the data was carried out through the 'call for case studies', which was sent to the IEA EBC Annex 57 participants in 2013, again in 2014 and finally in 2015. Case studies were requested in the form of a prepared template, designed to allow the widest variety of studies which addressed the specific questions, while ensuring a transparent, complete and comparable set of data. The submitted templated case studies were given a suffix identifying the country of origin and numbered in the order in which they were received.

Following the data collection exercise, the literature review identified additional published case studies for comparison and extension of the analysis. A separate subtask group was responsible for the major literature review for the combined project of Annex 57 (Chae and Kim, 2016; Birgisdottir et al., 2017).

The following stages of the research synthesis were defined by Cooper as the meta analysis and integration of the data, followed by its interpretation. The authors conducted this through 4 separate stages of analysis: the first and second were the identification of methodological variations and analysis of their impacts (reported in Rasmussen et al., 2018), and the development of design approaches for low embodied impacts (Malmqvist et al., 2018). This paper reports the other two stages, an integrated analysis of the combined quantitative results, followed by an analysis of the impact of context within real world settings.

The final stage of the research process was defined by Cooper (2009) as 'public presentation'. As well as the multiple academic outputs, Annex 57 has produced a large number of publications as IEA EBC reports, as well as a series of guidelines for stakeholders, which are available to download within IEA member countries (IEA EBC, 2016)

The additional qualitative studies were further supported by two questionnaires sent to the Annex 57 participants (Birgisdottir et al., 2016a). The first asked for information about individual countries, including questions about building regulations and sustainability certification schemes, the existence of databases, tools, EPD, and national initiatives. The second asked which stakeholders are seen as driving Life Cycle Assessment of building construction in their country.

The full set of case studies is published as (Birgisdottir et al., 2016b) and further detail of this process is provided in Malmqvist et al. (2014). A detailed list is given in Appendix 1 of this paper, which furthermore provides background information about each case study, including the applied database and reference study period.

The numerical results presented in this paper are based on the reported figures from the case study collection. Normalization of impacts are carried out based on the details provided for each case study (see Appendix 1). Thus, normalization per year is based on the reference study period of the case studies. Normalization per m2 is based on the chosen reference area of the individual case studies; most report results normalized per gross floor area (GFA), while others report results per conditioned floor area or gross internal floor area (see Appendix 1). No additional conversion between the normalization units were performed as part of this study. Not all case studies contained results of all life cycle stages in focus for this paper. Some case studies were purely qualitative, some had a material focus and some had a limited scope of included life cycle stages (see Appendix 1 for an overview) Hence, only the case studies reporting impacts for the specific life cycle stages in focus for each subsection are included in the following figures.

3. Results and discussion

3.1. Embodied impacts of new buildings

This section provides results from the case studies for the initial, 'cradle to gate' life cycle stage, modules A1-A3. It then adds in the effects of replacements of materials and components during the building lifecycle, module B4. Finally it considers end of life impacts, focusing on modules C3-4. These three stages were those considered most comparable across the Annex 57 case studies. Nevertheless there remains some disparity between the terms used and the processes included in the life cycle stages, and the authors interpreted these as accurately as possible given the information. In the following analyses, results reported as non-renewable primary energy demand (PEnren) or non-renewable cumulative energy demand (CEDnr) are shown to represent the embodied energy of the cases. PEnren and CEDnr are often used interchangeably and both terms refer to the accounting of mainly fossil energy resources used (see Frischknecht et al., 2015a, for a description of the different approaches to calculating the use of energy resources, and Lützkendorf et al. (2016) pp14-18 for a full list of definitions). Global warming potential (GWP) is shown to represent the embodied greenhouse gas emissions of the cases. All life cycle stages are named after EN 15978 (CEN, 2012b); product stage is A1-A3, replacements are B4 and waste treatment and disposal is C3-C4.

The range of values and the relative impacts of stages A1-3, B4 and C3-4 are indicated in Figs. 2 and 3, for embodied greenhouse gas emissions and embodied energy respectively, normalized as described in the previous section and for each case study as specified in Appendix 1. Note that the impacts from the replacements (B4) are calculated for differing reference study periods, i.e. between 50 and 150 years, depending on the reference study period set for each case study.

The results show that the product stage (A1-3) generally contributes the most significant embodied impact, both in terms of greenhouse gases and energy, followed by replacements and then end of life. The median values of the embodied greenhouse gas emissions (Fig. 2) for each stage were 64%, 22% and 14% of the total, respectively, while those for embodied energy (Fig. 3) were 66%, 27% and 7% of the total. Details of each of the three main life cycle stages and the individual case studies are considered in more detail below.

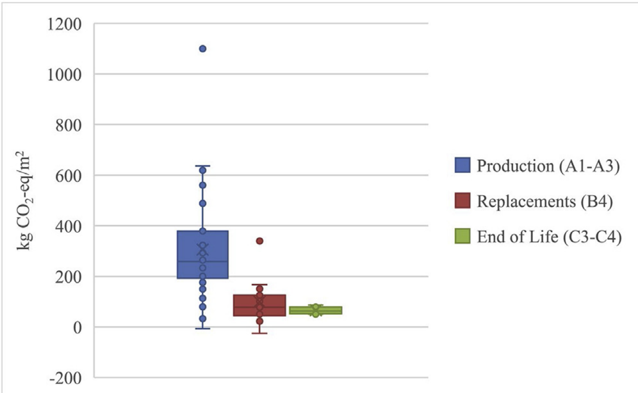

Fig. 2. Variations in embodied greenhouse gases from different life cycle stages representing product stage A1-A3 (56 cases), replacements B4 (42 cases) and end-of-life C3-C4 (9 cases).

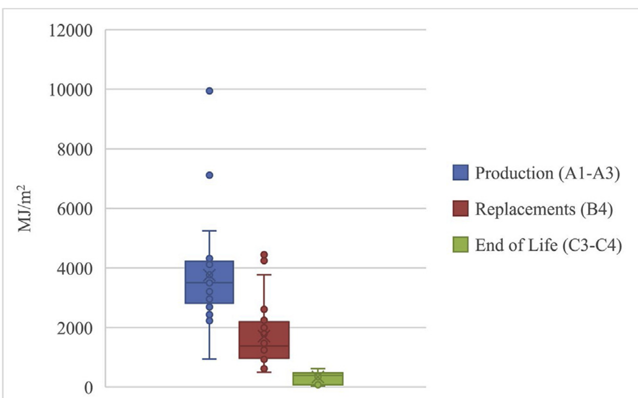

Fig. 3. Variations in embodied energy (non-renewable) for the different life cycle stages representing product stage A1-A3 (37 cases), replacements B4 (30 cases) and end-of-life C3-C4 (7 cases).

3.1.1. Cradle to gate (modules A1-A3)

The material, or production, life cycle stages A1-3 are shown in Fig. 4a, which plots the values for both embodied energy and greenhouse gases normalized per m2 of floor area for the 47 case study buildings for which data was comparable. Details of the applied database and type of building for each case are given in Appendix 1.

The values of embodied impacts even for this stage show very significant variation. While the values for Fig. 4 have been normalized as far as possible, the variations represent not just different building designs but also different physical system boundaries and methodological choices. The Swedish studies (prefix SE) report relatively low product stage embodied greenhouse gas emissions; SE2a for instance calculates a figure of 165 kgCO2e/m2. This is partly because of the low impact timber structure. However these studies only considered the main construction elements, which is a frequent choice of focus for assessments at early-to mid-design stage, when details of finishes are unknown and when major changes to superstructure materials can be made. In contrast study NO4, at the far right of the graph, has a much higher value of over 600 kgCO2e/m2; this study was carried out after the building had been completed, using a detailed material inventory and a large number of specific product EPD. This demonstrates clearly, although not surprisingly, that the more detailed the assessment, the higher the calculated impact is likely to be.

Fig. 4b shows how these figures differ for the three main building types which are examined in the case studies, office, residential and school buildings. The highest figure for the residential buildings was the Norwegian study NO4, a ‘Living Lab’ project in Trondheim whose aim was zero operational carbon, with no focus on optimizing material/embodied emissions. The databases used were Ecoinvent and SimaPro. Swiss study CH6 provided the highest product stage figure for a school, and used Ecoinvent as the material database.

Fig. 4c shows the product stage impact for the studies divided into the three main databases used as sources of materials data; however only the studies which used a single database are reported in this figure, and therefore UK5, for example, is omitted from this plot.

While Fig. 4b suggests that office buildings tend towards slightly higher product stage figures, the two highest data points for office buildings are JP6 and JP5, which both used Input-Output data which includes all upstream processes. The high results shown in the Japanese case study JP5 is also partly due to the specifics of the design of the building for earthquake resistance, necessitating considerable extra concrete and other materials. Cases JP4 and KR3 were the only other two studies to use I-O data. KR3 was a study of a building with a high level of recycled content, so although it used I-O data (which has wider system boundaries) the product stage impacts are not especially high. JP4 is of a large library building in Tokyo, and therefore isn't included in Fig. 4b.

This brief analysis demonstrates that it is important to study Fig. 4a–c together with the further details of the individual case studies provided in Appendix 1 and the information supporting the original case studies, which allows more careful scrutiny of the individual figures than might be possible within a systematic literature review based on results published for a different original purpose.

Finally Fig. 5 plots the conversion between greenhouse gas emissions and non-renewable energy for this stage, showing the relationship for the 32 studies which calculate both indicators. The coefficient of determination R2 is 0.66, indicating that 66% of the data fits this correlation model.

3.1.2. Replacement of materials and components (module B4)

A number of the case studies included the replacement of individual components (life cycle stage B4) during the RSP as part of the assessment. In the Korean studies (KR1, KR2, KR5) these were reported together with the initial product stage impacts A1-3, but in most the two are separated. Fig. 6 (for embodied greenhouse gas emissions) and Fig. 7 (for embodied energy) show the results for A1-3 and B4, for the cases where results were available. These figures have been normalized to show impacts per metre squared per year for comparability. The service life or reference study period (RSP), which is shown separately in the figure, varies across case studies (Rasmussen et al., 2018).

Many of the studies show the embodied greenhouse gas impact of replacements, B4, to be a significant proportion of the total; the mean B4 impact was 46% of A1-3. However for DE2, DE4, AT2, AT5 and Dk3b the impact of stage B4 was equal to or higher than the product stage A1-3. Studies which have included services components and floor and wall finishes are likely to show a higher impact for the replacement stage, since these components have a rather shorter design life than that of the building structure. For example, case study DE4 considered all physical components of a timber administration building with a concrete floor slab and foundations, as well as a solar PV array

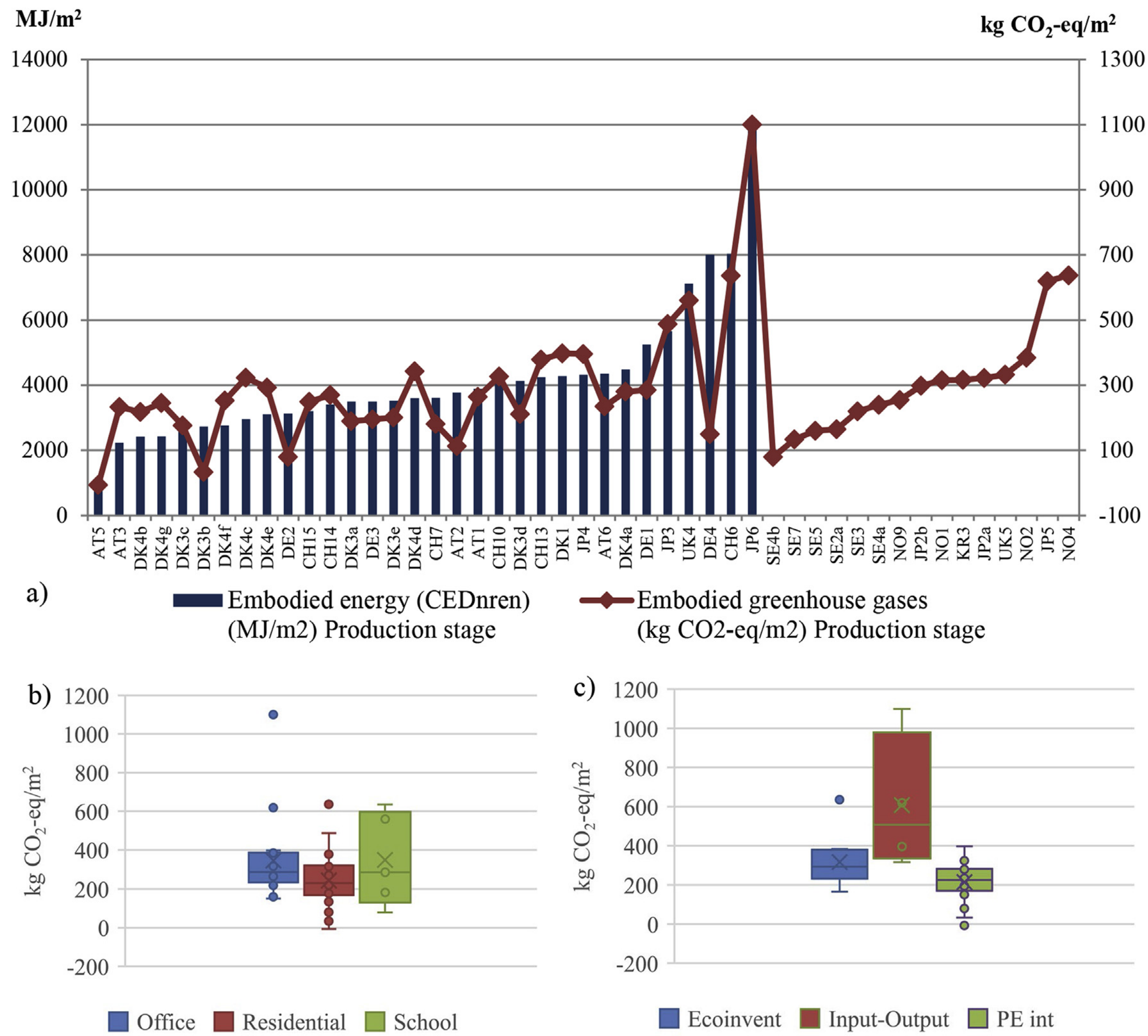

Fig. 4. ac a) Production stage, cradle-to-gate (stages A1-3) embodied energy (primary energy, non-renewable) and greenhouse gas emissions per metre squared for 'new buildings' of the Annex 57 case studies. Adapted from Rasmussen et al. (2018). Production stage, cradle-to-gate (stages A1-3) embodied greenhouse gas emissions per metre squared for b) building types in the sample and c) parent database of case studies (see Appendix 1).

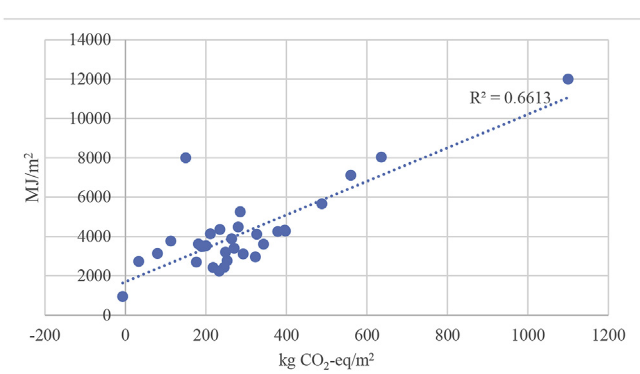

Fig. 5. Relationship between production stage, cradle-to-gate (stages A1-3) embodied energy (non-renewable) and embodied greenhouse gases.

covering the roof. The design life and reference study period (RSP) of the building was taken as 50 years, while the life of the PV system was assumed to be 25 years, and so the initial embodied impacts from the PV system will be repeated halfway through the building lifetime. Case studies AT2, AT5, and DE2 are buildings with timber superstructures; in these cases this is due to their relatively lower product stage greenhouse gas impacts. A number of these studies (DE3, DK3a-e, CH10, CH14, CH15, NO1, AT4) are also of residential buildings.

3.1.3. End-of-life (modules C3-C4)

Only a few of the Annex 57 case studies calculated values for the 'end of life' impacts from buildings. This limited consideration of end of life is common in both published literature and industry studies, as shown by Moncaster et al. (2018, p 392). Examining the Annex 57 data more closely shows that the majority only include waste processing (C3) and disposal (C4) while excluding demolition processes and transport off site (C1 and C2). Figs. 8 and 9 put these figures in the context of the other life cycle stages, where results are comparable. Impacts vary between 50 and 87 kg CO2-eq/m2 corresponding to between 5 and 22% of the whole life embodied

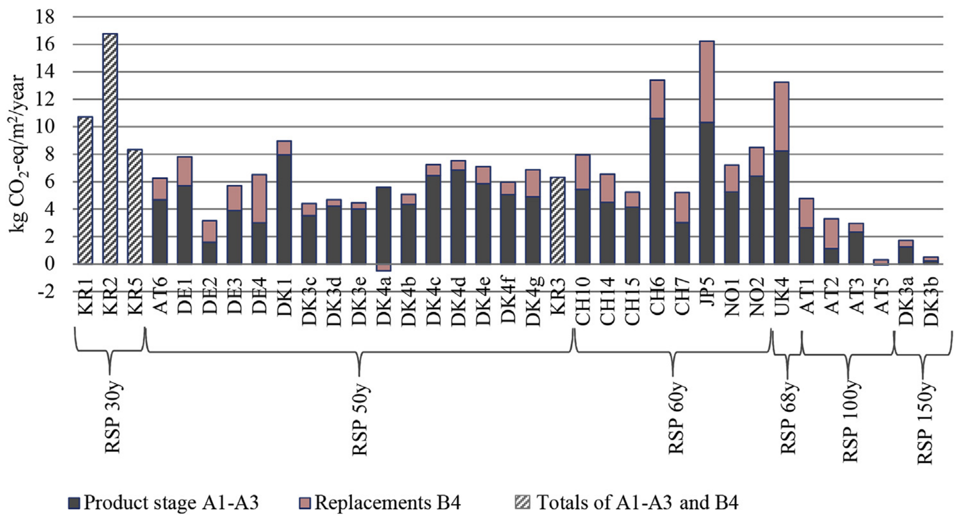

Fig. 6. Cradle-to-gate (stages A1-3) plus replacement (B4) embodied greenhouse gas emissions per metre squared per year for the Annex 57 case studies. Adapted from Birgisdottir et al. (2016a).

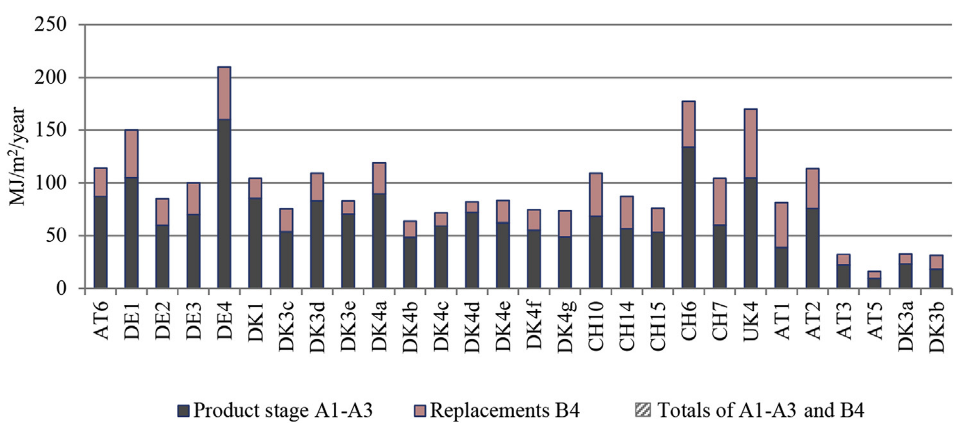

Fig. 7. Cradle-to-gate (stages A1-3) plus replacement (B4) embodied energy (non-renewable) per metre squared per year for the Annex 57 case studies. Adapted from Birgisdottir et al. (2016a).

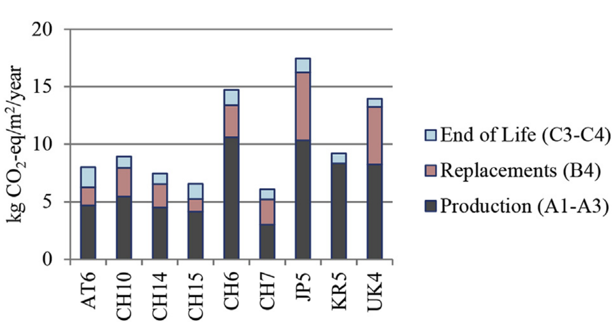

Fig. 8. Cradle-to-gate (stages A1-3) plus replacement (B4) plus waste processing and disposal (C3-4) embodied greenhouse gas emissions per metre squared per year for the Annex 57 case studies. Adapted from Birgisdottir et al. (2016a).

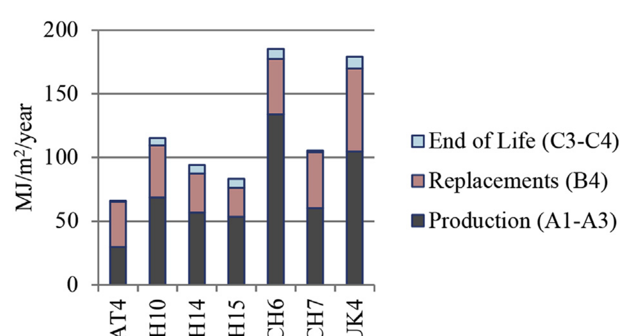

Fig. 9. Cradle-to-gate (stages A1-3) plus replacement (B4) plus waste processing and disposal (C3-4) embodied energy (non-renewable) per metre squared per year for the Annex 57 case studies. Adapted from Birgisdottir et al. (2016a).

impacts of the buildings, which is somewhat lower than for other life cycle stages. However as Moncaster et al. (2018) point out the figures are frequently based on limited evidence. The effect of adding demolition activities and transport to suitable processing sites (stages C1-2) would also increase the figures and percentages for the end of life stage.

For the greenhouse gas impacts, where there are robust national targets for the decarbonisation of national energy, future impacts from both replacement of components and end of life activities (as well as operational impacts) should allow for a reduced carbon:energy intensity (Zhang and Wang, 2017). While the treatment of waste many years in the future is one of many uncertainties in Life Cycle Assessment, it is important for designers and modelers not to neglect it and in so doing leave a legacy of a difficult and environmentally costly process at the end of life of our modern buildings. Finally, for calculations which have assumed sequestration of carbon, the reporting of end-of-life processes is essential to ensure proper counterbalancing of the credits given in the production modules (RICS, 2017).

3.2. Embodied impacts of refurbishment projects

As for new building projects, the impacts of refurbishment projects can be calculated for the product stage impacts of the new replacement materials being installed, their future replacement over the remaining life of the building, and their end of life impacts. Figs. 10 and 11 show the embodied greenhouse gases and energy for the refurbishment case studies submitted to Annex 57. All of these studies used a RSP of 60 years, and the results have been normalized to impacts per metre squared per year.

Such projects may include the replacement of large numbers of components and materials in a building which has fallen into disrepair, but they are more usually initiated for other reasons. An increasingly common reason is that of improving the energy performance of the original building, as was the case for these Annex 57 refurbishment case studies, while others may enable a change of use of the building or improve marketability. These examples were all of projects which combined the addition of higher levels of insulation with the installation of new energy-efficient services, and sometimes of low carbon energy technologies. For these relatively comparable projects, the median product stage (that is to say, for the initial refurbishment works) impacts were 125kgCO2eq/m2, and 1892MJ/m2, and the median replacement stage (for the replacement of these components during the RSP of 60 years) impacts were 104kgCO2eq/m2, and 1719MJ/m2. However it is difficult to consider any 'average' figures for refurbishment projects, which often include a number of different measures in which energy efficiency is only one. Therefore there is a need for benchmarking impacts of achieving typical performance specifications, such as improved insulation and air tightness.

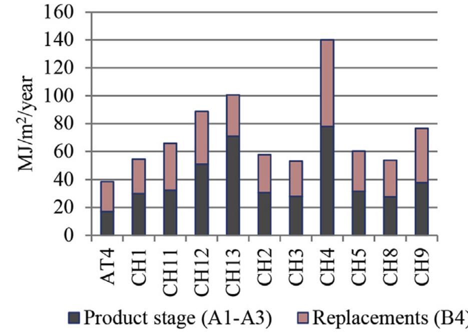

Fig. 11. Embodied energy (non-renewable) in refurbishment projects with RSP of 60 years.

Comparing these results with those in Figs. 6 and 7 demonstrate that retention of buildings, where feasible, is likely to significantly reduce whole life embodied impacts. Refurbishment projects are highly unlikely to include the replacement of sub- and superstructure elements. The effect of the exclusion of this major component can be seen in the comparison of Figs. 4 and 10; the median value of product stage (A1-3) embodied greenhouse gases for the new buildings in the Annex 57 case studies was 254 kgCO2e/m2 while it was just 125 kgCO2e/m2 for refurbishment projects. However often policies seem to encourage demolition and rebuild to improve operational energy efficiency, as well as for economic regeneration (Boardman, 2006; Power, 2008; Hackworth, 2016). It is clear that whole life cycle assessments (embodied plus operational) should be undertaken in order to support a clear picture of the impacts of demolition and rebuild versus retention and refurbishment.

3.3. Embodied greenhouse gas emissions and energy of different building elements and materials

The Annex 57 case studies were also used to compare the impacts of different building assemblies, elements and materials. Since frequently a specific element or assembly is likely to be constructed of a limited range of materials, these two aspects are

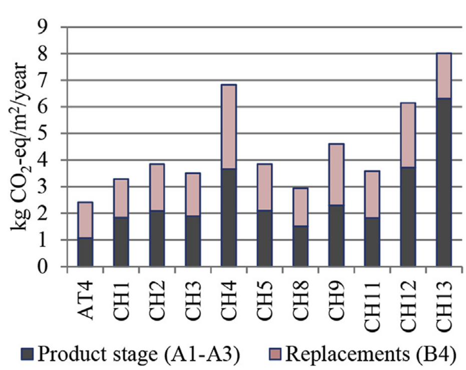

Fig. 10. Embodied greenhouse gases in refurbishment projects with RSP of 60 years.

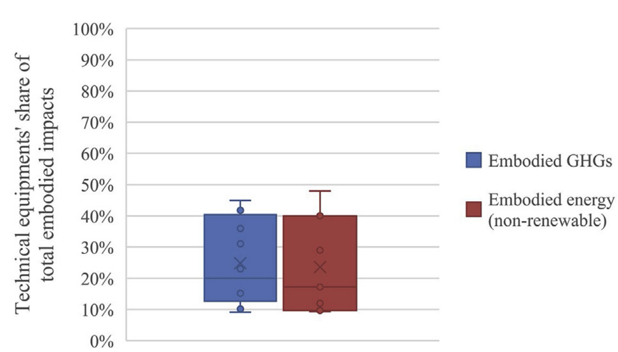

Fig. 12. Percentage share of embodied impacts from technical equipment reported in 12 cases of new buildings.

most usefully considered together.

There is no general pattern for the number or type of assemblies which the Annex 57 cases are divided into, which depends partly on the focus of the study and partly on different national conventions; Swedish case studies SE2–SE3 for example are based on simplified calculations at the early design stage, and are divided into: Internal walls; Floor structure; Basement and foundations; Attic and roof; and External walls, including windows and doors.

One important category excluded by most of these simplified studies is that of 'technical equipment'. This can include items such as plumbing, mechanical and electrical heating, ventilation and lighting services, and low carbon energy technologies, and is included to a greater or lesser extent in several of the Annex 57 case studies (DE1-DE4, JP1, JP5, JP6, JP7, NO1, NO2, NO4, NO9 and SE7). Where it is included it is often shown to have a considerable impact, from 9% to 45% (DE4) of the total life cycle embodied greenhouse gases and from 9% to 48% (DE2) of embodied energy (Fig. 12). The case studies from Japan also show high impacts from 'mechanical and electrical equipment', equal to 19% of the total life cycle embodied greenhouse gases in JP7.

Photovoltaic arrays alone contribute a significant proportion of the total life cycle embodied greenhouse gases, being 32% for Norwegian case study NO1, a 'zero emission building' of a two storey residential building, and 25% for the conventional office building NO2. For NO4 the PV and their aluminum mounting frames are responsible for 30% of the total for the product life cycle stage. Similarly for case study DE4, the technical equipment, which includes a photovoltaic system also powering heat pumps, is responsible for well over a third of the total life cycle embodied greenhouse gas emissions.

Case study UK4 of a school building finds instead that the second highest impact, at around 30% of the total life cycle embodied energy, is due to its 'fittings, fixtures and furniture', which need frequent replacements over the life of the building. This is an opportunity for designers to make a significant reduction in impacts through the specification of durable fixtures and fittings for a building which is likely to suffer high wear and tear such as a school. The assessment of these components as a separate category wasn't included in most other Annex 57 case studies many exclude these items from their inventory altogether, while others include them as part of other assemblies, such as technical equipment, making comparisons between building types impossible.

All elements which are likely to require replacement over the life of the building, including services components, cladding, or fixtures and fittings, can make a significant impact on the whole life embodied energy and greenhouse gases. The results found in the Annex 57 studies are considerably higher than those found in a recent literature review (Dixit, 2019) and suggest that more LCA studies are needed, both of the impacts of initial installations and of the replacement over the life of the building. Such impacts also depend heavily on the assumptions made about the design life, service life, or reference study period (RSP) (Rauf and Crawford, 2015; Janjua et al., 2019), which varies between 30 and 150 years for the Annex 57 studies (Fig. 6).

The embodied greenhouse gas impacts are also frequently divided within the Annex 57 studies into impacts from different construction materials; these tend to be divided into many more categories than the assemblies, with for example case study JP1 including more than 70 materials. As stated earlier, assemblies and materials are often closely related. Where concrete is used in the superstructure for structural frame and/or floor slabs (for example DK1, SE2a, SE2b and KR2), it can be responsible for between 40 and 80% of the total impacts. However, this proportional approach should be treated with caution, since it depends on what other physical elements, and what life cycle stages, are being calculated within the case study. For NO2, a conventional office building with concrete foundations and floor slabs and steel frame, but which also included PV, the concrete was only 22% of the total embodied greenhouse gas emissions, with steel from the frame and reinforcement making 15%, and the photovoltaic panels on the roof and south façade, as mentioned earlier, responsible for 25%.

Metals such as structural and reinforcement steel, and aluminium in cladding components, are also major contributors of embodied impacts in many buildings. In the Korean office building KR3 for example the steel construction is 65% of the total embodied greenhouse gas impacts for the product stage. Where case studies consider the embodied energy, rather than greenhouse gases, of different materials, metals again were found to be responsible for a considerable proportion, while the impact of concrete was relatively lower. In DK1 concrete was responsible for 20% of the embodied energy impacts while metals accounted for 40%, and in CZ1 metals contributed around 30% embodied energy; in the latter case insulation materials contributed slightly more than 30% embodied energy.

Since concrete is often irreplaceable as a material for foundations and basements, and the structural properties of steel can make it the only viable material, both the concrete and steel industries have a responsibility to continue to focus on reducing the carbon intensity of their products (Favier et al., 2018), while designers should ensure efficiency in their designs (Orr et al., 2019). A recent report by the IEA makes a strong case for improving the efficiency of cement, steel and aluminum use in construction (Pales et al., 2019). However concrete and structural steel are often concentrated in the main sub- and super-structure components which will not need replacing over the course of the building's lifetime, and in these cases it is important to note that their relative proportion of the total life cycle embodied impacts will reduce as the building lifetime increases.

One option for reducing embodied greenhouse gases often considered is the substitution of materials as discussed in the introduction, and a number of the case studies looked at this. The substitution of timber for steel or concrete structural frames, and/or for cladding systems, was considered in case studies DE1, KR1, SE2b, NO2, UK5 and UK9, which provided evidence for timber buildings having lower embodied greenhouse gas impacts (Table 2, Malmqvist et al., 2018). However the total embodied energy was not demonstrated to be necessarily lower. The range of calculated values is due partly to the wide variation in coefficients for timber in materials databases, and it is essential that the LCA community agrees on a standard approach to issues such as sequestration and end of life treatment.

3.4. Impact of context

A small group of case studies looked at qualitative aspects of projects, asking what circumstances, factors and actions support the reduction of embodied impacts from buildings. These included a number of studies which specifically considered the circumstances in which embodied impacts were measured and reduced in industry practice. There has been considerably less research in this area to date, which was reflected in the much smaller number of case studies, all of which were from the UK. This data was supported by the two questionnaires sent to Annex 57 colleagues (see section 2), as well as an additional analysis of the quantitative case studies.

The influencing factors can be broadly divided into: the national context for building design and construction, including policies, standards, certification schemes; and those factors that influence the circumstances in which innovation happens within individual projects. This section is divided accordingly.

3.4.1. National context

Several examples of how the context varies between countries are provided by analysis of the quantitative case studies submitted. Three out of four of the Korean case studies (KR1, KR2 and KR4) have a service life or reference study period of 30 years, while five out of the seven Austrian case studies (AT1-3, AT5 and AT7) have an RSP of 100 years. The case studies which consider refurbishment is also significant. Most of these were based in Switzerland (CH1-5, CH8-9, CB11-13), although there were also refurbishment case studies from Italy (IT2), Sweden (SE6), Austria (AT4), Norway (NO8) and the UK (UK2). While one Japanese case study also considers refurbishment, all others are within Europe. Here the number and age of existing buildings (Lavagna et al., 2018; Moncaster et al., 2018a) means that refurbishment is both a significant construction impact, and offers a clear opportunity to reduce energy use from the built environment.

The extent to which methodology varies within a country is also indicated by the quantitative case studies; for instance, the Austrian, Swiss, German and Danish case studies perform the LCIA calculations within a national certification framework, leading to a considerable level of consistency at a national level (see Appendix 1).

The surveys revealed that a further disparity in the national contexts is caused by the existence of a large number of general environmental/sustainability assessment schemes, including BREEAM, originating in the UK, and LEED, from the US, both used in multiple countries, as well as the German DGNB used in Germany, Austria and Denmark, and GreenStar used in Australia and neighbouring counties. Others such as CASBEE in Japan, and Miljöbyggnad in Sweden are limited to individual countries. Many of these schemes include some consideration of embodied greenhouse gas emissions, and several are linked to similarly varying national databases of EPD. Appendix 1 shows the stated national database used in each case study, and the 'parent' database from which this has been derived where available. Fig. 4 shows the variation in figures from the two main process-based 'parent' databases, PE International and Ecoinvent, and the input-output databases.

Qualitative study UK10 considers the variation of databases and tools available within the UK. The two most commonly used databases of embodied impacts were identified as the BRE Green Guide to Specification (Anderson et al., 2009) and the Bath Inventory of Carbon and Energy (Hammond and Jones, 2011), but a great number of others were also identified which had been developed by industry and were often only available within individual companies, reflecting a discrepancy found in industry assessments between different projects (Pomponi et al., 2018).

The quantitative case studies also included some which were based on national industry initiatives to provide best practice exemplar buildings. DK3a-e, for example, were studies of six single family dwellings built by the Realdania Foundation in Denmark in order to demonstrate and promote a number of different methods of reducing embodied greenhouse gases through the whole life of the building. These methods included the use of recycled materials, the extension of the design life of the building, the reduction of maintenance, prefabrication of components, and design for flexibility (Rasmussen et al., 2019). This research also considered the role of occupants in the whole life greenhouse gas emissions. Meanwhile the Swedish case study SE7 was of a low-energy multi-dwelling building, funded by the Swedish building industry and a number of construction sector stakeholders. The whole life energy and greenhouse gas emissions were calculated, and reported at an industry conference in 2014 organised by the Royal Swedish Academy of Engineering Sciences and the Swedish Construction Federation. One direct impact of this project was the Government commissioning of the National Board of Housing, Building and Planning to develop recommendations on reducing environmental impacts from building and construction, and a number of other projects have since been commissioned, including a proposal for regulation on embodied greenhouse gas emissions (Boverket, 2018). These studies show how within some countries national and industry initiatives are encouraging low embodied impact building design, and developing new knowledge in this area.

As discussed in the introduction, the importance of national building regulations in reducing impacts from the operational stage of a building has long been proved, and therefore the growing incorporation of embodied impacts into regulation, started by the Netherlands, is welcomed. However these national schemes are already paving the way towards low embodied impact buildings.

3.4.2. Project context

To achieve significant reductions in embodied impacts of buildings, innovation in design and construction is essential. This is often initiated within individual projects, rather than as a response to regulation. It is therefore important to understand the effect of different project contexts, and this is considered mainly within the qualitative UK case studies.

UK1 and UK9 offer examples of innovation in reducing embodied impacts which have been encouraged by regional Government and local planning authorities. UK1 describes the role that the Greater London Authority (GLA) has had for building projects across London. The latest London Plan has since included a requirement for all developments referred to the Mayor to be assessed for whole life impacts, showing the effect that regional authorities can have in setting targets higher than national regulations. UK9 is an example of the impact of a local planning authority, the London Borough of Hackney, as well as of a developer. The planning authority required a proportion of the operational energy for new developments to come from on site renewable energy technologies. Instead of the addition of costly technology, the developer successfully argued that a change in construction material from reinforced concrete frame to cross-laminated timber would save the equivalent of 10% of the operational greenhouse gas emissions, through the savings of the same amount of embodied emissions.

Innovation can often be supported in major, exemplar projects. One such was the London 2012 Olympics, whose client body, the Olympic Delivery Authority (ODA), stated from the start that their aim was to reduce greenhouse gas emissions by 50% compared with standard practice. As part of this aim, UK11 explains how the London 2012 Olympic Park used its considerable purchasing power and its prestige status to develop 'sustainable concrete', using recycled aggregate and batched on site to reduce both transport emissions and supply risk. UK8 meanwhile focuses on the embodied greenhouse gas reduction of three of the Olympic venues. The Velodrome used a lightweight cable structure instead of a standard steel arch system, thus saving 1500 tonnes of CO2 from the steel and an additional 1,100 tonnes of CO2 from reduced concrete foundations (Knight, 2013). The Aquatics Centre used reusable scaffolding for temporary stands, while the Olympic Stadium used steel reclaimed from gas pipes for the truss structure.

It is often noted that innovation takes place in niches (Geels, 2004; Seyfang et al., 2014), and that these are not necessarily major projects. The four schools projects described in UK6 document one such niche innovation. The structural engineer for one project pushed through a change in construction material from steel frame to cross-laminated timber, partway through the design process, arguing for its lower embodied impacts. The use of this innovative material (for the UK at that time) was then supported by the contractor, who introduced it to a second school project, and it has since spread to an increasing number of UK school projects. While clearly the size and prestige of projects such as the Olympics can easily facilitate and fund innovation, even smaller projects and individual designers can therefore make a significant difference.

4. Conclusions

There are an increasing number of published life cycle assessment case studies of buildings. However the results vary considerably between studies, due to a number of methodological choices which are often left unstated; these disparities have long presented a major challenge for politicians, designers and other decision makers. This paper has used a novel method, research synthesis and meta-analysis, to draw a number of conclusions about embodied impacts of buildings and their calculation from a collection of eighty case studies.

The first conclusion is confirmation that the novel approach used in this research is useful in allowing valid comparisons to be made, and meaningful conclusions to be drawn, from a large set of case studies following multiple methodologies across different national contexts. The methodology has been demonstrated to be an effective and rigorous approach for use in this diverse field.

Secondly, the quantitative analyses have added to the growing body of literature in this field, both reconfirming some existing findings and providing some new insights. The evidence presented confirms that the product stage (A1-A3) would appear to have the highest impact within the whole life embodied impacts for most buildings, with a median figure of around two thirds of the total embodied energy and greenhouse gas emissions. The replacement of components during the life of the building was responsible for around 25%, and the remainder due to end of life processing of materials. However in five buildings the replacement of components during the life of the building was responsible for over 50% of the total life cycle impact, once normalized per metre squared and per year, demonstrating just how important this stage is in certain buildings. Cement and metals were also found to be generally the material groups that contribute the highest impacts during the product stage, confirming findings in much of the previous literature. However it should be noted that the analyses presented here, as elsewhere (see Pomponi and Moncaster, 2016), omitted a number of embodied impact life cycle stages, including construction process stages A4 and 5, in use stages B1-3 and B5, and end-of-life processes C1-2 (see Fig. 1).

The case studies included eleven which reported refurbishment projects to bring existing buildings up to higher levels of energy efficiency. These were found to have considerably lower embodied impacts than new build; the median product stage greenhouse gas emissions for the refurbishment projects was 125 kg kgCO2e/m2, just under half the median value for the new build projects of 254 kgCO2e/m2. While further research is required to compare the operational energy use in the new and refurbished buildings, this is an important finding that adds to the existing literature. Twelve studies also calculated the impacts from technical equipment and internal fixtures and fittings. These are both frequently excluded from assessments, but the analysis demonstrated that they can be responsible for a very high proportion of embodied impacts over the life of the building, up to 45% of the whole life embodied greenhouse gases and up to 48% of the whole life embodied energy.

These points point towards a key message for modelers of embodied impacts of buildings, to expand the temporal boundary beyond the product stage, and expand the physical boundary. Additional focus is still needed for transport and construction/demolition phases A4-5 and C1-2, and on in use phases B1-5 defining the in use impacts from maintenance and repair. More modeling is also needed of the whole life embodied impacts of technical equipment, including services components and low carbon energy technologies, and of internal fixtures and fittings.

Finally, the paper has also demonstrated how the results from qualitative case studies can be used to understand the impact of contextual factors at both policy and project level in significantly reducing the embodied environmental impacts of buildings. The case studies have shown that planning authorities, major clients such as the ODA, developers, and individual designers, can all play an important role in reducing embodied impacts, and through supporting innovation in design. The effectiveness of policy and regulation can only be inferred from the impact that it has had on reducing operational energy from buildings. It is to be hoped that national governments will follow the example of the Netherlands and others in now regulating for the life cycle assessment of buildings, including the embodied impacts through the whole life as well as the operational impacts.

Future work in this area is now continuing as part of IEA EBC Annex 72 (http://annex72.iea-ebc.org/) which is focusing on the whole life (embodied plus operational) impacts, and expanding and developing the qualitative analysis of decision-making.

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Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2019.06.233.

Appendix 1

Case study	Specified database	Parent database (added by the authors)	RSP	Product			Construction		Use					End-of-Life					New/refurb	Building type	Floor area specified: GFA - Gross Floor Area, GIFA - Gross Internal Floor Area, CFA - Conditioned Floor Area, N/S - Not Stated, N/A - Not Applicable
				Raw material supply	Transport to manufacturer	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction	Transport to EoL	Waste processing	Disposal	Reuse, recovery, recycling potential			
Austria																					
AT1	baubook eco2soft	PE int	100	x	x	x						x	x						New	Office	GFA
AT2	baubook eco2soft	PE int	100	x	x	x						x	x						New	Residential	GFA
AT3	baubook eco2soft	PE int	100	x	x	x						x	x						New	Office	GFA
AT4	EcoBat	Ecoinvent	60	x	x	x						x		x			x		Refurb	Residential	GFA
AT5	Baubook eco2soft	PE int	100	x	x	x						x	x						New	Residential	GFA
AT6	Ökobau 2009	PE int	50	x	x	x						x				x	x		New	Office	GFA
AT7	baubook eco2soft	PE int	100	x	x	x						x				x	x		New	Residential	GFA
Switzerland																					
CH1	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	School	CFA
CH2	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	School	CFA
CH3	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	School	CFA
CH4	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	School	CFA
CH5	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	School	CFA
CH6	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	New	School	CFA
CH7	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	New	School	CFA
CH8	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	Residential	CFA
CH9	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	Residential	CFA
CH10	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	New	Residential	CFA
CH11	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	Residential	CFA
CH12	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	Residential	CFA
CH13	EcoInvent 2.2	Ecoinvent	60	x	x	x						x				x		x	Refurb	Residential	CFA
CH14	EcoInvent 2.2	Ecoinvent	60	x	x	x						x			x				New	Residential	CFA
CH15	EcoInvent 2.2	Ecoinvent	60	x	x	x						x			x				New	Residential	CFA
Czech Republic																					
CZ1	Envimat	–	60	x	x	x													New	Residential	N/S
CZ2	Ecoinvent 2.2	Ecoinvent	100	x	x	x	x	x						x	x	x	x		–	Material	N/A
Germany																					
DE1	Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	School	GFA
DE2	Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	School	GFA
DE3	Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Residential	GFA
DE4	Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
Denmark																					
DK1	PE int	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
DK2	PE int	PE int	50	x	x	x													New	Residential	GFA
DK3a	ESUCO/ Ökobau 2011	PE int	150	x	x	x						x				x	x	x	New	Residential	GFA
DK3b	ESUCO/ Ökobau 2011	PE int	150	x	x	x						x				x	x	x	New	Residential	GFA
DK3c	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x	x			x	x	x	New	Residential	GFA
DK3d	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Residential	GFA
DK3e	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x	x			x	x	x	New	Residential	GFA
DK4a	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
DK4b	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
DK4c		PE int	50	x	x	x						x				x	x	x	New	Office	GFA

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Case study	Specified database	Parent database (added by the authors)	RSP	Product			Construction		Use					End-of-Life					New/refurb	Building type	Floor area specified: GFA - Gross Floor Area, GIFA - Gross Internal Floor Area, CFA - Conditioned Floor Area, N/S - Not Stated, N/A - Not Applicable
				Raw material supply	Transport to manufacturer	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction	Transport to EoL	Waste processing	Disposal	Reuse, recovery, recycling potential			
	ESUCO/ Ökobau 2011																				
DK4d	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
DK4e	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
DK4f	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
DK4g	ESUCO/ Ökobau 2011	PE int	50	x	x	x						x				x	x	x	New	Office	GFA
Italy																					
IT1	Various	–	–	x	x	x	x	x		x					x		x		–	Material	N/A
IT2	EcoInvent	Ecoinvent	50	x	x	x				x		x		x	x	x	x	x	New	Residential	N/S
IT2	EcoInvent	Ecoinvent	50	x	x	x				x		x		x	x	x	x	x	Refurbishment	Residential	N/S
IT3	EcoInvent	Ecoinvent	70	x	x	x	x	x		x			x	x	x			x	New	Residential	CFA
IT4	(Not specified)	–	–	x	x	x	x												–	Material	N/A
Japan																					
JP1	IO table Japan	Input-Output	90	x	x	x	x	x		x		x							New	Residential	GFA
JP2	(Not specified)	–	–	x	x	x													New	Residential	GFA
JP3	Various	–	60	x	x	x	x	x				x	x	x	x	x	x		New	Residential	GFA
JP4	IO table Japan	Input-Output	60/100	x	x	x													New	Office	GFA
JP5	IO table Japan	Input-Output	60	x	x	x	x	x	x		x	x	x	x					New	Office	GFA
JP6	IO table Japan	Input-Output	50/100	x	x	x	x												New	Office	GFA
JP7a	IO table Japan	Input-Output	–	x	x	x	x	x				x	x	x	x				Refurbishment	Office	GFA
JP7b	IO table Japan	Input-Output	–	x	x	x	x	x				x	x	x	x				New	Office	GFA
South Korea																					
KR1	KOR LCI	Input-Output	30	x	x	x	x					x				x	x		New	Residential	GFA
KR2	KOR LCI	Input-Output	30	x	x	x						x				x	x		New	Residential	GFA
KR3	KOR LCI	Input-Output	50	x	x	x	x	x									x		New	Office	GFA
KR4	KOR LCI	Input-Output	30	x	x	x						x				x	x		New	Residential	GFA
Norway																					
NO1	EcoInvent	Ecoinvent	60	x	x	x						x							New	Residential	CFA
NO2	EcoInvent	Ecoinvent	60	x	x	x						x							New	Office	CFA
NO4	EPD	–	60	x	x	x	x												New	Residential	CFA
NO8	EcoInvent	Ecoinvent	60	x	x	x						x							Refurb	Office	CFA
NO9	EcoInvent	Ecoinvent	60	x	x	x						x							New	Residential	CFA
Sweden																					
SE1	Swedish IO data	Input-Output	1	x	x	x	x	x		x	x	x	x	x					–	Policy	N/A
SE2a	EcoInvent, BECE	Ecoinvent	50	x	x	x													New	Residential	CFA
SE2b	EcoInvent, BECE	Ecoinvent	50	x	x	x													New	Residential	CFA
SE3		–	50	x	x	x													New	Residential	CFA

	EcoEffect, BEAT, EcoInvent																			
SE4a	EcoEffect, BEAT, EcoInvent	–	50	x	x	x												New	Residential	CFA
SE4b	EcoEffect, BEAT, EcoInvent	–	50	x	x	x												New	Residential	CFA
SE5	EcoEffect, BEAT, EcoInvent	–	50	x	x	x												New	Office	CFA
SE6	EPD, Ökobau 2013, EcoInvent, KBOB	–	1								x							Refurb	Office	CFA
SE7	IVL Miljödata, EPDs, EcoInvent, KBOB, ICE	–	50	x	x	x	x	x		x		x	x	x	x	x		New	Residential	CFA
United Kingdom																				
UK1	–	–	–															–	Policy	N/A
UK2	BATH ICE, ECEB	–	N/A	x	x	x	x	x						x				Refurb	Residential	N/A
UK3	(Not specified)	–	N/A					x										New	Residential	GIFA
UK4	BATH ICE, ECEB	–	68	x	x	x	x	x		x	x	x	x	x	x	x		New	School	GFA
UK5	ICE, EcoInvent, USLCI	–	20	x	x	x	x	x										New	Residential	GIFA
UK6	–	–	–															–	Policy	N/A
UK7	Bath ICE	–	60	x	x	x	x	x	x	x			x	x	x	x	x	New	Sports hall	N/S
UK8	–	–	–															–	Policy	N/A
UK9	EPD, ELCD, Industry data	–	–	x	x	x	x	x					x	x	x	x	x	New	Residential	GIFA
UK10	–	–	–															–	Tools	N/A
UK11	–	–	–															–	Policy	N/A
UK12	BATH ICE, Green Guide, ECEB	–	60	x	x	x	x	x	x	x	x	x	x	x	x	x		Refurb	Residential	GIFA

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