Building lifespan: effect on the environmental impact of building components in a Danish perspective

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ABSTRACT
Construction professionals must now integrate environmental concerns with life cycle assessment (LCA) early in the procurement process. Building lifespan is important to LCA, since results must be normalized on an annualized basis for comparison. However, the scientific literature shows that issues of building lifespan are inadequately addressed. The aim of this research is therefore to explore how environmental impact from building components is affected by building lifespans of 50, 80, 100 and 120 years in a Danish context. LCAs are undertaken for 792 parametric variations of typical construction solutions, covering all primary building components and based on contemporary practice. A full statistical analysis is carried out, which shows a significant statistical correlation between changes in building lifespan and environmental impact for all primary building components, except windows/rooflights. On average, a building lifespan of 80 years reduces environmental impact by 29%, 100 years by 38%, and 120 years by 44%, all in relation to a lifespan of 50 years. The results show that if construction professionals and policy-makers use short building lifespans, then resource allocation to reduce environmental impact during procurement may become disproportionately focused on the construction contra operational phases of the lifecycle.

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Introduction
Buildings now have to demonstrate improved environmental performance to reflect wider demands for sustainable development. The use of life cycle assessment (LCA) tools aims to support construction professionals in the procurement process by reducing environmental impact through well-informed decision-making. An important aspect is the nature of building lifespan, since LCA methodologies require results to be normalized on an annual basis to allow for comparison between construction and operational phases.

The use of LCA tools has grown in recent years, in part because research has shown that the environmental impact from construction is of the same magnitude as that from operation. However, the available scientific literature shows that the issue of building lifespan is inadequately defined and poorly validated, and that a very large environmental impact from construction materials is only documented for buildings with a short building lifespan.

The role of building lifespan therefore raises important issues that need careful consideration by construction professionals. What is the impact of using a shorter building lifespan, as stipulated by LCA tools used in Northern Europe, rather than a longer building lifespan with an empirical basis?
in current conditions? Can building lifespan itself become a dynamic factor to reduce environmental impact? This article aims to explore how the environmental impact from building components can be affected by assumptions relating to building lifespan in a Danish context. The conclusions can be seen as being broadly applicable to other North European countries with similar constructional, environmental and climatic conditions.

**Informing the procurement process with life cycle analysis**

Reflecting wider societal changes, there has in recent years been a growing demand for the improved sustainability of buildings. This has been implemented through the development of performance-based standards (European Committee for Standardization, 2008, 2011a), the regulation of building construction (European Parliament and the Council of the European Union, 2010) and the promotion of voluntary initiatives (DGNB, 2013). In Denmark, policy initiatives have been formulated to integrate low-energy strategies at the beginning of the procurement process (National Agency for Enterprise and Construction, 2011). Within this rapidly changing framework, construction professionals are now required to integrate environmental, economic and social sustainability in the earliest phases of the procurement process.

Environmental sustainability in construction projects is typically calculated with the use of well-established and scientifically validated LCA tools. A building life cycle covers all environmental impacts stemming from construction, usage, maintenance and demolition, spanning from upstream extraction to downstream end-of-life processes (European Committee for Standardization, 2011b). Many environmental assessment tools exist within the construction sector, such as BREEAM (Schweber & Haroglu, 2014), LEED (Al-Ghamdi & Bilec, 2015) and DGNB (König & De Cristofaro, 2012).

**Construction vs. operation in LCA**

The use of LCA tools aims to support decision-making processes by both clients and construction professionals in the procurement process, by allowing well-informed decisions to be made regarding how environmental impacts can best be reduced. One of the major areas of interest in theoretical and empirical studies has been the balance of environmental impacts that can be tied to the building materials in the construction phase vs. the energy consumption in the operational phase (Brown, Olsson, & Malmqvist, 2014; Cabeza, Rincón, Vilarinho, Pérez, & Castell, 2014; Chau, Leung, & Ng, 2015; Dodoo, Gustavsson, & Sathre, 2011). Building lifespan plays an important role in this process, since LCA methodologies require the results for the construction, operation and end-of-life phases to be normalized on an annualized basis to allow for direct comparison. This means that the environmental impact connected to building materials has to be discounted over the lifespan of the building (König & De Cristofaro, 2012).

LCA results in Northern Europe have previously shown that the annualized environmental impact from operational energy consumption is over 10 times larger than the environmental impact connected to building materials, and that the largest reductions in environmental impact can be achieved by having a procurement focus on the operational phase (Adalberth, 1997; Blengini & Di Carlo, 2010). However, for modern low-energy buildings, recent studies show that the environmental impact from building materials can be of the same magnitude or even equal to that of the operational phase, where reductions in space heating are achieved by extra materials consumption in the external building fabric (Berggren, Hall, & Wall, 2013; Cabeza et al., 2014). This change in balance between operational and construction phases implies that construction professionals need to have a greater procurement focus on the construction phase, and forms the reasoning behind the wider adoption of LCA tools in recent years (Buyle, Braet, & Audenaert, 2013; Lasvaux et al., 2013).
**Building lifespan in LCA**

It is interesting to observe that, whilst building lifespan plays a critical role in LCA, the issue is poorly covered in the available scientific literature. It is, for example, only for low-energy buildings with building lifespans of 50 years or under, that it can be documented that the environmental impact from building materials is of the same order of magnitude as that from the operational phase (Cabeza et al., 2014). A series of literature reviews, covering over 100 peer-reviewed scientific articles from over the last 20 years, show that issues relating to building lifespan are inadequately defined and poorly validated in the LCA process (Berggren et al., 2013; Buyle et al., 2013; Cabeza et al., 2014; Optis & Wild, 2010). Four particular areas of concern stand out in this literature:

1. There is typically no methodological documentation of any theoretical or empirical reasoning regarding the chosen selection of building lifespan.
2. A building lifespan of 50 years is dominant and is typically justified by reference to other research. Where other lifespans are used, they vary between 25 and 100 years.
3. There is no consistency in choice of building lifespan in relation to building type or geographical region.
4. It is not stated whether the replacement of materials or construction elements, after the end of their useful service life but before the end of the building’s lifespan, is taken account of.

Few studies have explicitly looked at the impact of building lifespan on environmental impact. Aktas and Bilec (2012) concluded that an arbitrary building lifespan and excluding interior renovation impacts introduced considerable error into LCA results. Mequignon, Haddou, Thellier, and Bonhomme (2013) studied the effects of using different loadbearing external walls, and showed that for materials with a very long lifespan, the annualized environmental impact has an inverse relation to the lifespan of the building.

**Service life prediction in LCA**

Within the fields of service life prediction and life cycle costing (LCC), considerable empirical and theoretical knowledge has been gained relating to the technical and economic basis for the service life planning and maintenance of buildings (Goh & Sun, 2016; ISO, 2011). LCC addresses economic sustainability by allowing present and future costs to be expressed as present-day values using economic discounting methods. This knowledge has, however, not been utilized to a great extent in the LCA field. Haapio and Viitaniemi (2008) showed that assumptions regarding the service life of building components and building lifespan had considerable effect on the environmental impact of the construction materials in Finland. Grant, Ries, and Kibert (2014) examined the effects of different North American service life models on the environmental impact of external claddings, and showed that environmental impact was dependent on the frequency of major material replacement. Rauf and Crawford (2015) examined the effect of building service life on embodied energy under Australian conditions, including materials replacement when their service life was less than the building’s, and concluded that the annualized embodied energy was reduced by 16% when comparing a building lifespan of 100 years to 50 years.

**Research aim and methodology**

It is a paradox that, whilst the wider adoption of LCA tools has been predicated by an argumentation that the environmental impact from building materials can be of the same order of magnitude as those from the operational phase, the actual assumptions that form the basis for this argumentation use inadequately validated short building lifespans. Whilst it would seem to be a truism that longer building lifespans would give lower environmental impacts, none of this surveyed literature actually
presents data to show how their results could differ if longer lifespans were used. There are thus little or no data available that can assist construction professionals early in the procurement process to evaluate assumptions regarding how building lifespan actually affects the balance between the environmental impact from construction and operation, nor how building lifespan could be used to reduce environmental impact.

The aim of this article is to therefore explore how the environmental impact from building components can be affected by assumptions relating to building lifespan. It is based on integrating Danish R&D initiatives regarding service life prediction and LCA methodologies. The research is structured as follows:

(1) Choice of lifespan: Since the environmental impact of building components is impacted by the lifespan of the building and of the individual materials, methods for defining both of these are developed.
(2) Choice of building components: Reflecting contemporary construction practice, the choice of 7 primary building components is explained, and the specification of 792 parametric variations of these detailed.
(3) Calculation methodology: A full LCA is carried out, based on the CEN standards for the sustainability of construction works and the Danish implementation of the DGNB certification system for sustainable buildings.
(4) Analysis of results: A full statistical analysis is carried out on each primary building component to determine the extent that building lifespan has an effect on environmental impact.
(5) Discussion: The implications of the research results for construction professionals are discussed in greater detail.

The Danish construction sector has carried out an extensive analysis to reach agreement on a national sustainability tool, with a Danish implementation of the DGNB system being selected because of methodological transparency and adherence to European standards (Birgisdottir, Mortensen, Hansen, & Aggerholm, 2013). The DGNB system is based on the CEN standards for the sustainability of construction works EN 15643-2 and EN 15978 (European Committee for Standardization, 2011a, 2011b), using midpoint impact category indicators, such as acidification potential (König & De Cristofaro, 2012). Extensive literature reviews show that this approach is well understood by construction professionals, and is the dominant LCA approach within the construction sector (Ortiz, Castells, & Sonnemann, 2009; Sharma, Saxena, Sethi, Shree, & Varun, 2011). This environmental approach forms the basis for this research.

Choice of lifespan

An individual building typically consists of hundreds of separate materials, and they all have unique production, replacement and disposal processes, and also different service lives (Haapio & Viitaniemi, 2008). The ISO standard 15686-1 (ISO, 2011) defines the service life of the materials according to their accessibility. As such, inaccessible, irreplaceable or structural materials should have the same intended service life as the building, whilst other materials with progressively shorter lifespans should be layered around these, such that materials with a shorter lifespan can be replaced without needing to remove those with a longer lifespan. This gives rise to buildings with a functionally layered constructive approach (Lstiburek, 2007), where materials with a shorter lifespan and differing function can be replaced without needing to remove those with a longer lifespan. This rational approach has become dominant in the Nordic countries since the 1970s as a response to growing insulation requirements and the need for industrialized prefabrication with greater aesthetic freedom and better performance (Marsh & Lauring, 2011).

As a consequence, whilst building components are one of the principal elements used to describe function during procurement (with descriptions such as ‘loadbearing concrete wall with brickwork
cladding and a U-value of 0.15 W/m²K), building components do not have a lifespan. Rather, it is the individual materials used in that component that have a lifespan, and this is determined by varying technical, economic, functional and design factors (Grant et al., 2014). The same material can therefore be used in functionally different layers with different lifespans, such that timber cladding typically has a shorter lifespan than loadbearing timber framing.

It is therefore important to distinguish between the lifespan of the building that the components are used in, and the lifespan of the materials that are used in that component. It is the lifespan of the material that becomes the determining factor when it is the same or less than that of the building, as shown in Figure 1. For a given material with a given environmental impact and lifespan, then the annual environmental impact will be the same when the lifespan of the material is the same or less than that of the building, also for buildings with different lifespans. This usually applies for claddings.

In contrast, it is the lifespan of the building that becomes the determining factor when it is the same or less than the expected lifespan of a material, as shown in Figure 2. For a given material with a given environmental impact and lifespan, the annual environmental impact will be larger when the lifespan of the building is less than that of the material, in comparison to when the lifespan of the building is the same as that of the material. This is usually the case for structural materials.

**Lifespan of materials**

For each material used in every layer of a building component, it is necessary to assign a lifespan. This is determined by using the lifespan tables for construction materials based on the functional layering of contemporary building components, as developed by Aagaard, Brandt, Aggerholm, and Haugbølle (2013) as part of the Danish Energy Agency’s policy initiative for sustainable construction. These

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**Figure 1.** Annualized environmental impact for a given material with a given environmental impact and lifespan, when the lifespan of the material is the same or less than the lifespan of the building, also for buildings with different lifespans.
Tables are based on national data, and draw from relevant theoretical research and North European empirical experiences within the framework of the ISO standard 15686-1 (ISO, 2011). The range of lifespans contained in the tables is between 10 and 120 years. An example of the lifespan data for an external wall is shown in Table 4.

**Lifespan of buildings**

The lifespan of a building reflects whether it still fulfils the many functions for which it was established. Traditionally, a lifespan of between 35 and 60 years has been used in the calculation of a building’s life cycle cost, mainly because it is seen as economically irrelevant to calculate with a longer time span for the depreciation of construction investments (Aagaard et al., 2013; Goh & Sun, 2016), and it is for this reason that the DGNB system uses 50 years for the building lifespan (DK-GBC, 2012). However, empirical data regarding current building lifespans, coupled with annual rates of new construction, renovation and demolition, indicate that an average building lifespan of 100 years or more would be more accurate in sustainability assessments, reflecting changing social, technical and economic factors in a wider European context (Aagaard et al., 2013; Brown et al., 2011; Ravetz, 2008).

A statistical analysis of the Danish building mass shows that different building types have differing average lifespans, thus reflecting the balance between construction economics and changes in building usage, with housing having a longer lifespan and buildings for commerce and production having a shorter lifespan (Aagaard et al., 2013), as shown in Table 1. For the purposes of this research,
building lifespans of 50, 80, 100 and 120 years are selected. Fifty years is chosen to reflect the DGNB system, as used in Denmark. The other three lifespans are chosen to represent all major building types, comprising over 65% of the total completed floor area of all new construction in Denmark over the last 10 years (Statistics Denmark, 2016).

**Choice of building components**

The primary building components from the major building types found in contemporary Danish construction practice have been analysed, based on a survey of relevant publications (Danish Architectural Press, 2012; Hansen et al., 2012; V&S Byggedata, 2013) and workshops with construction professionals representing Denmark’s major consulting architects and engineers. The vast majority of new buildings are between one and five storeys in height, without basements, and with loadbearing external walls, and loadbearing internal party or diaphragm walls.

**Primary building components**

For the purpose of this study, seven primary building components have been selected. As described previously, modern building components are typically functionally layered. Based on the seven primary building components, this gives thirteen different typologies, where components are divided into layered functional variations, as shown in Table 2.

Table 1: Average lifespan for various building types in Denmark.

| Building type          | Average lifespan |
|-----------------------|------------------|
| Agricultural buildings| 40               |
| Storage buildings      | 60               |
| Production facilities  | 80               |
| Office buildings       |                  |
| Retail buildings       |                  |
| Nursery/education      | 100              |
| University/research    |                  |
| Medical buildings      |                  |
| Sports facilities      |                  |
| Detached housing       | 120              |
| Terrace housing        |                  |
| Multi-storey housing   |                  |
| Cultural buildings     |                  |

Source: Aagaard et al. (2013).

Typical materials reflecting contemporary Danish construction practice, and covering both traditional materials and newer solutions with supposedly lower environmental impacts, have been selected for each layer of all typologies. Each variation of the external building components is specified on the basis of three different U-values, representing the levels used in the current and expected future building regulations. Each variation of the internal building components is specified on the basis of three different thicknesses, representing varying structural or fire-related demands. These variations can therefore be seen as covering most functional and aesthetic demands with a variety of in situ and prefabricated constructional solutions, reflecting the diversity of factors that construction professionals may need to address early in the procurement process. Danish construction practice is broadly similar to that found in other North European countries. The variations in each layer for the 7 primary building components and all 13 typologies are shown in Supplementary Materials (Appendix Tables A1 to A13).

**Parametric variations**

On the basis of the 7 primary building components and 13 typologies with differing layer variations, U-values and thicknesses, it is possible to generate 792 parametric variations. For each variation, an
| Primary Building Component | Typology  | Schematic illustration | Internal layer                              | Middle layer                        | External layer                        |
|----------------------------|-----------|-------------------------|---------------------------------------------|-------------------------------------|---------------------------------------|
| External Wall              | Typology 1| ![Schematic](image1)    | Heavyweight loadbearing                      | Insulation & ties                   | Heavyweight finish                    |
|                            | Typology 2| ![Schematic](image2)    | Heavyweight loadbearing                      | Insulation & framing                | Lightweight finish                    |
|                            | Typology 3| ![Schematic](image3)    | Lightweight finish                           | Loadbearing framing & insulation     | Lightweight finish                    |
| Roof                       | Typology 1| ![Schematic](image4)    | Heavyweight loadbearing                      | Insulation                          | Lightweight finish                    |
|                            | Typology 2| ![Schematic](image5)    | Lightweight finish                           | Loadbearing framing & insulation     | Lightweight finish                    |
|                            | Typology 3| ![Schematic](image6)    | Lightweight finish                           | Loadbearing framing & cavity/insulation | Lightweight finish                    |
| Ground Floor               | Typology 1| ![Schematic](image7)    | Heavy/lightweight finish                     | Heavyweight loadbearing             | Insulation on terrain                 |
| Foundations                | Typology 1| ![Schematic](image8)    | Heavyweight loadbearing                      | Insulation & ties                   | Heavyweight finish                    |
| Window/rooftlight          | Typology 1| ![Schematic](image9)    | –                                            | Glazing unit                        | Frame                                 |
| Internal Wall              | Typology 1| ![Schematic](image10)   | Finish                                       | Heavyweight                          | Finish                                |
|                            | Typology 2| ![Schematic](image11)   | Finish                                       | Framing & insulation                | Finish                                |
| Internal Floor             | Typology 1| ![Schematic](image12)   | Floor finish                                 | Heavyweight                          | Finish                                |
|                            | Typology 2| ![Schematic](image13)   | Floor finish                                 | Framing & insulation                | Finish                                |
inventory is prepared, describing the resource consumption required for a functional unit of one square metre of each building component, except for the foundation typology, which uses a functional unit of one linear metre. All materials are covered, including fixings and finishes.

For each of the four building lifespans of 50, 80, 100 and 120 years, the total material consumption is defined with a consumption multiple, thus including both the originally installed materials, and the materials which are replaced due to having a lifespan shorter than the building’s. This replacement is determined by using the material’s average lifespan in relation to the building lifespan at a decimalized annual replacement rate using data from Aagaard et al. (2013), as described in the previous section. An example for one variation is shown in Table 3. This ensures a consistent approach for dealing with methodological uncertainty, allowing for the calculation of all environmental impacts from production, use and end of life.

### LCA methodology

The LCA is carried out using the calculation tool DK LCA-Calc, which was developed for the Danish implementation of the DGNB system. This tool draws LCA inventories for materials from the ESUCO and Ökobau databases (Birgisdottir et al., 2013; DK-GBC, 2012). These use the CML 2002 life cycle impact assessment methodology with midpoint impact category indicators that translate impacts into environmental themes (Joint Research Centre, 2010). In line with the CML 2002 methodology and the DGNB system, the optional steps of normalization and weighting are not part of the LCA.

### Generic vs. specific inventory data

Uncertainty regarding the accuracy of environmental data is an important factor, with the use of environmental product declarations (EPDs) for product-specific materials being the primary recommendation within the CEN standard for the sustainability of construction works EN 15978 (European Committee for Standardization, 2011b). However, there are valid arguments as to why product-specific EPDs cannot be used, and why the use of generic data is an accepted alternative. Firstly, whilst a growing number of international products are covered by EPDs, very few EPDs are available for specific Danish construction materials and the great number of generic materials. Secondly, issues relating to public procurement within the EU often mean that buildings are constructed with different materials from those specified earlier in the procurement process, thus reducing the accuracy of a product-specific LCA approach. Finally, it has been shown that the use of generic

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**Table 3. Resource consumption, lifespan and consumption multiple for all materials used in each layer of a functional unit of one square metre of a typical external wall with a U-value of 0.15 W/m²K, based on building lifespans of 50, 80, 100 and 120 years.**

| Internal layer (Units/m² façade area) | Thickness (mm) | Weight (kg) | Material lifespan (Years) | Consumption multiple based on building lifespan of: |
|--------------------------------------|----------------|-------------|---------------------------|-----------------------------------------------|
|                                      |                |             |                           | 50 years | 80 years | 100 years | 120 years |
| Paint finish                         | –              | 0.13        | 15                        | 3.33     | 5.33     | 6.67      | 8.00      |
| Concrete, C30-37                     | 180            | 414.00      | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Steel reinforcement                  | –              | 10.00       | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Insulating layer                     |                |             |                           |          |          |           |           |
| Polyethylene vapour barrier          | –              | 0.13        | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Galvanised steel framing             | –              | 4.40        | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Mineral wool insulation              | 250            | 7.50        | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Fibre cement sheet                   | 8              | 13.60       | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Galvanised steel fixings             | –              | 0.10        | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| External layer                       |                |             |                           |          |          |           |           |
| Timber battens                       | 22             | 1.05        | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Galvanised steel fixings             | –              | 0.10        | 120                       | 1.00     | 1.00     | 1.00      | 1.00      |
| Timber cladding with finish          | 25             | 13.23       | 50                        | 1.00     | 1.60     | 2.00      | 2.40      |
| Galvanised steel fixings             | –              | 0.10        | 50                        | 1.00     | 1.60     | 2.00      | 2.40      |
Both the ESUCO and Ökobau databases contain specific and generic data, which is representative of typical European or German construction materials, and their suitability for use within the Danish context has been determined (Schmidt, 2012). The databases contain LCA inventories covering upstream extraction and manufacturing, and downstream end-of-life processes. The adopted methodology ensures a valid and consistent approach to deal with uncertainty regarding data accuracy.

System boundaries, environmental impacts and calculation procedure

The stages included in a building’s LCA, and which set the system boundaries, are defined by the CEN standard for the sustainability of construction works EN 15978 (European Committee for Standardization, 2011b). For the purposes of this research, all stages relating to the materials’ life cycle are included, except those relating to the construction/installation process and the building’s operational energy use. The same CEN standard also describes the categories for environmental impacts and resource consumption that have been scientifically validated. Seven of these are used in the DGNB system and in this research, as shown in Table 4. All energy consumption is calculated as kilowatt hours, since this is the unit used to calculate primary energy consumption in the Danish Building Regulations (Hansen et al., 2012).

The 7 categories for environmental impacts and resource consumption are calculated for each of the 792 typological variations for the four building lifespans of 50, 80, 100 and 120 years, as shown in Figure 3. All results are calculated for the functional unit of each variation on an annualized basis to create an LCA consisting of seven midpoint impact category indicators. Typical LCA results for two external wall typologies are shown in Table 4.

Analysis of results

The large quantity of parametric data allows for a statistical analysis. Within the LCA field, the limited research using statistical analysis has shown that there is a high correlation between specific environmental impact categories (Huijbregts et al., 2006, 2010; Rydh & Sun, 2005). Statistical methods have been used to examine large amounts of parametric building energy data to simplify decision-making in procurement (Asadi, Amiri, & Mottahedi, 2014; Valovcin, Hering, Polly, & Heaney, 2014). These

Table 4. LCA results for a functional unit of one square metre for two external wall typology variations with a U-value of 0.15 W/m²K and building lifespan of 120 years.

| Impact categories                          | External wall typology 1         | External wall typology 3         |
|--------------------------------------------|----------------------------------|----------------------------------|
| Global warming potential                   | 1.13E+00                         | 4.55E−01                         |
| Ozone depletion potential                  | 3.64E−08                         | 3.11E−08                         |
| Photochemical ozone creation potential     | 3.09E−04                         | 3.16E−04                         |
| Acidification potential                    | 3.80E−03                         | 2.71E−03                         |
| Eutrophication potential                   | 4.03E−04                         | 2.20E−04                         |
| Total primary energy                       | 3.48E+00                         | 3.58E+00                         |
| Non-renewable primary energy               | 3.36E+00                         | 1.78E+00                         |
| Internal layer                             | Reinforced concrete              | Plasterboard                     |
| Insulating layer                           | Brickwork                        | Steel framing with mineral wool  |
| External layer                             | Mineral wool insulation with ties| Pine timber cladding             |
| Impact categories                          |                                  |                                  |
| 7 Primary Building Components | 13 Typologies | 792 Variations | 4 Building Lifespans | 7 Environmental Impact Categories |
|--------------------------------|----------------|----------------|----------------------|----------------------------------|
| External Wall                  | External wall Typology 1 | 24 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
|                                | External wall Typology 2 | 348 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
|                                | External wall Typology 3 | 84 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
| Roof                           | Roof Typology 1          | 72 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
|                                | Roof Typology 2          | 60 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
|                                | Roof Typology 3          | 12 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
| Window/Rooflight               | Window/rooflight Typology 1 | 30 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
| Ground Floor                   | Ground floor Typology 1  | 18 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
| Foundations                    | Foundations Typology 1   | 18 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
| Internal Wall                  | Internal wall Typology 1 | 12 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
|                                | Internal wall Typology 2 | 24 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
| Internal Floor                 | Internal floor Typology 1| 36 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |
|                                | Internal floor Typology 2| 54 variations | 50 yrs | 80 yrs | 100 yrs | 120 yrs | Ei1 | Ei2 | Ei3 | Ei4 | Ei5 | Ei6 | Ei7 |

**Figure 3.** Overview of parametric calculations carried out in this research in relation to primary building components, typologies, variations, building lifespans and environmental impact categories.
examples show that the statistical analysis of parametric data can have a scientific validity and relevance to guide decision-making for construction professionals.

The parametric nature of the analysis means that the data can be aggregated at different levels, as shown in Figure 3. For the purposes of this research, the primary building components are compared. For each of these, the data sets were analysed for skew and kurtosis in the distribution of values, and for their respective standard errors, and this showed that the data sets’ distribution did not significantly differ from a normal population distribution. Therefore, no data sets were log transformed to account for skewed distributions (Trochim & Donnelly, 2006). With the choice of statistical methods informed by Sheskin (2007), the following analyses were carried out on the data sets for the primary building components:

(1) A one-way analysis of variance (ANOVA) was carried out to determine whether building lifespan has a very significant effect on the seven categories of environmental impact.

(2) If the ANOVA showed that building lifespan has a very significant effect on environmental impact, then a full bivariate linear regression analysis was carried out to determine the correlation in environmental impact between a building lifespan of 50 years and lifespans of 80, 100 and 120 years, respectively.

(3) For each of the building lifespans of 80, 100 and 120 years, respectively, the difference in environmental impact in relation to a building lifespan of 50 years was calculated using the linear regression equations and the LCA data sets.

**Building lifespan and effect on environmental impact**

When the lifespan of a material is the same or less than the lifespan of the building, then the annual environmental impact is constant, regardless of building lifespan, as discussed previously and shown in Figure 1. It is therefore first necessary to examine the primary building components to determine whether they have an annual environmental impact that is constant, regardless of building lifespan.

For all construction variations within each of the seven primary building components, a one-way ANOVA was conducted to compare the effect of building lifespans of 50, 80, 100 and 120 years on each of the seven environmental impact categories. The results in Table 5 show the significant effect of building lifespan on the environmental impact for the categories with the maximum and minimum values. This shows that it is only the window/rooflight component where the building lifespan did not have a significant effect on the environmental impact for each of the seven categories at

| Primary Building Component | Null hypothesis: Building lifespan has no significant effect for all seven environmental impact categories | Environmental impact category with maximum significant effect | Environmental impact category with minimum significant effect |
|----------------------------|----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| External wall              | Rejected                                                                                                  | Total primary energy                                         | Eutrophication potential                                    |
|                            |                                                                                                          | \( F(3, 1820) = 1005.33; \ p < .001 \)                       | \( F(3, 1820) = 133.71; \ p < .001 \)                        |
| Roof                       | Rejected                                                                                                  | Total primary energy                                         | Eutrophication potential                                    |
|                            |                                                                                                          | \( F(3, 572) = 219.40; \ p < .001 \)                        | \( F(3, 572) = 26.40; \ p < .001 \)                         |
| Window/rooflight           | Accepted                                                                                                 | Ozone depletion potential                                     | Eutrophication potential                                    |
|                            |                                                                                                          | \( F(3, 116) = 0.284; \ p = .837 \)                         | \( F(3, 116) = 0.008; \ p = .999 \)                        |
| Ground floor               | Rejected                                                                                                  | Global warming potential                                      | Ozone depletion potential                                    |
|                            |                                                                                                          | \( F(3, 68) = 30.20; \ p < .001 \)                          | \( F(3, 68) = 3.05; \ p = .035 \)                          |
| Foundations                | Rejected                                                                                                  | Eutrophication potential                                     | Total primary energy                                         |
|                            |                                                                                                          | \( F(3, 68) = 81.78; \ p < .001 \)                          | \( F(3, 68) = 56.13; \ p < .001 \)                         |
| Internal wall              | Rejected                                                                                                  | Ozone depletion potential                                     | Non-renewable primary energy                                 |
|                            |                                                                                                          | \( F(3, 140) = 8.21; \ p < .001 \)                          | \( F(3, 140) = 4.88; \ p = .003 \)                         |
| Internal floor             | Rejected                                                                                                  | Eutrophication potential                                     | Global warming potential                                     |
|                            |                                                                                                          | \( F(3, 356) = 94.40; \ p < .001 \)                         | \( F(3, 356) = 16.98; \ p < .001 \)                        |
the $p < .01$ level, varying between $F(3, 116) < 0.01, p > .99$ and $F(3, 116) = 0.28, p = .84$, thus accepting the null hypothesis. This occurs because all material lifespans are the same or less than the shortest building lifespan for the specified windows and rooflights.

**Correlation between change in building lifespan and environmental impact**

When the lifespan of the building is the same or less than the lifespan of a material, then the annual environmental impact will be larger for shorter building lifespans, as shown in Figure 2. It is therefore necessary to examine the remaining primary building components to determine whether there is a correlation between changes in building lifespan and environmental impact.

For the six remaining primary building components, both individually and all together, a full bivariate linear regression analysis was carried out to determine if there is a significant correlation for each of the seven environmental impact categories between a building lifespan of 50 years and building lifespans of 80, 100 and 120 years, respectively, giving 147 data sets and regressions. The regression equations were optimized using a linear least-squares fit to find appropriate values of the slope and intercept. The regression analysis was used to determine the numerical value, sign and statistical significance of the correlation coefficient, together with the effect size of the correlation, expressed as the coefficient of determination.

For all the 147 pairs of data sets, the correlation coefficient was determined as being statistically significant with a probability value of less than .001, thus rejecting the null hypothesis. All data sets show a positive correlation, meaning that the variables move in the same direction. For each building component, both individually and all together, the results in Table 6 show the correlation coefficient and the coefficient of determination for the environmental impact categories with the maximum and minimum values.

Correlation does not equate causation, and there is always the possibility that another variable influenced the results, meaning that statistical results are always open to a degree of interpretation. The correlation coefficient, $r$, can vary numerically between an absolute value of 0.0 and 1.0, where the closer it is to 1.0, the stronger the relationship between the two variables. It is generally accepted that an absolute value of the correlation coefficient equal to or greater than 0.70 represents a strong direct relationship with a high correlation, whilst a value equal to or greater than 0.90 represents a very high correlation (Sheskin, 2007; Taylor, 1990).

The coefficient of determination, $R^2$, can vary from 0.0 to 1.0 and represents the proportion of the variation in the results that is shared by both variables. Mathematically, the coefficient of determination is the square of the correlation coefficient. Using a threshold of 0.90 for the correlation coefficient gives a coefficient of determination equal to or greater than 0.81, indicating that more than 81% of the variance in the results can be explained by the linear relationship between the variables. Of the 147 regressions that were analysed, only 17 had correlation coefficients under 0.90, and all these were above 0.76. It can therefore be concluded that there is a significant and consistent statistical correlation between changes in building lifespan and environmental impact for all six primary building components and for all environmental impact categories.

**Difference in environmental impact correlated to change in building lifespan**

The results allow for an estimation of the difference in environmental impact that can be correlated to the change in building lifespan from 50 years to 80, 100 and 120 years, respectively. This can done both on the basis of the linear regression equations, and can then be compared with the actual LCA data sets.

For each of the primary building components individually and all together, and for each of the seven environmental impact categories, the mean and standard deviation of the calculated LCA values of environmental impact for a building lifespan of 50 years were determined, giving 49 data sets. Based on this, 10,000 values of the environmental impact for a building lifespan of 50
Table 6. Results from full bivariate linear regression analysis, showing the environmental impact categories with maximum and minimum correlation between a building lifespan of 50 years and lifespans of 80, 100 and 120 years, respectively, for the given primary building components.

| Primary building component | Environmental impact category with maximum correlation coefficient, \( r \), and coefficient of determination, \( R^2 \) | Environmental impact category with minimum correlation coefficient, \( r \), and coefficient of determination, \( R^2 \) |
|----------------------------|-------------------------------------------------|-------------------------------------------------|
| **External Wall**          | Eutrophication potential                        | Total primary energy                             |
| Building lifespan of 80 years | \( r(454) = 0.99, p < .001; R^2 = 0.98 \)       | Total primary energy                             |
| Building lifespan of 100 years | \( r(454) = 0.97, p < .001; R^2 = 0.95 \)       | Total primary energy                             |
| Building lifespan of 120 years | \( r(454) = 0.96, p < .001; R^2 = 0.91 \)       | Total primary energy                             |
| **Roof**                   | Global warming potential                         | Total primary energy                             |
| Building lifespan of 80 years | \( r(142) = 0.99, p < .001; R^2 = 0.99 \)       | Total primary energy                             |
| Building lifespan of 100 years | \( r(142) = 0.98, p < .001; R^2 = 0.96 \)       | Total primary energy                             |
| Building lifespan of 120 years | \( r(142) = 0.96, p < .001; R^2 = 0.93 \)       | Total primary energy                             |
| **Ground floor**           | Ozone depletion potential                        | Total primary energy                             |
| Building lifespan of 80 years | \( r(16) = 0.99, p < .001; R^2 = 0.98 \)        | Total primary energy                             |
| Building lifespan of 100 years | \( r(16) = 0.97, p < .001; R^2 = 0.95 \)        | Total primary energy                             |
| Building lifespan of 120 years | \( r(16) = 0.96, p < .001; R^2 = 0.92 \)        | Total primary energy                             |
| **Foundations**            | Global warming potential                         | Ozone depletion potential                       |
| Building lifespan of 80 years | \( r(16) = 1.00, p < .001; R^2 = 1.00 \)       | Ozone depletion potential                       |
| Building lifespan of 100 years | \( r(16) = 0.99, p < .001; R^2 = 0.98 \)       | Ozone depletion potential                       |
| Building lifespan of 120 years | \( r(16) = 0.98, p < .001; R^2 = 0.96 \)       | Ozone depletion potential                       |
| **Internal wall**          | Photochemical ozone creation potential           | Ozone depletion potential                       |
| Building lifespan of 80 years | \( r(34) = 1.00, p < .001; R^2 = 0.99 \)       | Ozone depletion potential                       |
| Building lifespan of 100 years | \( r(34) = 0.99, p < .001; R^2 = 0.98 \)       | Ozone depletion potential                       |
| Building lifespan of 120 years | \( r(34) = 0.98, p < .001; R^2 = 0.97 \)       | Ozone depletion potential                       |
| **Internal floor**         | Photochemical ozone creation potential           | Eutrophication potential                         |
| Building lifespan of 80 years | \( r(88) = 0.99, p < .001; R^2 = 0.97 \)       | Eutrophication potential                         |
| Building lifespan of 100 years | \( r(88) = 0.97, p < .001; R^2 = 0.93 \)       | Eutrophication potential                         |
| Building lifespan of 120 years | \( r(88) = 0.94, p < .001; R^2 = 0.88 \)       | Eutrophication potential                         |
| All (external wall, roof, ground floor, foundations, internal wall and internal floor) |  |  |
| Building lifespan of 80 years | \( r(760) = 0.99, p < .001; R^2 = 0.98 \)     | Total primary energy                             |
| Building lifespan of 100 years | \( r(760) = 0.97, p < .001; R^2 = 0.94 \)     | Total primary energy                             |
| Building lifespan of 120 years | \( r(760) = 0.95, p < .001; R^2 = 0.90 \)     | Total primary energy                             |

years were randomly generated based around the mean and standard deviation for each of the 49 data sets.

Using these randomly generated values, the linear regression equations were then used to calculate the estimated environmental impact for building lifespans of 80, 100 and 120 years, respectively, giving 147 data sets. The 10,000 results were then expressed as percentage reductions in relation to
the value for a building lifespan of 50 years, and the mean reduction and standard deviation calculated for each environmental impact category. Since the results are expressed as percentages, this also allows for the calculation of mean reduction and standard deviation across the seven environmental impacts. The results are summarized in Table 7 and presented graphically in Figure 4, where they show a pattern with consistent mean values with very low standard deviations.

Results for the actual LCA data sets are dealt with similarly. For each of the six primary building components and for each of the seven environmental impact categories, the percentage reduction in environmental impact for building lifespans of 80, 100 and 120 years, respectively, in relation to a building lifespan of 50 years was calculated, and the mean reduction and standard deviation were calculated for each environmental impact category. The results are also summarized in Table 7.

A full bivariate linear regression analysis was then carried out to determine whether there is a correlation between the results calculated by the linear regression equations and those from the LCA data sets. For this pair of data sets, the correlation coefficient was determined as being statistically significant, thus rejecting the null hypothesis \( r(124) = 0.99, p < .001, R^2 = 0.98 \). It can therefore be concluded that the results calculated by the linear regression equations represent the LCA data sets to a significant degree.

Discussion

The results show that building lifespan plays a critical role in LCA. Traditionally, a lifespan of around 50 years has been used in LCA and LCC calculations, based on depreciation principles for construction investments. However, factual data for current building lifespans and annual rates of new construction, renovation and demolition indicate that an average lifespan of 100 years or more would be more accurate in LCA calculations in a wider European context. The use of an empirical basis for building lifespan, rather than short-term economic assumptions, would seem more appropriate in relation to general sustainability aims, so this has several implications for construction professionals in their use of LCA tools.

Sustainability tools and short building lifespans

Sustainability tools in the Nordic countries consistently use short building lifespans in their environmental assessment methodologies, with the Danish DGNB system using 50 years, and the Norwegian BREEAM system using 60 years as the basis for calculation (DK-GBC, 2012; NGBC, 2012). However, the results from this research show a significant statistical correlation between longer building lifespans and lower environmental impacts. On average, the environmental impact of an 80-year building lifespan is 29% lower than that of a 50-year lifespan, whilst a 100-year lifespan is 38% lower, and a 120-year lifespan is 44% lower.

The effect of this can be illustrated by looking at the results of a series of LCAs, carried out as part of the implementation of the Danish DGNB system (Birgisdottir et al., 2013). Here, the global warming potential for the construction materials and the operational energy has been calculated on an annualized basis, based on a building lifespan of 50 years. Expressed as a mean value for six buildings, the construction materials are responsible for about one-third of the total environmental impact. The data for construction materials can be recalculated, using the results from this research, to estimate the environmental impact assuming building lifespans of 80, 100 and 120 years, as shown in Figure 5. This shows that the construction materials’ global warming potential being almost halved for a building type with a lifespan of 120 years. This implies that the short building lifespans used in LCA assessment tools can almost double the annualized environmental impact of construction materials, which could shift the focus of construction professionals away from reducing environmental impact in the operational phase.
Table 7. Results showing the difference in environmental impact that can be attributed to the change in building lifespan from 50 years to 80, 100 and 120 years, respectively, for the given primary building components, calculated on the basis of the linear regression equations and the LCA data sets.

| Primary construction component | Generated by regression Equations | Calculated from LCA data |
|-------------------------------|----------------------------------|--------------------------|
|                               | 80 years | 100 years | 120 years | 80 years | 100 years | 120 years |
|                               | Mean reduction | Standard deviation | Mean reduction | Standard deviation | Mean reduction | Standard deviation | Mean reduction | Standard deviation | Mean reduction | Standard deviation |
| External wall                 | −31.2% ±4.5% | −40.6% ±6.8% | −47.0% ±2.2% | −31.1% ±4.2% | −40.3% ±5.9% | −46.3% ±2.7% |
| Roof                          | −25.5% ±5.7% | −32.8% ±7.3% | −37.8% ±1.7% | −25.1% ±4.9% | −32.6% ±6.4% | −37.6% ±2.1% |
| Ground floor                  | −33.6% ±5.3% | −44.6% ±8.0% | −51.9% ±2.5% | −32.9% ±4.9% | −43.7% ±6.6% | −50.8% ±4.7% |
| Foundations                   | −36.0% ±1.3% | −47.6% ±5.7% | −55.3% ±0.8% | −36.0% ±0.2% | −47.6% ±0.4% | −55.3% ±0.8% |
| Internal wall                 | −19.0% ±10.2% | −25.3% ±11.3% | −29.5% ±3.1% | −19.0% ±11.0% | −25.3% ±14.6% | −29.5% ±2.7% |
| Internal floor                | −26.3% ±7.5% | −34.8% ±8.9% | −40.4% ±2.9% | −25.2% ±6.2% | −33.0% ±8.4% | −38.3% ±2.2% |
| All (external wall, roof, ground floor, foundations, internal wall and internal floor) | −29.2% ±6.6% | −38.0% ±8.4% | −44.0% ±2.1% | −29.0% ±5.2% | −37.7% ±6.9% | −43.4% ±2.4% |
Different building types, lifespans and LCA results

It is not uncommon to find the same building components used in office, research and multi-storey residential buildings in contemporary Danish construction practice. This means that the same building components used in different building types could have different LCA results because of different building lifespans. This implies that building components cannot be simply rated by their environmental impact, as happens with U-values to rate thermal performance, because component environmental impact is dependent on assumptions regarding building lifespan. It would instead be necessary to rate building component environmental impact for building lifespans of 80, 100 and 120 years. This complication would make it more difficult to market this type of environmental benefit to construction professionals, despite recommendations that this is necessary to ensure the uptake of sustainable construction solutions (Peat, 2009).

Conversely, this issue would also imply that certain building types will have a large environmental impact from construction, as shown in the available literature (Berggren et al., 2013). Offices and commercial buildings can be expected to have a larger environmental impact from construction, not

Figure 4. Difference in annualized environmental impact that can be attributed to the change in building lifespan from 50 years to 80, 100 and 120 years, respectively, for the given primary building components individually and all together, on the basis of the calculated regression equations.

Figure 5. Mean values of the annualized global warming potential for operational energy and construction materials for buildings analysed as part of the implementation of the DGNB system in Denmark, based on building lifespans of 50, 80, 100 and 120 years. Source: Birgisdottir et al. (2013) and this research.
necessarily because of a problematic choice of materials, but because the building type has a shorter building lifespan used as the basis for calculation.

**Long lifespans deliver low environmental impacts**

The results show that increasing building lifespan can be a legitimate and effective tool to reduce environmental impact. It is interesting to note that under the DGNB system, a reduction of only 30% in the environmental impact from construction materials is the maximum that can be rewarded (DK-GBC, 2012). However, this research has shown that increasing the building lifespan from 50 to 100 years would give a 38% reduction in environmental impact.

This research has been based on the empirically based assumption that building types have static lifespans. However, it can also be argued that building and material lifespans should be dynamic design factors, with the use of specific design and construction solutions being rewarded with longer lifespans in LCA tools. This would imply that construction professionals should be designing for long building lifespans. Unfortunately, modern society is also characterized by patterns of fluid social and economic change (Baumann, 2000). Most industrialized societies have since the 1980s experienced a transformation towards a knowledge-based society, and in this process, buildings now have to meet rapidly changing functional and technological demands (Gann, 2000). This is especially true for retail and commercial buildings, where change happens over shortening temporal cycles (Bullen, 2007).

The challenge for construction professionals would therefore seem to be between balancing empirical and environmental concerns that point towards longer building lifespans, and shortening retrofit cycles to meet new demands. This implies that new buildings need to be designed to allow for future functional changes and retrofitting, and that there is a need to examine the nature of changes that can be expected to occur in buildings over time (Slaughter, 2001). There is a need to develop specific design strategies that can increase the ability of buildings to accommodate change. This could be through the positioning of structural elements and the distribution of building services to allow change with minimal retrofitting, or through the design and detail of fixtures, finishes and lightweight claddings to ensure the easy dismantling and recycling of materials with shorter lifespans.

**Conclusions**

This research has shown that there is a significant correlation between building lifespan and the environmental impact from all primary building components, except windows and rooflights. Whilst the results reflect the Danish context, it can be argued that they are broadly applicable to other North European countries with similar constructional, environmental and climatic conditions.

**Construction professionals**

Construction professionals need to make well-argued decisions regarding building lifespan in the procurement process. The results show that if construction professionals use short building lifespans, then resource allocation to reduce environmental impact during procurement may become disproportionately focused on the construction contra operational phases of the lifecycle. Empirical data indicate that a building lifespan of about 100 years would be more realistic in Northern Europe, and the results also show that a longer lifespan also delivers a lower environmental impact.

**Policy implications**

The introduction of national sustainability tools typically occurs on the basis of widespread consensus and cooperation between public and private sector actors across the construction and property
sectors, as has happened in the Nordic countries (Birgisdottir et al., 2013). This means that there is a risk that environmental strategies stemming from the use of unreasonably short building lifespans may become widely adopted by the construction sector without question, since they are seen as part of the existing discourse. Policy-makers therefore need to take account of the institutional limitations that are created by the operational frameworks of such voluntary programmes, to ensure that resource allocation during procurement to reduce environmental impact does not become disproportionate to the actual impacts in the construction and operational phases of the lifecycle.

Further research

The results show that there is a variation in the reduction in environmental impact, depending on primary building component. With functionally layered building components, the lowest reductions in environmental impact are from those having the largest proportion of materials with a lifespan shorter than the building. Further research could therefore benefit from examining building components and their environmental impact in relation to their layering of structural elements with longer lifespans and claddings with shorter lifespans. This would allow for the optimization of building component design for long lifespans and reduced environmental impacts.

The statistical approach developed with this research has given interesting results. A clear area of research would be to further develop these methods for the statistical analysis of large amounts of LCA data for whole buildings based on building size and geometry. This would allow for the parametric analysis of built form, looking at ratios of external and internal building components in relation to floor area, and the choice of structural system, looking at concrete, timber and steel as primary construction materials.

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