LCA profiles for building components: strategies for the early design process

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Construction professionals are required to integrate environmental concerns in the earliest design phases. However, environmental assessments need large amounts of precise data that are typically not available in the early design process, as most variables are still fluid. To address this concern, a new approach explores how environmental information on building components can be simplified for strategic use early in the design process in a Danish context. In this paper, life cycle assessments (LCAs) are undertaken for several hundred typical external wall solutions, based on relevant standards. A full bivariate linear regression analysis is performed, showing statistically significant correlations with strong direct relationships between environmental impact categories. A simplified LCA profile consisting of total primary energy, global warming potential and acidification potential is developed. This simplified LCA profile presents environmental data in a more understandable way, creating a strategic overview that can be easily used by non-technical clients and construction professionals in the early design stages. This has a scientific and statistical validity generated by environmental assessment standards, and creates a parallel between the precision of the approach and its time of use in the design process.

Keywords: building envelope, design process, life cycle assessment (LCA), strategic analysis

Introduction

The design process can be characterized as a series of decisions over time that progress the design to a greater level of detail as uncertainty is progressively eliminated. Reflecting wider societal changes, construction professionals are now required to integrate environmental concerns in the earliest phases of the design process. This can give rise to a conflict because environmental assessments need large amounts of precise data that are typically not available in the early design process, since most variables are still fluid. Most energy and environmental calculation tools are used for technical specification and cannot be used in the early design stages.

The aim of this paper is to explore how complex environmental knowledge, stemming from performance-based standards and used in the environmental assessment of buildings, can be simplified for strategic use early in the design process. The research focus is the life cycle assessment (LCA) of building components in the Danish construction sector, and it is structured as follows:

- **Choice of building components**
  Based on multiple workshops with construction professionals, and reflecting contemporary construction practice, the choice of external wall solutions is explained, and the specification of typological variations detailed.

- **Choice of lifespan**
  Since the environmental impact of building components is impacted by the lifespan of both the building and the individual materials, the method for defining these is described.

- **Calculation method**
  A full LCA is carried out, based on the European Committee for Standardization (CEN) standards for the sustainability of construction works and the Danish implementation of the Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB) certification system for sustainable buildings.

- **Analysis of results**
  A full bivariate linear regression analysis carried out shows a statistically significant correlation
between the environmental impact categories. This is used to develop a simplified LCA profile, which can be easily understood by non-technical clients and construction professionals early in the design process.

A discussion of the results examines the appropriateness of the assessment method, and highlights the causality that may lie behind the shown correlation. The conclusions indicate that simplified design tools can have a scientific and statistical validity that creates parallelity between the precision of the approach and its time of use in the design process.

**LCA early in the design process**

In both the theoretical and the empirical literature, the design process in construction projects is characterized as a series of iterative decision processes over time, each of which progresses the design to a greater level of detail, so that uncertainty is progressively eliminated, as illustrated in Figure 1. Through the passage of time, the design matures from the initial conceptual stages, where many variables are fluid and the design team explores various strategic and parametric variations, through to project completion, where all uncertainty is removed in the finished building (Lawson, 2005; Mitchell, Frame, Coday, & Hoxley, 2011; Tunstall, 2006). This approach is used by construction professionals to codify the organization of the procurement process (Phillips & Lupton, 2000).

Reflecting wider societal changes, there has in recent years been a growing demand for the improved energy and environmental performance of buildings. This has been implemented through the broad development of performance-based standards (CEN, 2008, 2011a), the regulation of building construction (European Parliament and Council of the European Union, 2010) and the promotion of voluntary initiatives (DGNB, 2013). In Denmark, policy initiatives have been formulated to ensure the integration of 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 concerns in the earliest phases of the design process.

However, the assessment of energy and environmental performance in the early design stages can be problematic. A survey of common building performance simulation tools shows they were too complex and detailed for architects, providing excessive amounts of information without communicating the results visually, thus making dialogue with clients difficult (Weytjens, Attia, Verbeeck, & De Herde, 2011). A survey of 390 North American energy assessment solutions shows that 90% were evaluative tools aimed at engineers, and that only 1% was aimed at the early design stages (Attia, Gratia, De Herde, & Hensen, 2012). Studies of environmental assessment methods show assessment happens after design and specification is complete (Schlueter & Thesseling, 2009; Schweber & Haroglu, 2014). A design tool had been proposed (Donn, Selkowitz, & Bordass, 2012) for use at the early stages of design to enable designers to explore options and improve the design based on evidence from post-occupancy evaluations.

Integrating environmental concerns early in the design process can therefore give rise to a contradiction, since most design variables are fluid in the early design process and only few strategic parameters are fixed. In contrast, energy and environmental assessments demand large amounts of data and use complex calculation methods for technical specification and code compliance, and cannot be used in the early design stages (Gervásio, Santos, Martins, & de Silva, 2014).

**Research aim and design**

Since few parameters are fixed early in the design process, it can be argued that it is not possible to base simplified methods on the exact same data and precision that are used in complex calculation and specification tools. Instead, there should be parallelity between the precision of the approach and its time of use in the design process. The aim of this paper is therefore to explore how complex environmental knowledge, which is generated by performance-based
standards and used for environmental assessment, can be simplified for strategic use early in the design process by non-technical clients and construction professionals, as shown in Figure 2.

The subject of analysis is the LCA of building components. The aim is to explore how LCA data for building components can be made more accessible early in the design process within the context of the Danish construction sector.

Choice of an LCA framework
Many different sustainability assessment tools exist within the construction sector, such as Building Research Establishment Environmental Assessment Method (BREEAM) (Schweber & Haroglu, 2014), Building for Environmental and Economic Sustainability (BEES) (Suh & Lippiatt, 2012), Leadership in Energy and Environmental Design (LEED) (Al-Ghamdi & Bilec, 2015), and DGNB (König & De Cristofaro, 2012). Two broad approaches can be identified in environmental assessments, reflecting whether mid- or endpoint LCA methodologies are used (Chau, Leung, & Ng, 2015; Dong & Ng, 2014; Lewandowska, Noskowski, Pajchrowski, & Zarebska, 2015).

Endpoint methodologies use normalization and weighting to give endpoint environmental damage categories that can be directly compared and aggregated, such as in the BREEAM tool. However, methodological issues can introduce greater levels of uncertainty and inaccuracy, and the results may be difficult to understand for construction professionals (Dong & Ng, 2014). Whilst the first Danish LCA methodologies used this approach (Wenzel, Hauschild, & Rasmussen, 1996), the first Danish assessment method for buildings used normalization, but not weighting, because of data uncertainty (Dinesen & Hansen, 1999).

Midpoint methodologies use midpoint impact category indicators, such as total primary energy and acidification potential. These are benchmarked in the interpretation phase of the LCA by comparing the results with midpoint LCA benchmarks per functional unit for typical buildings to show a percentage improvement, such as in the DGNB tool. Although the individual impact category indicators cannot be directly compared, they are better understood by construction professionals, and extensive literature reviews show this is the dominant LCA approach within the construction sector (Ortiz, Castells, & Sonnemann, 2009; Sharma, Saxena, Sethi, Shree, & Varun, 2011).

The Danish construction sector 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 (CEN, 2011a, 2011b), and it uses benchmarked midpoint LCA indicators (König & De Cristofaro, 2012). This framework informs the basis for this research.

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 multiple workshops with construction professionals representing Denmark’s major consulting architects and engineers.

External wall typologies
Modern building components are typically functionally layered to give a rational construction process and better performance quality during the construction process and building lifespan (Lstiburek, 2007). This gives a multiplicity of solutions, where external walls can be divided into three layered typologies based on variations in the choice of materials for the load-bearing construction and cladding material. This research is based on these three typologies, as shown in Table 1.

These typologies can be built with a multitude of combinations for all layers. In Denmark, the vast majority of new buildings are between one and five storeys in

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**Figure 2** Simplified life cycle assessment (LCA) guidance is needed early in the design process, as most design variables are still fluid.
height and use load-bearing external walls. 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 each of the three typologies. Each typology is also specified on the basis of three different $U$-values, representing the levels used in the current and expected future building regulations. These variations can therefore be seen as functionally equivalent as load-bearing elements with differing aesthetic appearances and levels of insulation, and covering a variety of in-situ and prefabricated constructional solutions. As such, they reflect the diversity of factors that construction professionals may need to address early in the design process. The variations for each layer of the three typologies are summarized in Tables 2–4. Full versions are shown in Tables A1–A3 in Appendix A in the supplemental data online.

For each material an inventory is prepared, describing the resource consumption required for a functional unit of 1 m$^2$ of the building component. All materials are covered, including fixings and finishes. On the basis of the three typologies with differing layer variations and $U$-values, it is possible to generate 432 parametric variations. An example of the resource consumption for one of the variations is shown in Table 5.

### Choice of lifespan

It is important to distinguish between the lifespan of the building in which the building components are used and the lifespan of the materials used in the building component. The lifespan of a building reflects whether it still fulfils the many functions for which it was established. For an entire building, the lifespan of the materials that are irreplaceable, usually the load-bearing structure, will equal the building’s lifespan. This then necessitates the periodic renovation of the materials with shorter lifespans, typically lightweight or cladding materials (Brown et al., 2011). This gives rise to buildings with the functionally layered constructive approach (Listiburek, 2007), where materials with a shorter lifespan can be replaced without needing to remove those with a longer lifespan.

### Lifespan of a building

The lifespan of a building can have an effect on the environmental impact from the construction materials (Grant, Ries, & Kibert, 2014). It is the lifespan of the building that becomes the determining factor when it is less than the lifespan of a material. 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 the lifespan of the material, in comparison with when the

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**Table 1** Functional layering of the external wall typologies found in contemporary Danish design and construction practice, which are covered by this research

| Typology | Schematic | Internal layer | Insulating layer | External layer |
|----------|-----------|----------------|------------------|---------------|
| 1        | ![Schematic 1](image1) | Heavyweight load-bearing | Insulation and ties | Heavyweight cladding |
| 2        | ![Schematic 2](image2) | Heavyweight load-bearing | Insulation and framing | Lightweight cladding |
| 3        | ![Schematic 3](image3) | Lightweight cladding | Load-bearing framing and insulation | Lightweight cladding |

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**Table 2** Variations for external wall typology 1 with internal heavyweight load-bearing layer, insulation and external heavyweight cladding

| Layers and number of variations (total = 12) | Description |
|--------------------------------------------|-------------|
| Internal layer: | Brickwork |
| heavyweight load-bearing: four variations | Lightweight concrete blocks |
| Insulating layer: | Reinforced lightweight concrete |
| insulation and ties: three variations ($U$-values = 0.15, 0.12 and 0.09 W/m$^2$ K) | Reinforced concrete |
| External layer: | Mineral wool insulation with ties |
| heavyweight cladding: one variation | Brickwork |
The lifespan of the building is the same as the lifespan of the material. This will usually be the case for the load-bearing materials in a building.

In contrast, it is the lifespan of the material that becomes the determining factor when it is less than the lifespan of the building. 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 less than the lifespan of the building, also for buildings with different lifespans. The environmental impact is determined by the material's average lifespan at a decimalized annual replacement rate, and is usually applicable for claddings, windows, etc.

It is therefore necessary to define the lifespan of the building in which the construction component will be used. Traditionally, a lifespan of between 35 and 60 years has been used to calculate a building’s life cycle cost, based on the depreciation of construction investments (Aagaard, Brandt, Aggerholm, & Haugbølle, 2013). However, factual data regarding current building lifespans, coupled with annual rates of new construction, renovation and demolition, indicate that an average lifespan of 100 years or more would be more accurate, reflecting changing social, technical and economic factors in a wider European context (Aagaard et al., 2013; Brown et al., 2011).

A statistical analysis of the Danish building mass shows that different building types have differing average lifespans (Aagaard et al., 2013), with housing having a longer lifespan of 120 years, and buildings for commerce and production having a shorter lifespan of 80 years. This research is based on housing, which is the dominant building type for new construction in Denmark, representing approximately

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**Table 3** Variations for external wall typology 2 with internal heavyweight load-bearing layer, framing/insulation and external lightweight cladding

| Layers and number of variations (total = 336) | Description                                                                 |
|---------------------------------------------|-----------------------------------------------------------------------------|
| Internal layer:                             | Brickwork                                                                   |
| heavyweight load-bearing: four variations   | Lightweight concrete blocks                                                 |
|                                             | Reinforced lightweight concrete                                             |
|                                             | Reinforced concrete                                                         |
| Insulating layer:                           | Mineral wool with steel framing                                             |
| insulation and framing: 12 variations       | Cellulose insulation with steel framing                                     |
| (U-values = 0.15, 0.12 and 0.09 W/m² K)     | Mineral wool insulation timber framing                                      |
|                                             | Cellulose insulation with timber framing                                    |
| External layer:                             | Pine timber cladding                                                        |
| lightweight cladding: seven variations      | Larch timber cladding                                                       |
|                                             | Fibre cement panel                                                          |
|                                             | Natural stone cladding                                                      |
|                                             | Clay tile panel                                                             |
|                                             | Aluminium sheet                                                             |
|                                             | Zinc sheet                                                                  |

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**Table 4** Variations for external wall typology 3 with internal lightweight cladding, load-bearing framing/insulation and external lightweight cladding

| Layers and number of variations (total = 84) | Description                                                                 |
|---------------------------------------------|-----------------------------------------------------------------------------|
| Internal layer:                             | Plasterboard                                                                |
| lightweight cladding: one variation         |                                                                            |
| Insulating layer:                           | Steel framing with mineral wool                                             |
| insulation and framing: 12 variations       | Steel framing with cellulose insulation                                      |
| (U-values = 0.15, 0.12 and 0.09 W/m² K)     | Timber framing with mineral wool                                            |
|                                             | Timber framing with cellulose insulation                                     |
| External layer:                             | Pine timber cladding                                                        |
| lightweight cladding: seven variations      | Larch timber cladding                                                       |
|                                             | Fibre cement panel                                                          |
|                                             | Natural stone cladding                                                      |
|                                             | Clay tile panel                                                             |
|                                             | Aluminium sheet                                                             |
|                                             | Zinc sheet                                                                  |
35% of the total completed floor area over the last 10 years (Statistics Denmark, 2014).

**Lifespan of the materials**

For each material used in a building component, it is necessary to assign a lifespan, which can be determined by varying technical, economic, functional and design factors (Grant et al., 2014). The same material can be used in functionally different layers, where timber cladding will have a shorter lifespan than load-bearing timber framing. For functionally layered building components, the materials with the longest lifespans are typically the load-bearing layers, whilst the surface finishes and claddings have the shortest lifespans.

The average lifespan of each material in every layer is determined by using the lifespan tables for construction materials based on the functional layering of contemporary building components, as developed by Aagaard et al. (2013) as part of the Danish Energy Agency’s policy initiative for sustainable construction. These tables are based on national data, and draw from relevant theoretical research and North European empirical experiences. The range of lifespans contained in the tables is between 10 and 120 years. An example of the lifespan data for one of the external wall variations is shown in Table 5.

**Calculation method**

For the functional unit of 1 m² of each of the 432 parametric variations of the external wall typologies, an LCA is carried out. The calculation tool DK LCA-Calc is used. This was developed for the Danish implementation of the DGNB system.

**LCA methodology**

The DK LCA-Calc tool draws LCA inventories for materials from the ESUCO and Ökobau databases, as used in the DGNB system (Birgisdottir et al., 2013; DK-GBC, 2012). These databases use the CML 2002 life cycle impact assessment methodology, using a problem-oriented approach 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 carried out in the LCA.

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 (CEN, 2011b). However, there are valid arguments as to why product-specific EPDs cannot be used, and why the use of generic
European data is an accepted alternative. Firstly, whilst a growing number of materials produced by international businesses are covered by EPDs, very few are currently available for specific Danish construction materials, especially the great number of generic materials such as fixtures, fittings, membranes or gravel. Secondly, there are issues related to contractual and public procurement policies within the European Union, which often mean that buildings are constructed from different materials than 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 data in a national context has a methodological validity and relevance (Silvestre, Lasvaux, Hodková, de Brito, & Pinheiro, 2015). Therefore, since few parameters are fixed early in the design process and the precise specification of all materials may not possible, then the use of generic data can be seen as acceptable, thus creating parallelity between the precision of the approach and its time of use in the design process.

Both the ESUCO and Ökobau databases contain specific and generic data, which are 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. As such, the choices of construction materials made by this research, together with their attendant environmental data and levels of uncertainty, are identical to those being made by Danish construction professionals when working to meet DGNB requirements.

### System boundaries

The stages included in a building’s LCA, and which are used to set the system boundaries, are defined by the CEN standard for the sustainability of construction works EN 15978 (CEN, 2011b). At present not all these processes are included in the DGNB system (DK-GBC, 2012), such as the construction/installation process, and some are also not relevant for the scope of this research, such as the building’s operational energy use, as shown in Table 6.

The LCA is carried out for the functional unit of 1 m² of external wall. All materials are included for the

| Building life cycle stages defined by CEN standards | Included in the DGNB system | Included in this research |
|-----------------------------------------------|----------------------------|--------------------------|
| Life cycle stages                              | Processes                  |                          |
| Product                                        | Raw materials supply       | Yes                      | Yes                      |
|                                               | Transport                  | Yes                      | Yes                      |
|                                               | Manufacturing              | Yes                      | Yes                      |
| Construction process                           | Transport                  | No                       | No                       |
|                                               | Construction/installation  | No                       | No                       |
| Use                                            | Use                        | Yes                      | No                       |
|                                               | Maintenance                | No                       | No                       |
|                                               | Repair                     | No                       | No                       |
|                                               | Replacement                | Yes                      | Yes                      |
|                                               | Refurbishment              | No                       | No                       |
|                                               | Operational energy use     | Yes                      | No                       |
|                                               | Operational water use      | No                       | No                       |
| End of life                                    | Deconstruction/demolition  | No                       | No                       |
|                                               | Transport                  | No                       | No                       |
|                                               | Waste processing           | Yes                      | Yes                      |
|                                               | Disposal                   | Yes                      | Yes                      |
| Next product system                            | Reuse/recovery/recycling potential | Yes                      | Yes                      |

Sources: European Committee for Standardization (EN) (2011b); DK-GBC (2012)
whole lifespan of the building, both the originally installed materials and the materials replaced due to having a lifespan shorter than the building’s. This replacement is determined by using the material’s average lifespan at a decimalized annual replacement rate using data from Aagaard et al. (2013), as described above. This ensures a consistent methodology is applied to all external wall typologies to deal with uncertainty regarding the lifespan of materials in the operational life cycle stage. This then allows for the calculation of all environmental impacts from production, use and end of life.

Environmental impacts
The CEN standard for the sustainability of construction works EN 15978 (CEN, 2011b) describes the categories for potential environmental impacts and resource consumption that have been scientifically validated. Eight of these are used in the DGNB system and in this research, as shown in Table 7. All energy consumption categories are calculated as megajoules (MJ). They are then converted to kilowatt-hours (kWh) to aid understanding among construction professionals, since this is the unit used to calculate primary energy consumption in the Danish Building Regulations (Hansen et al., 2012).

Using this approach, the eight categories for environmental impacts and resource consumption are calculated on the basis of the production, use and end of life of the various construction materials used in each external wall variation, drawing data from the LCA inventories of the ESUCO and Ökobau databases. As shown in Table 6, the operational energy of the building is not included. All results are calculated for the functional unit of 1 m² of each external wall variation on an annualized basis to create an annualized LCA profile consisting of eight midpoint impact category indicators.

Analysis of the results
Typical LCA results for a functional unit of 1 m² of three external wall variations with a U-value of 0.15 W/m²K are shown in Table 8. It should be noted that the different categories of environmental impact cannot be compared. As is typical for such tools, DK LCA-Calc produces extensive quantitative results in a scientific notation with a precision of three significant figures. The figures for global warming potential are also of different orders of magnitude, making a quick comparison to determine the best environmental profile difficult for non-technical clients and construction professionals.

Presenting eight environmental data in this way can be seen as problematic, since this complexity and detail does not fit with the fluid nature at the early design stages. To simplify the decision-making process, a first step would be to present the results graphically so that non-technical clients and construction professionals can picture the results (Weytjens et al., 2011). This

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Table 7  Environmental impact and resource consumption categories defined by the CEN standard for the sustainability of construction works EN 15978 and included in the DGNB system and this research

| Impact type                | Category                             | Unit/year          | Included in the DGNB system |
|----------------------------|--------------------------------------|--------------------|-----------------------------|
| Environmental impact       | Global warming potential             | kg CO₂-equivalent  | Yes                         |
|                            | Ozone depletion potential            | kg R11-equivalent  | Yes                         |
|                            | Photochemical ozone creation potential| kg ethene-equivalent| Yes                         |
|                            | Acidification potential              | kg SO₂-equivalent  | Yes                         |
|                            | Eutrophication potential             | kg PO₄-equivalent  | Yes                         |
| Abiotic depletion potential|                                      | kg Sb-equivalent   | No                          |
| Resource consumption       | Non-renewable primary energy         | MJ                 | Yes, but converted to kWh and shown as: Total primary energy (non-renewable + renewable + secondary) |
|                            | Renewable primary energy             | MJ                 | Non-renewable primary energy |
|                            | Secondary energy                     | MJ                 | Ratio of renewable energy to total primary energy |

Sources: European Committee for Standardization (CEN) (2011b); DK-GBC (2012)
can be seen in Figure 3, which presents the same data as Table 8. The individual results for each impact category are now easier to compare with each other, but it is difficult to deduce which building component performs best in relation to all eight categories at the same time. Whilst the total primary energy is approximately the same for the three building components, there seems to be an inverse relationship between the global warming potential and the ratio of renewable to total primary energy, where a fall in one reflects a rise in the other. There also seems to be a positive relationship between several of the other categories, where a rise in acidification potential reflects a rise in non-renewable energy. This would indicate that there could be a relationship between the different impact categories for the 432 external wall variations. If this correlation could be demonstrated statistically, then the number of result categories could be reduced to create a simplified environmental profile.

### Statistical analysis

Within the LCA field, the limited research using statistical analysis has shown 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 analysis data to simplify decision-making in the early design stages (Asadi, Amiri, & Mottahedi, 2014; Valovcin, Hering, Polly, & Heaney, 2014), whilst the application of heuristic optimization algorithms to sustainable building design problems have also gained considerable interest (Evins, 2013). These examples show that simplified approaches based on statistical and parametric data can have a scientific validity that makes them relevant for use early in the design process.

Four sets of full bivariate linear regression analysis have been carried out on the results from the LCA calculation, one for each of the three sets of external wall typologies based on $U$-values, with 144 variations in each, and one for the total number of 432 variations. Each of the parametric variations produces datasets for the eight impact categories. These eight datasets have been individually plotted against each other, as illustrated in Figure 4, which shows non-renewable primary energy consumption plotted against global warming potential for the three $U$-value variations.

Each dataset was analysed for skew and kurtosis in the distribution of values. A comparison of the skew,
Results from the life cycle analysis presented graphically for a functional unit of 1 m² of three external wall typology variations.
kurtosis and their respective standard errors showed that the datasets’ distribution did not significantly differ from a normal population distribution. Therefore, only the datasets for the acidification and eutrophication potentials, which had a skewness of greater than 1.0 or less than –1.0, were log-transformed to account for their skewed distributions (Miles & Shelvin, 2001).

A one-way analysis of covariance (ANCOVA) was carried out on the results of the linear regression. For the relationships between all pairs of datasets for the impact categories, controlling for the U-value of the external wall typologies was determined as not being statistically significant, F(2, 428) < 0.43, p > 0.65, thus accepting the null hypotheses. The U-value appears to have no effect on these relationships because the extra materials used have a very small effect on the individual wall’s impact categories, with average increases of less than 4%. This supports other experiences in the Nordic context, where improved levels of insulation give a very small increase in embodied energy, but deliver large reductions in operational energy over the building’s lifetime (Dodoo, Gustavsson, & Sathre, 2011; Wallhagen, Glaumann, & Malmqvist, 2011). Since the U-value is shown to have no statistically significant effect on the relationships between all impact categories, this research is based on the regression analysis of all external wall typologies, with a total number of 432 variations.

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. The regression equations were optimized using a linear least-squares fit to find appropriate values of the slope and intercept. For each pair of datasets there are 430 degrees of freedom, and for all pairs the correlation coefficient was determined as being statistically significant with a probability value of less than 0.05, thus rejecting the null hypothesis. The results can be used to create a matrix, which plots all eight datasets against each other, as shown in Figure 5 for the correlation coefficient and in Figure 6 for the coefficient of determination.

In Figure 5, the correlation coefficient, $r$, can vary numerically between an absolute value of 0.0 and 1.0, and have a positive or a negative value. The closer the absolute value is to 1.0, the stronger the relationship between the two variables, whilst a correlation of 0.0 indicates the absence of a relationship. A positive coefficient means that the variables move in the same direction, whilst a negative coefficient means that the variables move in opposite directions. The majority of datasets show a positive correlation, the only exception being the ratio of renewable to total primary energy, which shows a negative correlation.

In Figure 6, 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. If the coefficient of determination is 0.75, this means that 75% of the variance in the results can be explained by the linear relationship between the two variables. Mathematically the coefficient of determination is the square of the correlation coefficient.

**Simplified LCA profile**

Since the correlations have been shown to be statistically significant, it should be possible to select a reduced set of environmental impact categories that have a significantly large correlation in relation to the other categories, thus creating a simplified LCA profile.

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. 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 (Sheskin, 2007). Using a
threshold of 0.71 for the absolute value of the correlation coefficient gives a coefficient of determination equal to or greater than 0.50, indicating that more than 50% of the variance in the results can be explained by the linear relationship between the variables.

As argued previously, there should be parallelity between the precision of design tools and their time of use in the design process. It can therefore be argued that it is appropriate to base simplified LCA profiles on statistically significant correlations that have a strong direct relationship, where more than 50% of the variation in the results can be predicted by the relationship between the variables. On this basis, the results can be presented showing the pairs of datasets where the absolute value of the correlation coefficient is equal to or greater than 0.71 and the coefficient of determination is equal to or greater than 0.50 (Figure 7).

The results show that a minimum of three categories need to be selected to ensure the strong correlations cover all eight categories. The following are therefore proposed as the basis for the simplified LCA profile:

- **Total primary energy**
  This category has no strong positive correlation with other categories, so it needs to be included. Total primary energy is an important parameter used for defining operational energy consumption in the Danish Building Regulations (Hansen et al., 2012).

- **Global warming potential**
  This category has a strong positive correlation with acidification potential and non-renewable primary energy, together with a strong negative correlation with the ratio of renewable to total primary energy. Global warming potential is an important parameter that is broadly referenced in literature on building LCA (Sharma et al., 2011).

- **Acidification potential**
  This category has a strong positive correlation with all categories except total primary energy and the ratio of renewable to total primary energy.

The selected linear regression equations are shown in Table A4 in Appendix A in the supplemental data online. It should be noted that the correlations show that whilst the environmental categories move in the same positive or negative direction, the variation in the relative intensity across the shown correlations may not be the same.

With these results, a graphical presentation of the simplified LCA profile has been developed, based on holding multiple workshops with construction professionals representing Denmark’s major consulting architects and engineers. This is shown in Figure 8, which presents the three building components previously shown in Table 8 and Figure 3. For a functional unit of 1 m² of each external wall construction, the profile is based on

![Figure 5 Matrix with graded thresholds for the value and sign of the correlation coefficient for the eight categories for environmental impact and resource consumption for a functional unit of 1 m² of the external wall typologies](image-url)
using the area of a circle to represent the calculated value for total primary energy consumption, global warming potential and acidification potential. The maximum circle area is defined by the graphical layout and is then used to represent the maximum environmental impact for each category, which is defined by the largest value among the 432 variations that have been analysed. In the centre of each circle the numerical value of the environmental impact is also given. Since the three environmental categories cannot be compared with each other, each category is represented with a different colour (but shown as grey tones in Figure 8).

For each external wall construction, the three environmental categories are placed horizontally in relation to each other. The different external wall constructions are then placed vertically above each other in a publication, structured around the typological categories presented previously. It is then possible vertically to compare the same environmental category from different external wall constructions.

Comparing Table 8, Figure 3 and Figure 8, it can be seen that these three broadly communicate the same environmental data. However, the simplified LCA profile does it in a more easily understandable way, creating a strategic overview that can be easily understood by non-technical clients and construction professionals early in the design process.

**Discussion**

The results show that it is possible to develop a simplified LCA profile for use early in the design process that has a scientific and statistical validity stemming from performance-based environmental assessment standards. This gives rise to a series of discussion points.

**Is the assessment method appropriate?**

The appropriateness of the simplified LCA profile can be assessed in relation to the existing methodologies outlined above. Endpoint methodologies use normalization and weighting to give environmental damage categories that can be aggregated. However, they can be difficult for construction professionals to understand and they have historically not been recommended or used within the Danish construction sector. Since the DGNB system does not utilize endpoint methodologies, then the development of simplified endpoint tools would not find uptake amongst construction professionals within the Danish context, and would thus not be appropriate.

Midpoint methodologies use midpoint impact category indicators, which are then be compared with midpoint benchmarks per functional unit to show a percentage improvement. The DGNB system follows this approach, with specific impact categories being better understood by construction professionals, and midpoint methodologies dominating LCA research in the...
### Figure 7

Matrix showing correlation coefficients where a strong direct relationship exists ($r > = \pm 0.70$) and coefficient of determinations where more than 50% of the variance can be explained by the relationship between the variables ($R^2 \geq 0.50$) for the eight categories for environmental impact and resource consumption for a functional unit of 1 m$^2$ of the external wall typologies.

|                          | Global Warming Potential | Ozone Depletion Potential | Photochemical Oxidation Potential | Acidification Potential | Eutrophication Potential | Total Primary Energy | Non-Renewable Primary Energy | Ratio Renewable to Total Primary Energy |
|--------------------------|--------------------------|---------------------------|-----------------------------------|-------------------------|-------------------------|----------------------|-------------------------------|------------------------------------------|
| **Coefficient of determination R$^2$** |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Global Warming Potential |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Ozone Depletion Potential |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Photochemical Oxidation Potential |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Acidification Potential |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Eutrophication Potential |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Total Primary Energy     |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Non-Renewable Primary Energy |                          |                           |                                   |                         |                         |                     |                              |                                          |
| Ratio Renewable to Total Primary Energy |                          |                           |                                   |                         |                         |                     |                              |                                          |

Values of $r$:
- $\geq 0.00$ to $\leq 0.71$
- $>0.71$ to $\leq 1.00$
- $<0.71$ to $>1.00$

Values of $R^2$:
- $\geq 0.00$ to $\leq 0.50$
- $>0.50$ to $\leq 1.00$
- $>0.50$ to $\leq 1.00$

### Figure 8

Simplified LCA profile for a functional unit of 1 m$^2$ of three external wall typology variations:

**Concrete Insulation**
- **Brickwork**
  - 200 mm steel reinforced concrete with paint finish
  - 250 mm mineral wool insulation with stainless steel ties
  - 108 mm brickwork with mortar
  - $U = 0.15$ W/m$^2$ K
  - 3.5

**Lightweight concrete Insulation & framing**
- **Aluminium**
  - 100 mm lightweight concrete blocks with render/paint finish
  - 275 mm cellulose insulation with l-post timber framing
  - 8 mm fibre cement sheet
  - Galvanized steel profiles
  - 1.5 mm aluminium sheet
  - 3.1

**Plasterboard Framing & insulation**
- **Timber**
  - 25 mm plasterboard with paint finish
  - 45 mm galvanized steel framing with mineral wool insulation
  - Polystyrene vapour barrier
  - 200 mm C-post galvanized steel framing with mineral wool
  - 8 mm fibre cement sheet
  - Timber battens
  - 25 mm pine timber cladding
  - LCA Categories:
    - **Total primary energy**: $\text{KWh/m}^2$ year
    - **Global warming**: $\text{kg CO}_2$/m$^2$ year
    - **Acidification**: $\text{g SO}_2$/m$^2$ år
  - 3.6

- 0.7

- 2.7
construction sector. However, midpoint methodologies can create extra data complexity that does not fit well with the fluid nature of the early design process.

The simplified LCA profile therefore provides an improvement to midpoint approaches by reflecting the needs of construction professionals early in the design process, whilst both following the DGNB approach and further developing current research tendencies within the construction sector. The choices of construction materials, together with their attendant environmental data and levels of uncertainty, are identical to those being made by Danish construction professionals when working to meet DGNB requirements. The three selected impact categories are correctly calculated in relation to LCA methodology, and have highly significant statistical correlations with the five remaining impact categories, where it has been argued there is causality stemming from fossil fuel consumption. It can therefore be argued that the simplified LCA profile has a methodological and statistical validity when benchmarking environmental performance in the early design stages, thus creating parallelity between the precision of the approach and its time of use in the design process.

Is there causality behind the correlation?
The results show a statistically significant correlation between the selected impact categories, and this raises the question as to whether there is causality. It is generally accepted that the size of the impact across many categories stems from the use of fossil fuels used during the production life cycle stage (Gustavsson & Sathre, 2006), thus indicating the causality that lies behind the correlation. However, there are exceptions to this rule, with cement- and plaster-based materials having a relatively high global warming potential because of calcination (Flower & Sanjayan, 2007), and metals having a relatively high acidification potential from metallurgical processing (Norgate, Jahnshahi, & Rankin, 2007). Both these examples show that specific production processes can result in specific categories with a larger impact.

However, building components typically consist of many different materials, as shown in Tables 2–5, and each has its own environmental profile. When they are combined together in a building component, there is no one dominant material, and instead there is a balancing out of the total result. Whilst all the lightweight wall elements do not contain concrete, they do contain plasterboard with a relatively shorter lifespan. Similarly, whilst there are some wall elements with a very high timber content, they also contain various fixtures and fittings made of galvanized steel. The potential positive or negative environmental qualities of specific materials are thus being neutralized by the totality of the building component, and thus ensuring that the causality from fossil fuel consumption remains.

How can the results be used?
The simplified LCA profiles are intended for publication, both printed and digital. The results can be used at the early design stages to define typical building components and their attendant environmental impact, which can then be used as a benchmark to identify building components with the same U-value and functional requirements, but with an improved environmental performance. It would also be expected that design professionals would carry out more extensive and precise environmental assessments later in the design process.

A major area of interest in building LCA is the relationship between the environmental impact in the production and operational phases (Sharma et al., 2011). Whilst the operational phase is usually the dominant factor, it is also clear that production begins to play a major role in buildings with a very low primary energy consumption in the operational phase (Dodoo et al., 2011; Wallhagen et al., 2011). It is therefore important that construction professionals are able to identify building components early in the design process that give a low environmental impact in the production and operational phases. The simplified LCA profile is able to support this approach, since it is possible to identify solutions that have a lower U-value and a lower environmental impact than typical solutions.

The database that has been developed in producing the simplified LCA profile could in future be used in the development of building information modelling (BIM) and computer-aided design (CAD) tools, such that the digital specification of building components could be used to pull data from the database, allowing for the calculation of the environmental impact for whole buildings. This would help in calculating the total environmental impact from the production and operational phases of a building.

Limitations
As with all statistical approaches, there is a level of uncertainty that has been minimized, but which needs to be kept in mind. The correlations show that the environmental categories move in the same direction, but that the variation in the relative intensity between the shown correlations may not be the same. As such, the correlations cannot be used to calculate the size of the correlated environmental impact categories. The simplified LCA profile aims to support decision-making early in the design process, with more extensive and precise calculations needing to be carried out at the appropriate later stages. In professional contexts that traditionally have experience
using endpoint environmental methodologies, the use of simplified LCA profiles based on midpoint methods would also have limited relevance.

Conclusions

The aim of this research has been to explore how information on the LCA of building components can be made more accessible to construction professionals early in the design process within the context of the Danish construction sector. The simplified LCA profile can make environmental data more understandable for non-technical clients and construction professionals early in the design process, and has a scientific and statistical validity generated by performance-based environmental assessment standards.

Further research

The results were based on the LCA of external wall solutions for housing with a lifespan of 120 years. There is a need to expand the research to other primary external and internal building components. Since other building components, such as roof and floor decks, have considerable structural requirements because of the spans they need to cover, it could mean that no statistical significance would be seen in the analysis, or that other impact categories would have to be used in a simplified profile.

There is also a need to replicate the research in relation to building types with shorter lifespans than housing. It would be reasonable to assume that an identical analysis based on shorter building lifespans would produce broadly similar conclusions, but with the results being proportionally higher because of the shorter lifespan in relation to 120 years.

The development of statistical analysis methods to calculate simplified LCA results for whole buildings, based on the methods presented in this article, would also seem to be an area of considerable research interest. This would allow construction professionals to make LCA estimates for whole buildings based on limited design parameters early in the design process.

Construction professionals

For construction professionals, the results show that it is possible to develop simplified design tools with parallelity between the precision of the approach and its time of use in the design process. Experiences from this research project have shown that involving construction professionals from major consulting architects and engineers in multiple workshops has considerable advantages. This can be contrasted with the previously mentioned surveys of traditional energy and environmental calculation tools, which showed that the majority were developed in engineering research environments without the involvement of other end-users. There is a great need for non-technical clients and construction professionals to become more actively involved in the research and development of environmental assessment tools, to ensure that the results are tailored to the sectors needs in the early design process.

Policy implications

With LCA methods within the construction sector now well codified within the framework of the relevant CEN standards, and with LCA methods being implemented in practice through systems such as DGNB, it would seem relevant to explore how the LCA of buildings could be integrated into national building regulations. This could happen in a manner similar to how building component U-values and operational energy consumption targets are regulated, by setting minimum environmental impact targets for building components at specific U-values and for whole buildings. In this way, environmental assessment would move from being an isolated, voluntary activity that happens after a building is designed, to being a fixed performance-based target that is known in advance and has to be met during the design process.

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Supplemental data

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