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# Rethinking life cycle cost drivers for sustainable office buildings in Denmark

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## Abstract

**Purpose** – Sustainable building design suffers from a lack of reliable life cycle data. The purpose of this paper is to compare life cycle costs of sustainable building projects, examine the magnitude of various cost drivers and discuss the implications of an emerging shift in cost drivers.

**Design/methodology/approach** – This paper is based on data from 21 office buildings certified in Denmark according to the sustainable certification scheme DGNB.

**Findings** – The paper supports previous findings that construction costs and running costs each roughly make up half of the life cycle costs over a 50-year period. More surprising is the finding that the life cycle costs for cleaning are approximately twice as high as the supply costs for energy and water.

**Research limitations/implications** – The data set is based on actual construction costs of office buildings constructed in 2013-2017. Although all running costs are calculated rather than measured, they are based on a more detailed, specific and industry-supported set of calculation assumptions than is usual for life cycle costing studies because of extensive collaborative work in a number of concomitant national research and development projects.

**Practical implications** – Authorities, clients and building professionals heavily emphasise energy-saving measures in new Danish buildings. The paper suggests redirecting this effort towards other more prominent cost drivers like cleaning and technical installations.

**Originality/value** – This paper provides a notable contribution to the academic understanding of the significance of different cost drivers as well as the practical implementation of life cycle costing.

**Keywords** Procurement, Economics, Sustainable buildings

**Paper type** Research paper



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This paper is based on a conference paper presented at the International Research Week 2017 at the University of Salford, September 2017. By subsequent invitation to this special issue of the journal, the conference paper has been rewritten and extended, several new references have been added and the number of empirical cases has been doubled.

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## Introduction

As pointed out by Cole and Sterner (2000), the limited direct use of life cycle costing (LCC) in green building design is related mainly to constraints in data accuracy and in current design practices. Despite the huge promise of building information modelling (BIM), the data problem of LCC continues to be a challenge. While the use of BIM design tools promises to automate quantity take-offs, the real-world problems of establishing robust and reliable models without flaws in the quantities persist. Further, other problems exist in relation to ensuring interoperability between software producing three-dimensional (3D) models containing quantities, price-calculations software containing unit prices and LCC tools containing discount rates, price development indexes, lifetimes, etc. (Lee *et al.*, 2014; Monteiro and Martins, 2013). Consequently, the "Garbage In Garbage Out" problem continues to challenge researchers, practitioners and policy-makers.

In a Royal Academy of Engineering paper from 1998, Evans *et al.* (2004) coined a distribution ratio of 1:5:200 between construction costs, maintenance and building operating costs and business operating costs. This seminal paper did not offer empirical evidence to support this ratio, and it has not been possible to reproduce this ratio, as pointed out by Hughes *et al.* (2004). Still, this ratio has travelled long and far, including through Constructing Excellence in the UK and the Danish Association of Construction Clients, though with slightly lower figures.

LCC has a long history in Denmark. A strong emphasis has been on energy savings as the main driver of life cycle costs. Indeed, the very first publication from the Danish Building Research Institute (SBi) in 1949 was on the economic optimisation of insulation (Becher, 1949). A number of publications on other topics relating to LCC has since followed. These include studies on insulation of pipes (Becher and Engelsen, 1957), an SBi Guideline on the economic assessment of energy-saving measures (Johnsen and Andersen, 1982) and evaluation of ten demonstration projects on LCC (Haugbølle and Henriksen, 2002). Especially the oil crises in the 1970s sparked off a strong focus on energy savings in the built environment through consecutive energy policies, support schemes etc. This emphasis on energy savings is also prevalent in the Danish Building Regulations, for example, the requirement to make profitability analyses of energy savings over a 30-year period with regard to windows, insulation, etc., when refurbishing an existing building. While this focus on energy savings is understandable from an environmental perspective (Birgisdóttir *et al.*, 2017 and Rasmussen *et al.*, 2018), newly constructed buildings in Denmark have a very low energy consumption rendering energy costs less pronounced. Hence, a shift in focus may be needed.

Recently, the national building research institute released tables of service life times (Aagaard *et al.*, 2013) and the national calculation tool LCCbyg (Haugbølle *et al.*, 2016). A wide range of initiatives, etc., has been launched during the past 20 years or more to support the uptake and dissemination of LCC in Danish construction. These include:

- publication of manuals and guidelines for designers and managers;
- development of calculation tools;
- publication of reference books about service life times and depreciation tables for cooperative-housing as well as insurance companies;
- national standards for overall financial calculations, operating principles and calculation of economic indicators;
- establishment of databases with key figures for the construction and operation of public housing, facility management benchmarking especially for office buildings; and
- evaluations and compilations of lessons learned, nationally as well as internationally.

For many years, calculating LCC has been mandatory in both social housing projects and governmental building projects, but the approaches have been quite different. While the social housing sector has developed and applied a consecutive set of sector-specific tools since 1998, the government building agency was strongly criticised in 2013 by the Danish National Audit Office and the Danish Public Accounts Committee for effectively neglecting its obligations to apply and disseminate knowledge on LCC. Since then, the government building agency has taken the lead on LCC in public building projects.

Another new strong driver of LCC in Denmark is the recent establishment of the DGNB certification scheme for sustainable buildings and urban areas. In the late 2000s, the construction industry started pushing for a certification scheme for buildings. This led to a thorough investigation of four major certification schemes, namely BREEAM, LEED, DGNB and HQE, and a test of each of these on two office buildings (Birgisdóttir *et al.*, 2010). Following this work, a joint committee of policy-makers, business representatives and researchers suggested adopting the German certification scheme, DGNB. Supported strongly by the industry, the Green Building Council Denmark (DK-GBC) was established to manage the DGNB scheme and promote sustainable construction more generally.

DGNB assesses buildings on the basis of six criteria groups, divided into approximately 50 individual criteria. The six criteria groups cover:

(1) environmental quality;
(2) economic quality;
(3) sociocultural and functional quality;
(4) technical quality;
(5) process quality; and
(6) site quality.

The criteria group on economic quality accounts for 22.5 per cent of the total score, which exceeds by far the use of LCC in, for example, BREEAM or LEED. In turn, this has provided the stimulus for a number of related national research and development activities on LCC to establish a solid industry-supported basis for calculating life cycle costs. These activities provided among others industry standards of calculation assumptions, tables of service life times, key figures for cleaning costs, etc.

Data are now becoming available from DGNB-certified office buildings in Denmark, offering a unique opportunity to assess the performance of office buildings in a consistent manner because of the standardised assessment procedure of DGNB. This paper fills a knowledge gap on life cycle cost data by providing a thorough and systematic foundation to pursue the following three objectives:

(1) First, this paper compares life cycle cost data from 21 Danish DGNB-certified building projects.
(2) Second, the paper critically examines the magnitude of various life cycle cost drivers.
(3) Third, the paper discusses the implication of an emerging shift in life cycle cost drivers (at least in Denmark) from energy costs towards other cost drivers.

This study is based on measurements of actual construction costs and calculations of running costs. Although the running costs are calculated, the applied assumptions rest on the newly developed industry standards. Despite these limitations, it is the hope that this paper may stimulate researchers to redirect attention to other more important cost drivers and support practitioners who risk making erroneous decisions based on false assumptions of relevant cost drivers.

## State-of-the-art: life cycle costing

This section characterises LCC as a mature approach with a rather weak uptake in industry, provides an overview of three recent trends revitalising the implementation of LCC and presents some notable data with regard to improved life cycle management.

### *Mature approach: weak uptake*

Whole life costing broadens the narrow focus on construction costs to include the running costs over time to promote a long-term perspective on buildings, ensure fair comparison of solutions with different cost profiles over time, inform the decision-making process and create more attractive facilities. Whole life costing, including life cycle costing, is defined in the international standard ISO15686 series on service life planning (ISO, 2008) followed by the European standard EN15643 series on sustainability of construction works (CEN, 2012). Part 5 of the ISO 15686 standard defines whole life costing as an:

> [. . .] economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability. (ISO, 2008: 9)

By definition, LCC includes costs only for construction, operation, maintenance and end-of-life, while whole life costing also includes externalities, non-construction costs and income. This paper addresses LCC only. LCC is part of the wider field of strategic investment and financing (Hedegaard and Hedegaard, 2008). While the terms whole life costing and LCC are applied in construction, the term total cost of ownership (TCO) is generally applied in other business sectors (Ellram, 1993) and in the recent European directive on public procurement (Directive 2014/24/EU).

A number of different approaches and guidelines on LCC have emerged over the years (Bjørberg *et al.*, 1993; Dhillon, 2010; Farr, 2011; Caplehorn, 2012; Ellingham and Fawcett, 2006). In addition, a range of different tools exists. Haugbølle *et al.* (2016) provide a typology of existing tools divided into three categories with distinct characteristics and associated benefits and drawbacks:

(1) spreadsheets;
(2) stand-alone applications; and
(3) web services.

A fourth type – apps for mobile platforms – is not yet relevant as a calculation tool.

With two international standards, several guidelines and a multitude of tools, LCC has become a mature field in many respects. However, the uptake and implementation has been rather weak. The reasons are diverse and include weak financial incentives to take a long-term perspective in building projects; the institutionalised separation of construction and facility management; the absence of generally accepted standards for calculation assumptions (especially with regard to the discount rate and service lifetime of buildings and components); and the difficulties in getting access to reliable data (Bird, 1987; Sterner, 2000; Gluch and Baumann, 2004; Marshall, 1987). Salvado *et al.* (2018) discuss current limitations on the information availability on buildings' economic performance throughout its life cycle and propose a research roadmap highlighting the links and limitations to be addressed within and between LCC and building management.

*Revitalising life cycle costing: three new trends*

In recent years, a number of new trends have revitalised the focus on LCC in the built environment among researchers, policy-makers and practitioners internationally and in Denmark. First, the challenge of sustainability has fostered a diverse set of actions and studies. The establishment of various certification schemes like the American LEED, the British BREEAM and the German DGNB include LCC to differing degrees. The recent German scheme, DGNB, in particular puts strong and equal emphasis on economics in relation to social and environmental concerns. In 2012, the DGNB certification scheme for sustainable buildings and urban areas was adopted in Denmark by the Green Building Council Denmark (DK-GBC). Renewed research interest in LCC has studied different technologies like heat pump concepts for new nearly zero-energy residential buildings in Finland (Paiho *et al.*, 2017); different flooring systems (Harris and Fitzgerald, 2017); prefabricated fibre-reinforced composite versus masonry buildings in three different locations in the USA (Samani *et al.*, 2018); university dormitories in southeast China (Huang *et al.*, 2018); and integrated life cycle costing and life cycle assessment of bridges (Du, 2015). Other studies have focused on the factors affecting the results of LCC calculations, for example, the prominence of the discount rate in an evaluation of energy retrofit of buildings (Copiello *et al.*, 2017) and the factors causing uncertainties during the operational period due to external factors like functional, technological and regulatory changes (Arja *et al.*, 2009).

Second, new international and national policies are pushing for an increased use of LCC. The new European procurement directive from 2014 (Directive 2014/24/EU) introduces the use of total cost of ownership or LCC as an award criterion in competitive tendering in line with lowest price or best price-quality ratio. On a national level, new governmental regulation on quality assurance, public–private partnerships and LCC in public construction was issued in 2013, which requires all public clients (including municipalities and regions) to apply LCC in projects above certain thresholds. Among other things, recent research has focused on the use of standards in public procurement as a driver of innovation (Rainville, 2016) and on developing decision support models for energy-efficiency improvements of entire building stocks (Junghans, 2013).

Third, researchers and practitioners have lately shown increasing interest in LCC in relation to the new technological opportunities offered by BIM. Several different approaches to this promising integration of BIM and LCC are being pursued. Kehily and Underwood (2017) demonstrate how LCC can be integrated into the 5D BIM process by embedding an LCC calculation model into an existing 5D BIM technology. Another approach is taken by Jalaei *et al.* (2015), who propose a methodology integrating BIM with Multiple Criteria Decision-Making techniques to optimise the selection of sustainable building components at the conceptual design stage of building projects. Some have focused on using BIM to design for better maintenance accessibility and developed plug-ins to support this process (Liu and Issa Raja, 2014). Others have attempted to bridge the differences between BIM design tools and facility management systems through using, for example, the COBie standard for data exchange between different tools and platforms (Tu *et al.*, 2016; Tu *et al.*, 2016). However, Edirisinghe *et al.* (2017) state in an extensive literature review that convincing results of the full use of BIM-enabled facilities management in practice are yet to emerge.

*Results: data for improved life cycle management*

With regard to the economic effects of sustainable construction, the Sustainable Building Task Force of the government of California conducted a study of the financial costs and benefits of green buildings (Kats *et al.*, 2003). Data came from 25 LEED-certified office buildings and 8

LEED-certified schools located in the USA. Construction costs were compared with the costs of the buildings, as if they had been constructed as conventional buildings. The study concludes:

> In the most comprehensive analysis of the financial costs and benefits of green building conducted to date, this report finds that a minimal upfront investment of about 2 per cent of construction costs typically yields life cycle savings of over 10 times the initial investment. For example, an initial upfront investment of up to $100,000 to incorporate green building features into a $5 million project would result in a savings of at least $1 million over the life of the building, assumed conservatively to be 20 years. (Kats et al., 2003, p. 7)

A subsequent study of 30 schools in the USA examined the additional costs of building green and the LCC effects compared with traditional building (Kats, 2006). The increased costs of construction are less than 2 per cent and provide economic benefits that are 20-times higher. However, most gains benefit society through better education, while only a small part of these gains ends at the school in terms of, for example, reduced costs for the consumption of energy, water and health insurance. Even so, these gains are four-times higher than the additional costs. Similarly, studies of green office buildings in England have demonstrated that the benefits of greater productivity and lower labour costs for the occupants amount to six times the energy savings over a 20-year period (Edwards, 2006). Hence, the gains on productivity and health are considerably higher than on reduced energy costs.

Syphers *et al.* (2003) states that it is possible to build at normal costs and obtain a LEED certificate by choosing an appropriate strategy at the planning and design stage. Studies from Seattle, one of the leading American municipalities on green buildings, documented a downward trend towards lower additional costs over time. In 2000, the additional costs of a LEED Silver certification varied between 4 per cent for large buildings and up to 6 per cent for small projects. Only three years later, in 2003, these costs were reduced to near zero per cent, regardless of the size of the project.

A recent review by Goh and Sun (2016) of 45 peer-reviewed articles and books suggests that there is renewed interest in LCC calculations, but much work is still needed to extend LCC to include considerations for sustainability. The review includes studies over a period of 50 years from the emergence of the concept of LCC in the late 1950s in the USA over the increased interest in the 1980s and 1990s to the turn in the 2000s from focusing on conventional buildings to sustainable or green buildings. Goh and Sun (2016) conclude that together the studies show consistent patterns and trends of different categories of buildings with regard to service lifetime, discount rate and the ratio of capital costs to operating costs. With regard to service lifetime, the studies cover service lifetimes from 20 to 109 years, with an average of 48 years, although with peaks around 25 and 50 years. With regard to the discount rate, the studies cover discount rates ranging from 2 to 11 per cent. The average discount rate ranges from 5.8 to 6.6 per cent. With regard to the ratio of capital costs to operating costs, the assumed capital costs as a percentage of the life cycle costs vary dramatically from 6 to 80 per cent. Consequently, the assumed running cost as the percentage of life cycle costs varies from 20 to 94 per cent. The average ratio of capital costs to operating costs is around 42 per cent; hence, the average of assumed running costs as a percentage of life cycle costs is around 58 per cent.

## Methodology

The data set covers 21 office building projects from 2013-2017 and it was generated as part of the ongoing efforts of the DGNB certification scheme. The calculation of life cycle costs follows the directions set out in DGNB guideline NBK2014 for new office buildings, version

2014 (Green Building Council Denmark, 2014). For some of the early projects from 2013, the original calculations of life cycle costs were recalculated with regard to water and sewage because of changes in the price index development and pricing of units. The size of the projects spanned from 1,500 $m^2$ to 41,000 $m^2$, with an average of some 11,000 $m^2$. All projects passed the threshold for certification at the highest possible level with regard to the criteria for economic quality, but the projects did not necessarily achieve the same overall score. This study does not include data from preliminary certifications, but only data from final certifications of projects.

The study calculates life cycle costs using the net present value (NPV) method, but revenues, for example, from the sale of electricity from photovoltaic production, are not included. Calculation of life cycle costs is sensitive to a number of assumptions. Hence, Green Building Council Denmark established a technical committee to discuss and inform about the selection of appropriate general calculation assumptions with regard to the calculation period, discount rate and price developments for different cost groups. The general calculation assumptions are:

- Calculation period: 50 years;
- Year of calculation: year of obtaining DGNB certificate;
- Discount rate (nominal): 5.5 per cent;
- General price development (nominal): 2 per cent per year;
- Potable water and sewage price development (nominal): 3 per cent per year; and
- Energy price development (nominal): 4 per cent per year.

Floor space is calculated using the gross floor area according to the Danish Building Regulations, with one minor exception. Only half of the gross floor area of basements is included to reflect the lower unit price of these areas. This principle was introduced by the DGNB scheme to ease comparisons and simplify calculations as the system boundary originally followed the footprint of the building, not the entire property. Hence, manual recalculations were necessary to accommodate for differences in the chosen parking solution: parking in basements, parking on the rooftop or open-air car parking on the grounds. This principle is now abandoned.

The life cycle cost calculations include four main cost groups:

(1) construction costs;
(2) costs of maintenance and replacements;
(3) utilities costs; and
(4) cleaning costs.

Construction costs are obtained from the project's accounts as actual costs. As construction and maintenance costs vary with the geographical location of the individual project, these cost types are normalised using a correction factor for location of 0.85-1.05 in accordance with customary practice for cost calculations in Denmark. The construction cost groups are based on the most widespread and well-known classification system named SfB, which has been in operation in Denmark since the 1950s (Byggecentrum, 1988). The calculations include only the first six main SfB groups, while costs for site, consultancy fees, furniture and equipment, VAT, etc., are omitted:

(1) substructure;
(2) structure, primary elements;

(3) completions;
(4) applied finishes;
(5) sanitation and HVAC services; and
(6) electrical and mechanical services.

The costs of maintenance and replacement are calculated according to the following principles:

- The reference service lifetime of building components follows the official table of service lifetimes provided by the Danish Building Research Institute.
- A component is replaced when its projected service lifetime expires.
- Replacement costs are assumed to be 125 per cent of the initial costs to include the costs of both acquiring a new component and replacing and disposing of the worn out component.
- Maintenance cost is set as a constant percentage for each building component, but varying from one building component to another.

The utilities costs are calculated as follows:

- Amounts of water and sewage are calculated using the DGNB water and sewage calculator.
- The amount of energy used for heating, hot water and electricity consumption for building services is extracted from the mandatory energy calculations to demonstrate compliance with the building regulations.

The cleaning costs are calculated based on the standard cost of cleaning per $m^2$ and with a standard frequency. They are calculated for three subgroups:

(1) grounds (although not applicable for offices in the 2014 DGNB manual);
(2) building, exterior – facades, solar shading, windows, etc.; and
(3) building, interior – spaces/type of rooms.

## Findings

The measurement of actual construction costs and calculations of life cycle costs of recently DNGB-certified office buildings in Denmark has provided a number of observations with regard to the main cost drivers. Based on the assumptions specified in the previous section on methodology, Figure 1 illustrates the relative distribution of net present value divided into the four main cost groups for office buildings.

In a 50-year perspective, construction costs seem to be of the same magnitude as the combined running costs. The life cycle costs for office buildings of each of the four main cost groups seem to be distributed with half of the NPV on construction costs, close to one-third of the NPV on maintenance and operating costs, and the remaining one-fifth of the NPV on utilities and cleaning costs. The relative distribution of supply costs versus cleaning costs seems to be 1:2, meaning that cleaning costs are approximately twice as high as supply costs in total (water, sewage and energy including electricity consumption).

This is a notable observation as cost savings because of energy savings have for long been considered a strong driver of a long-term perspective on construction, refurbishment and operation of buildings. As the energy performance of new buildings continues to

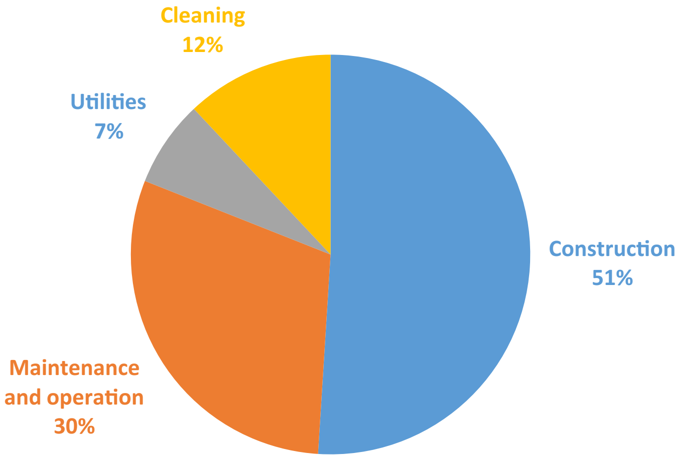


**Figure 1.**
Distribution of life cycle costs by main cost groups (per cent)

improve, energy savings as a driver in a life cycle perspective on new buildings are likely to continue losing their significance. Indeed, paying more attention to other and stronger cost drivers seems prudent, in particular the costs of cleaning, as cleaning costs are a more prominent cost driver in new office buildings than supply costs.

Figure 2 shows a box-and-whisker plot for each of the four main cost groups as well as the total sum in EUR/m$^2$. Box-and-whisker plots are a method within descriptive statistics for graphically depicting groups of numerical data through their quartiles. The benefit of box-and-whisker plots is their ability to display the variation in samples of a statistical population without making any assumptions of the underlying statistical distribution. The boxes in Figure 2 mark the lower (25 per cent) and upper quartiles (75 per cent), while the dots mark the outliers.

As indicated by Figure 2, the dispersion between the lowest and the highest figures for each cost category stays within 1.5 of the interquartile range (IQR) of both the lower and upper quartile (interquartile range defined as the difference between the upper quartile and

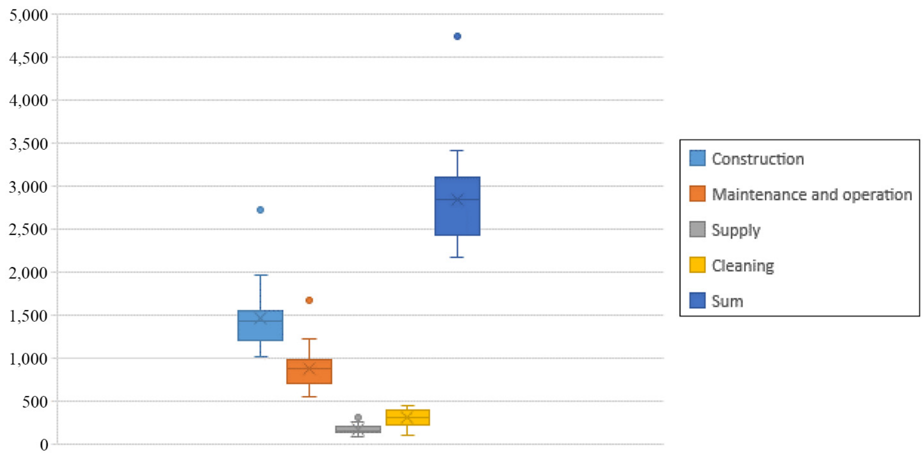


**Figure 2.**
Distribution of main cost groups and the range of values (EUR/m$^2$)

the lower quartile). The only exception is one of the building projects marked as an outlier that stands out as very expensive. It should be noted that due care should be taken in translating the absolute figures and dispersion to other contexts, as the costs are calculated in a Danish context. Among other factors, this context includes high labour costs and very strict energy requirements in the Danish Building Regulations.

Figure 3 shows the construction costs distributed between the six main groups of the SfB classification.
Figure 3 illustrates two notable observations. First, the construction costs of the building envelope (SfB Groups 1, 2 and 3) make up more than half of the total construction costs. Second, the construction costs of technical installations (SfB Groups 5 and 6) make up approximately one-third of the total construction costs, while the building envelope taken together with applied finishes make up some two-thirds.

Figure 4 shows the distribution of the maintenance and operating costs between the same six groups.

The analysis of the key performance indicators demonstrates that certain cost drivers are more important than others with regard to the life cycle costs. Taken together, Figures 3 and 4 indicate three notable observations. The first observation is that the first three SfB groups (substructure, structure and completions) account for more than half of the construction costs, but they only account for one-third of the maintenance and operating costs. The second observation is that the maintenance and operating costs of applied finishes are twice the construction costs of applied finishes. The third observation is that the last two SfB groups on technical installations (sanitation and HVAC services and electrical/mechanical services) account for only approximately one-third of the construction costs, but they make up more than half of the maintenance and operating costs.

## Discussion: Validity and implications

This section discusses how robust the findings of this study are by addressing three issues of validity: 1) measured versus calculated figures; 2) calculation assumptions; and 3) inventory of spaces.

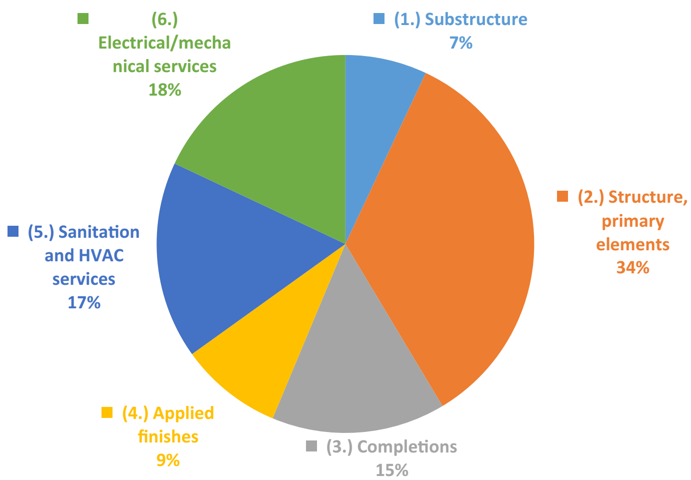


**Figure 3.**
Distribution of construction costs (EUR/m$^2$)

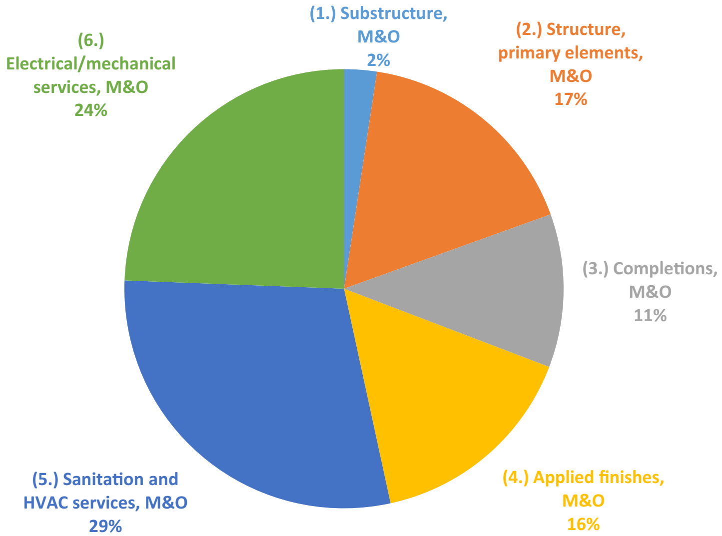


**Figure 4.**
Distribution of maintenance and operating costs (EUR/m$^2$)

The first issue is the validity of input data or figures used for the calculations, in particular whether input data are measured or calculated. The construction costs are based on actual figures from the completed construction projects, while all running costs are based on calculated figures. As all of the included buildings were constructed recently, it has not been possible to rely on measured running costs from the actual buildings. To reduce the potential invalidity of the calculations, the majority of running costs have been calculated based on typical industry standards. These include the mandatory energy calculations used for official building approval by the authorities and the service lifetime table of building components issued by the Danish Building Research Institute. Nonetheless, something that would be valuable in future studies is to compare the calculated costs with the actual costs of running comparable buildings to verify the calculations. This issue of agreement between calculated and measured energy costs continues to be an important aspect to address. As pointed out by, for example, De Wilde (2014), caution should be exercised, as the calculated energy consumption may differ from the actual energy consumption in buildings because of various factors like the concept of service (Shove, 2004), the rebound effect (Sorrell, 2007) and user behaviour (Gram-Hanssen, 2013).

The second issue is that the calculation assumptions applied in any study on LCC are critical for the results. Due care must, therefore, be taken to ensure appropriate calculation assumptions. While both of the international LCC standards ISO15686 and EN15643 define terms and methodologies, neither of them provides a set of calculation assumptions that can be applied in LCC studies. Hence, extensive work has been conducted in a number of subsequent national research and development projects to develop a more detailed, specific and industry-supported set of calculation assumptions with regard to, for example, discount rate, price index developments and service lifetimes. The discount rate has been set in line with other studies and policy recommendations, while the price index developments of various costs items are based on historical data of the past 25 years from the national statistical agency. Rather than setting a fixed lifespan for the entire building, this study has applied service lifetimes for individual building components, which reflects a more realistic scenario for stepwise replacements over time. Consequently, this study has been able to apply a more detailed, specific and industry-supported set of calculation assumptions than usual for LCC studies. Nonetheless, future studies may elaborate on these calculation assumptions and conduct extensive sensitivity analyses, Monte Carlo simulation, etc., to improve the robustness of these calculations.

The third issue is that the inventory of gross floor area, cleaning area, etc., is crucial, as these different types of spaces and surface areas are the denominator used in the calculations. In particular, special attention should paid to the difference in both construction and running costs associated with different types of spaces and surfaces. On one hand, parking areas and basements, for example, have comparably low construction costs and running costs. On the other hand, areas like surgical theatres in hospitals and laboratories with high intensity of installations have much higher costs than average with regard to both construction costs and running costs. Hence, it seems prudent to differentiate between different types of spaces in the LCC calculations as the relative distribution between low, medium and high cost spaces will impact on the resulting net present value.

With these precautions in mind, this study will point at a fundamental implication for clients and building professionals with regard to future design strategies and choices of building components. Energy savings have been high on the agenda for a great number of years, and the life cycle costs of energy consumption have long been viewed as the driver of long-term investments in energy saving. However, the significance of energy costs in new buildings is diminishing in a Danish context because of the continuous tightening of energy requirements in the Danish Building Regulations. Hence, the practical implication of this study suggests that authorities, clients and building professionals need to redirect their attention towards other and more prominent cost drivers. Specifically, closer attention needs to be paid to the importance of cleaning – especially of windows – when designing façade solutions, for example. Moreover, more focus is required on the technical installations – especially HVAC – because of their relatively short expected service life and high maintenance and operating costs. In addition, applied finishes drive maintenance and operating costs disproportionally compared with their construction costs.

## Conclusion

Sustainable life cycle management of buildings suffers from a lack of life cycle data. Several studies have addressed life cycle costing in individual case studies, but only few studies include larger coherent datasets. This paper fills the knowledge gap on life cycle cost data by providing a thorough and systematic contribution that supports the academic understanding of the significance of different cost drivers as well as the practical implementation of life cycle costing.

First, this paper compared life cycle cost data from 21 office buildings recently certified according to the Danish version of the DGNB certification scheme for sustainable buildings. The life cycle costs are based on the actual figures for construction costs from the completed building projects, while the calculation of future costs are far more reliable than typical as they are based on a more detailed, specific and industry-supported set of calculation assumptions than is usual for studies on LCC.

Second, this paper critically examined the magnitude of various life cycle cost drivers. The findings indicate that construction costs of office buildings amount to half of the life cycle costs over a 50-year period, while the other half of the life cycle costs is related to running costs. Further, the findings suggest that running costs are distributed by approximately one-third of the life cycle costs covering maintenance and operation, while the remaining one-fifth of the life cycle costs are divided between cleaning costs and utility costs for both energy and water at a ratio of some 2:1.

Third, this paper discussed the implication of an emerging shift in life cycle cost drivers (at least in Denmark) from energy costs towards other cost drivers related to cleaning, technical installations and applied finishes. In conclusion, it is the hope that this study will encourage policy-makers, clients and building professionals to rethink their design strategies and choices by redirecting their attention towards other more important cost drivers to avoid making costly, erroneous decisions based on false assumptions of relevant cost drivers.

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