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EXPLORING MATERIAL LIFESPANS IN DANISH ARCHITECTURAL HERITAGE – USING THE BUILDING HISTORICAL INVESTIGATION TO DISCUSS AND QUALIFY LCA IN THE B AND C-STAGES

BIRGITTE EYBYE AND HENRIETTE EJSTRUP

Abstract

Life Cycle Assessment [LCA] is becoming mandatory in the Danish construction sector, including works on existing buildings. Whereas calculations regarding the material extraction, production and transportation offer precise data, it is difficult to predict human behaviour in regard to energy consumption and maintenance and thus, provide exact data on the service life. Concurrently, many heritage buildings are statutorily agreed upon as not having an end-of-life and moreover, such buildings show that materials and components have very different lifespans.

This article examines the method of Building Historical Investigation [BHI] in heritage buildings as a means to discuss and qualify material lifespan scenarios in LCA. Initially, the study establishes a frame of understanding based on LCA and BHI. Then, the case study of the listed building, Agerskov House, is analysed with a focus on the load-bearing structure, the roof, the doors and windows and their age. These investigations frame the discussion, which evaluates on the chosen methods, elaborates on the findings and examines these in relation to the standard assessment of material lifespan. The article concludes that bulking findings from BHI could qualify the understanding of material lifespan in LCA and differentiate the formation of multiple scenarios.

Keywords:
life cycle assessment, building lifespan, service life prediction, architectural heritage, Denmark, material lifespan, building historical investigation, traditional building materials

1. Introduction

In 2023 it became a requirement in the Danish building regulations to calculate buildings' CO_2-emissions making Life Cycle Assessments [LCA] mandatory for new buildings. The legislative agreement also concerns increased sustainability in renovations and demolitions, yet in indefinite terms, and furthermore, it aims to survey why buildings of technical quality are demolished (Valdimarsson & Kristensen, 2021).

The application of LCA model addresses the urgent need to reduce CO_2-emissions in buildings, but it also poses a number of questions. LCA operates in a linear construction from material production stages (A-stages) over Usage (B-Stages) to End-of-life [EOL] (C-stages) and Beyond boundaries (D-Stages), often defined in a lifespan from 40-100 years (Birgisdottir & Rasmussen, 2015).

Regarding existing and heritage buildings, the application of the LCA model gives rise to questions on its functionality and legitimacy.[1] First, many heritage buildings have lifespans that by far surpasses the general EOL as implied by the LCA,[2] since they are culturally and statutorily agreed upon as not having an EOL. In architectural conservation, notions such as 'originality value' (Kulturarvsstyrelsen, 2011, p. 36) and 'Alterswert' (Riegl, 1996) or 'age value' (Orbasli, 2008, p. 40) concern the appreciation of the old and/or original materials and components of a building. Second, heritage buildings show that building materials and components have very different lifespans relating to e.g. type of material, position and architectural detailing for which reason it is questionable if a general or standardised reference period is operational. Mostly, LCA is executed without emphasis on individual usage (B6–B7) and maintenance (B2) such as micro renovation, which is pointed to as a method for prolonging service life of building components (Ejstrup et al., 2022). In this context, the knowledge area of architectural conservation works often concern repairs (B3) and replacements (B4) of minor parts such as the bottom rails and windowsills.

In relation to the general discussions on architecture and sustainability, more researchers such as Thomas Sieverts argue that in the future, buildings ought to last for centuries as in preindustrial times (Sieverts, 2017). Other researchers such as Michael Lauring predict that future building materials will be scarce and expensive (Lauring, 2014). These concerns juxtaposed with the limitations and challenges of the LCA model in regard to the B-stages concerning usage in relation to heritage and existing buildings, altogether highlight the need for further research into the lifespan of building materials and components.

1 For instance, a recent study conducted as a systematic literature review, examining LCA and preservation values exposed more gaps of knowledge in regard to LCA calculations of existing buildings. These gaps include lack of LCA data sets, imprecise climate impacts of the usage and retail stages, different reference study periods in relation to refurbishments and finally, the assessment of preservation values in connection to LCA. Furthermore, the review stressed that LCA results often are presented without any uncertainties despite the number of such related to the environmental data, study reference periods, energy in the operational stage etcetera (Petersen et al., 2021).

2 In general, many buildings have lifespans of more than 50 years. According to a retrieval of unit BygB40, Statbank Denmark, there are 4,811,562 buildings altogether in Denmark, of which 1,697,892 (35%) were constructed before 1970 and thus, are more than 50 years old. If the retrieval exclusively concerns permanent residences, the total is 1,631,859, of which 909,299 (almost 56%) were constructed before 1970 (Danmarks Statistik, accessed 31 May 2023).

2. Objective and design of the article

The objective of this article is to examine methods from the field of conservation as a means to discuss and qualify material lifespan in relation to the B- and C-stages of LCA. In doing so, the article investigates and compiles the methodologies of the Building Historical Investigation [BHI][3] and LCA. Consequently, the research question is:

How can knowledge of materials and components in heritage buildings qualify the standardisation of material lifetimes in LCA by applying BHI?

BHI targets the establishment of the chronological development of a building through determination of the age of the building and its materials and components and thus, seems highly relevant in this connection. Furthermore, case study research is applied, as this method is particularly suited for the production of in-depth information on a phenomenon (age of building materials and components) through a small number of dense case studies (architectural heritage) (Flyvbjerg, 2006; Yin, 2014). The main literature sources utilised in this article comprises theory on LCA, LCA data, building archaeology and the BHI, case study research and general literature on architecture, architectural theory, architectural heritage and conservation. Finally, case study material includes literature, drawings, photos and empirical studies.[4]

The chosen case is Agerskov House (*Agerskovhus*) located at Hornsgårdvej 7, 6510 Gram, Southern Jutland. The choice of case reflects four central criteria; A) The building materials and components of the Agerskov House are common to Danish building culture, for which reason generalisation on the subject is possible, B) The building was constructed in the year 1682 and thus, its age of more than three centuries provides a suitable study reference period, C) The house was not listed until 1997, for which reason earlier retention of historic fabric was not a formal request by any authorities and therefore, the building offers a reliable insight into the lifetime and durability of building components and materials since this building only recently has become an object of extraordinary statutory concern, D) The building has been subject to careful conservation works in the late 1990s which included meticulous building archaeological investigations performed by the highly experienced conservation architect and owner Jørgen Wilhelm Overby who has been working with architectural heritage since 1979. Despite these investigations, it is not possible to gain a complete overview of all the building materials used in the building throughout the centuries. Consequently, the case study is delimited to the main elements of the building including the load bearing structure (outer walls and roof construction), the roof, the doors and the windows. In doing so, the article draws on Stewart Brand and Bob van Reeth. According to Stewart Brand and his concept of ‘Shearing Layers’, a building comprises six layers; namely Site, Struc-

3 Translated from Danish ‘den bygningshistoriske undersøgelse’ (Hædersdal, 1997).

4 The authors have been granted the right of access to records regarding the chosen case from the Agency for Culture and Palaces (*Slots- og Kulturstyrelsen*).

ture, Skin, Services, Space Plan and Stuff (furniture).[5] All of these layers have different lifespans, ranging from the site to the furniture. The first being eternal, whereas the last is often changed. Moreover, Brand estimates the structure to last 30–300 years and skin (exterior surfaces) circa 20 years. (Brand, 1994, pp. 12-13). Relatedly, Bob van Reeth propounded the concept of 'The intelligent Ruin' in order to articulate 'architectural durability' in buildings while holding the position as Flemish Government Architect. To van Reeth, the structural frame and possible skin of the intelligent ruin should have a lifespan of 400 years (Schoonjans & Van Sande, 2008, p. 17). Furthermore, research into sustainability and Danish architectural heritage also highlights the importance of a robust structure with regard to accommodate changes and thus, being durable (Eybye, 2016, p. 130-133; Eybye, 2022).

5 The book *How buildings learn: What happens after they are built* by Stewart Brand (1994) is highly influential, yet it has also been subject to criticism, such as the approach and estimated lifetimes.

The article initiates the establishment of the theoretical and analytical frame of understanding which clarifies central concepts, introduces LCA and BHI as applied in the study. Next, the case study of the Agerskov House is presented with a particular focus on the load bearing structure, the roof, the doors and windows and their age, including the main findings of the study. The analytical investigations frame the discussion, which evaluates on the chosen method, elaborates on the findings and examines these in relation to LCA as well as the feasibility of BHI in regard to LCA. Lastly, the conclusion sums up the research and main results.

3. Theoretical and analytical frame of the study

3.1 Central concepts and clarification

The field of architectural conservation in Denmark is characterised by a certain degree of tacit knowledge and therefore, some confusion in regard to more of the primary notions. For instance, in context of Denmark, the term 'restoration' (*restaurering*) has developed from a particular approach (in which the building is rebuilt into not only the original state but may be taken a step further to an 'ideal' appearance, thus drawing on the theories of architect Eugene Viollet-le-Duc) into describing all sorts of deliberate and methodologically based dealings with architectural heritage including maintenance, repairing, preserving, renewing and restoring. For the purpose of illustration, the careful conservation works of the Agerskov House is called a restoration in Danish, though more building phases have been preserved and no post-and-plank construction restored. Internationally, the term restoration is mainly identical with the original understanding. Consequently, the term 'architectural conservation' is used to describe dealings with heritage building in order to avoid confusion.

Similarly, the Danish term 'renovation' (*renovering*) is rather vaguely defined. Etymologically, renovate means to renew (Hårbøl et al., 2005), and in the field of architectural conservation the process of renovation is generally considered to be non-methodical (thus opposing the strict and rigorous method of architectural conservation) and in the purpose of e.g. major replacement works of worn-out building elements, revitalisation or energy performance of a building. This article applies renovation on general or indefinite works on buildings, whereas 'energy refurbishment' is used to describe such particular interventions.

In relation to LCA, the terms 'lifetime' (*livstid*) and 'lifespan' (*levetid*) are often used indiscriminately. According to the Oxford Learner's Dictionary, 'lifetime' refers to "the length of time that somebody lives or that something lasts" whereas 'lifespan' is "the length of time that something is likely to live, continue or function" (Oxford University Press). Prospectively, this article applies lifespan, when referring to how theoretical assumption on how long a material is expected to last, and lifetime, when referred to concrete knowledge on how long a material have endured.

3.2 LCA – methodology and critiques

The idea of assessing the life cycle of a product originated in the food and packaging industry in the 1960s and 1970s, where energy consumption and waste production gained broader public attention (Guinée et al., 2011). It is structured around the principle of assessment of materials in four stages A) Production and construction B) Use C) End-of-Life [EOL] and D) Beyond boundaries. Each stage can be subdivided into further modules (e.g. A1–A5), thus representing detailed processes within the different stages (Kanafani et al., 2019). The LCA draws on data from Environmental Product Declarations [EPD], provided and made publicly accessible by the manufacturers of specific component or material (EPD Danmark).

Since the 1970s, the popularity of LCA has increased, and the tool was adopted by other industries, for instance by the building industry. In the 1990s, scientific investigations and standardisations of the method and terminology emerged and, in 2006, an ISO standard (14040:2006) was established to secure a standardised usage of the tool (Guinée et al., 2011). In Denmark, Aalborg University, Department of the Built Environment (BUILD)[6] has conducted a wide investigation into LCA and provided open source tools like *LCA-byg* to the construction industry. The research done by BUILD has, amongst others, been fundamental to the demands within the building regulations of 2023. Within recent years, research in LCA has expanded to existing buildings. The initial results indicate that renovation of existing buildings have a lower environmental impact than new constructions, since virgin materials for the construction as well as the disposal of existing buildings usually have a high environmental impact (Rasmussen & Birgisdóttir, 2015). Other novel studies, such as Serrano et al. (2022), take point of departure in assessing different interventions within a heritage building and concludes that architectural

6 BUILD was formerly known as Statens Byggeforskningsinstitut (SBi) which translates into the National Building Research Institute. The institute is partly financed by the State of Denmark, and obliged to provide research-based authority service to the government, municipalities etcetera. (BUILD; Finansministeriet).

conservation might have a similar or lesser impact than a standard energy refurbishment. In addition, the Danish organisation *Realdania By & Byg* has elaborated a retrospective LCA study on their building portfolio of 60 buildings, all heritage buildings that come in a great variety of typologies and ages. The study finds that architectural conservation or transformation have a lesser carbon impact than new constructions. In relation to this new field of knowledge on LCA in existing buildings, criticism has been put forth that there is a lack of consensus on LCA methodology in the case of renovation and transformation (Fufa et al., 2020; Realdania By & Byg, 2022).

Although ISO standard is established within the LCA, a variety of different methods have been developed and are contentiously discussed. E.g. cradle-to-gate, focusing mainly on the production stages and cradle-to-cradle, also considering the next lifecycle of a material (Bjørn & Hauschild, 2018; Tait & Cheung, 2016). Other uncertainties, for instance the energy performance of a building, can vary substantially from assessment to actual use. LCA in the stages A1–A3 provides rather precise calculations, whereas stages such as B-, C-, and D-stages are argued to be scenarios based on qualified guesses. In this connection, more research demonstrates user behaviour as unpredictable though energy consumption in the operational phase is a crucial matter in LCA. In most cases, inhabitants of low energy housing and regular housing tend to use more energy than calculated (the rebound effect) (Gram-Hanssen & Hansen, 2016, p. 14). Opposed to this, an energy-efficiency refurbishment case from Norway showed lower energy consumption than expected after the refurbishment, as the inhabitants were used to acting economically in regard to energy (Berg & Fuglseth, 2018). Studies of comparisons between new buildings and refurbishments establish this inconsistency, in which calculations indicate new buildings as the better choice when applying the calculated energy consumption, and refurbishment as the better choice when applying the actual energy consumption of a similar, new building (Petersen et al., 2021). As a consequence, novel methods of mediations illustrated by 'whiskers' indicate uncertainties in the results (Petersen et al., 2021, p. 33).

Another subject to criticism is that there is not enough data to substantiate concrete knowledge on material lifespan and how maintenance impacts on this, for instance the lack of EPDs on historic buildings materials and niche products, since small manufacturing companies rarely have finance for the making of EPDs and other legislative standards, e.g. fire testing (Beim et al., 2021; Petersen et al., 2021; Thomassen & Munch-Petersen, 2021). In relation to this discussion, the material EOL scenario is also being debated. For instance, tools like the 'pyramid of materials' (*materialepyramiden*) conveys only the A1–A3 stages in EPDs. It aims to establish the upfront carbon in relation to production stages as a certainty, but points to that material lifespan is more a technical design parameter and discussion than a generic lifespan assumption (CINARK / Det Kgl. Akademi og Vandkunsten). The pyramid has the ability to spark a discussion in the early design phases on how material choice implicates certain constructions and building techniques and, thereby having an upfront carbon outlet that might be radically different than if the full lifecycle is assessed (Munch-Petersen & Beim, 2022). As a result, the LCA may not be structured around the better choice when it comes to renovation versus new building, which emphasises the need for further attention to the building materials (Andersen & Negendahl, 2023).

3.3 The building historic investigation [BHI] – methodology and critiques

Conservation works on sites and monuments follow international charters, which have been widely agreed upon.[7] The so-called Venice Charter of 1964 laid out the international standards of modern conservation, as article 9 states that "The restoration in any case must be preceded and followed by an archaeological and historical study of the monument." In this way, archaeological and historic examinations were formalised as a mandatory element (ICOMOS, 2011) and today, the authorities request empirical investigations before conservation works can be carried out on listed buildings. In the field of architectural conservation, more terms coexist that denominate these empirical investigations such as 'architectural investigation' (England), building archaeology (Denmark) and 'building historical investigation' (Denmark, Germany). Prospectively, this article uses the term BHI to phrase this particular scholarly discipline, given that it is a collaboration between more professions.

The BHI is a method to gain knowledge of a building, as sources are scarce or non-existing except for the building itself. BHIs have been performed for centuries, especially with a view to determine the time of the construction and, the age and chronology of alterations of the building. Such knowledge is essential in order to understand and preserve the significance of the building in conservation works. Usually, the BHI comprises a number of approaches such as measurements, architectural surveys, archive studies, building archaeology, structural analysis, historic paint investigations and dendrochronology. All these approaches target the reading of the historic fabric, mainly by mere observations. Destructive interventions in the aim of clarifying assumptions about the building are always made as small as possible.

The readings of the historic fabric concern exterior and interior details in regard to e.g. architectural style, masonry, carpentry, joinery, forging, paint, tapestry and interior fittings such as heating stoves and fireplaces. Consequently, performing a BHI requires comprehensive knowledge of the use of materials, methods of different crafts at different times, architectural styles and designs and, constructions of different ages in order to date the building fabric and elements. In doing so, the architectural

7 ICOMOS has 107 national committees. Retrieved 6 December 2022. https:// www.icomos.org/en/about-icomos/committees/national-committees?start=5

approaches of the BHI draw theoretically on the formalist tradition of architectural history and, social and geographic diffusion, i.e. the spreading of architectural style/ techniques/ materials from gentry to peasantry class. In the Danish context, stylistic design features emerged in Copenhagen and then spread to the rest of the country – a process of circa 20 years (Vadstrup, 2004, p. 62-64).

In summary, the BHI contains both elements of analysis and synthesis, and a comprehensive BHI often takes up many resources. Since many of the datings are subject to uncertainty, attempts are made to validate the observations by cross-examinations such as archive studies or historic paint investigations. As a result, a report on a BHI tend to be very detailed, considering all possibilities. Sources of error are diverse, e.g. the widespread reuse of building elements may cause confusion in a BHI. According to Hodder, analogies suggested on the basis of observational data can only be more or less credible in the context of the compiled data and therefore, not verified or falsified in the tradition of the 20th century theory of science (Hodder, 1982, p. 9-27; Hædersdal, 1997; Cramer & Breitling, 2007; Bock, 2011).

3.4 BHI as a supplement to LCA

The expansion of the field of knowledge on LCA into the construction industry and further into renovation is far more complex and with a longer lifespan and uncertain EOL than its origins in the food and packaging industry. LCA generally operates with a theoretical standard of 50–80 years lifespan on materials. In contrast BHI originates in the context of the build environment and has documented material lifetime far beyond 80 years. To preserve and secure the lifespan of heritage buildings, maintenance is central. Since the adoption of the Act of Building Preservation (*Bygningsfredningsloven*) in 1918, the statutory practice has resulted in both official and private collections of experiences of prolonging the lifespan communicated through publications, guides and courses. Moreover, the methods and results have contentiously been scrutinised and discussed, re-caulked and refined amongst practitioners and theorists. The different practices and their effects are documented in the physical buildings, of which some have had a lifetime of many centuries. Arguably, buildings ought to have a much longer lifetime and usually encompass a large variety of different materials and components, and usage for which reason the future scenarios by default should be less deterministic. This questions whether the measurable A-stages of the LCA concerns a discussion and assessment methods different to the post-construction stages that are based on assumptions of future scenarios? In this case, BHI serves exactly the purpose of compiling such knowledge and can give indications on expected lifespan of buildings of different maintenance, materiality, functionality and architectural design.

Figure 1
Photocollage of the Agerskov House. 1. The main entrance with the segmental dormer (arkengaf). 2. The building seen from the south. 3. The building seen from the northeast with the fine and modest details in the masonry. 4. The living room with the fireplace. The eastern tie beam has traces of former timber joints, indicating a wooden wall. 5. The west gable with access to the stable. 6. Tie beam with traces of a brace (mortice and holes for pegs). These traces are seen in all tie beams (north and south side of the building), showing the origin as a post-and-plank construction. 7. View from the best room (pisel) through the middle room to the living room with the fireplace. PHOTOS TAKEN BY BIRGITTE EYBYE.

4. Case study: analysing the age of building materials and components of the Agerskov House

The aim of the case study is to provide qualified information about the materials and components used in the Agerskov House, especially regarding lifetime and maintenance. The analysis is based on empirical investigations in the building, drawings, literature including documents regarding the works on the listed building procured by right of access and interview with the building owner. Furthermore, the analysis is delimited to materials and components concerning the load bearing structure (outer walls and roof construction), the roof, the doors and the windows (equaling 'Structure' and 'Skin', see 'Objective and design of the article'). Lastly, building historic expositions tend to be very elaborated due to the large amounts of information, i.e. data, general knowledge, assumptions and refutations etcetera. To improve the readability of this case study, supporting material is found in the sidenotes.

4.1 Case presentation

The Agerskov House is situated in the rural area close to the town of Gram in Southern Jutland. The building is circa 7 meters wide, 24 meters long and east-west orientated with the main facade facing the road of Hornsgårdvej. It is a prime example of West Schleswig vernacular architecture due to its layout as a so-called byre house (*gårdstuehus*), the brick-built, whitewashed walls and thatched roof with half-hipped gables. A particular vernacular feature of the region is the segmental dormer (*arkengaf*) with a hatch to the hayloft marking the entrance, see figure 1. Inside, the entrance room divides the building into dwelling (east) and stables (west) and the room itself was historically used as a threshing floor, see layouts of figure 2.

According to dendrochronological dating, the Agerskov House was constructed around 1682[8] as a post-and-plank construction at the initiative of the count of Gram Gods. Due to the large amounts of oak timber required for such buildings, the Crown prohibited post-and-plank several times in the 15th and 16th centuries. In Southern Jutland, however, repairs to existing post-and-plank constructions were allowed. Despite this, construction of such buildings continued to the early 19th century (Stoklund, 1972, p. 45; Steensberg, 1974, p. 110; Brogaard, 1985, p. 29). The house belonged to the estate until 1992 and was mainly occupied by employees. In 1997, the building was listed and a conservation was carried out (Overby, n.d.; Overby, 1997).

8 This drilled dendrochronological sample was taken from a beam in the kitchen/ middle room with traces of inner braces, showing that this beam is part of the original, homogenous post-and-plank construction and that it had not been moved or repaired. Furthermore, the beam is made from a trunk in its full dimension. Consequently, it was dated to 1672 + circa 10 years, equalling a cutting year after 1680 and a construction year around 1682 which was established with a certainty of 99,993%. No dating is 100% sure, yet it may be perceived as such in case the percentage is above 99,9 (Slots- og Kulturstyrelsen, 2020, p. 40-45 (information from the dendrochronological lab)).

4.2. Main phases in the building history

Figure 2 features a timeline of the Agerskov House and the materials and components used since the construction in 1682. Overall, the BHI shows few, major changes to the building throughout the centuries, leading to four main phases in the history of the building. These are 1) the post-and-plank construction, 2) the transition into the brick building, 3) the

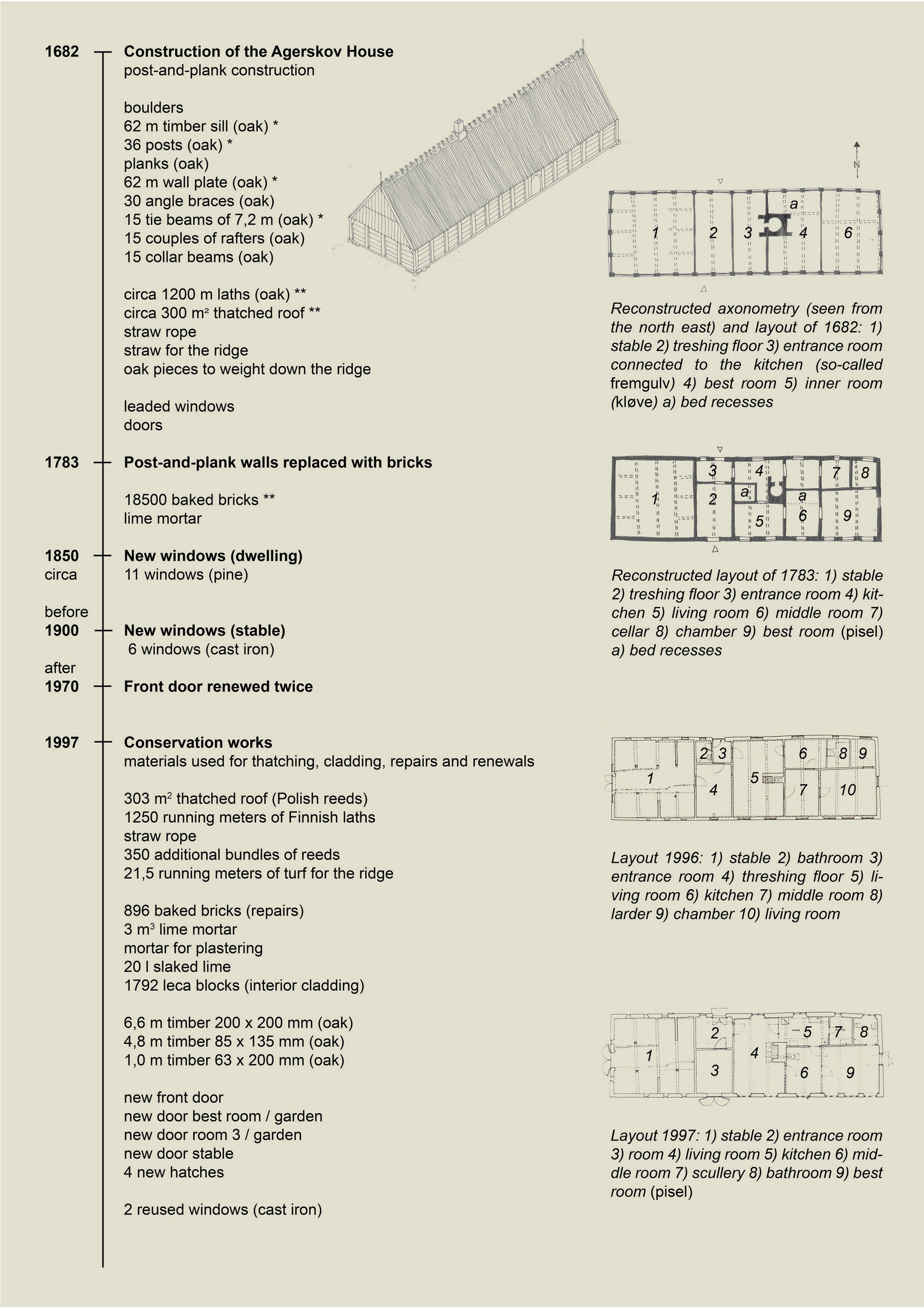

Figure 2
Timeline of the Agerskov House, showing the materials and components used for the building (load-bearing construction, roofing, walls, doors and windows) since 1682. Data is generated from observations of the building and the applied literature of this study, particularly the right of access to records from the Agency for Culture and Palaces. Entries marked with * indicate estimates and ** rough estimates. Axonometry and, layouts of 1682 and 1783 are based on Jørgen Overby's materials. Layouts of 1996 and 1997 are drawings by Jørgen Overby. FIGURE BY BIRGITTE EYBYE.

modified building and 4) the listed building which frame the analysis below. The following sections describe each phase in regard to alterations, building materials and components.

The post-and-plank construction (1682–1783)

The building initiated as a post-and-plank construction and, the investigations establish that only few different building materials were used; oak timber for the load bearing construction and outer walls and, boulders for the base. Materials for the thatched roof included most likely reed or straw, oak wood (laths and ridge)[9] and straw rope. Furthermore, it is very probable that the fireplace and chimney were built of baked bricks, since the rafters show no sign of smoke.[10] There is no evidence of the original doors and windows, and it is not possible to draw any conclusions on them, except that the first were wooden and the latter probably leaded.

Because of the existing building, its preserved original materials and knowledge of post-and-plank constructions in general, it is possible to determine the amounts of timber and roof materials fairly well, see figure 2.

Transition into the brick building (1783–1880)

In 1783, the post-and-plank construction was replaced with baked bricks according to the dendrochronological dating[11] and the carving on the mantel-tree.[12] At the same time, the interior was subject to some rebuilding (see reconstructed layouts of 1682 and 1783 in figure 2) such as the distribution of rooms and the fireplace (hence the new mantel-tree). The present placement of windows and doors in the dwelling results from this layout (Slots- og Kulturstyrelsen, 2020, p. 8). Furthermore, it is likely that the pitched gables of the post-and-plank construction also were altered into the current half-hipped gables at this time and thus, the building had reversed into an exemplar of West Schleswig vernacular architecture.

The transition into a brick building required around 18,500[13] baked bricks and lime mortar. Concurrently, the timber sill, the posts, the angle braces and the planks were dismissed. It is not possible to establish whether the leaded windows were reused in 1783, or if the dwelling was given new windows. The current windows of the dwelling originate from 1850 circa (Slots- og Kulturstyrelsen, 2020, p. 8).

9 The conservation works in 1997 revealed that the original laths were made of oak and doweled to the rafters. Moreover, historic photos of Gram vernacular architecture taken around 1865 show ridges made of straw weighted down with heavy oak pieces called *kragetræer* (Slots- og Kulturstyrelsen, 2020, p. 127). Hence, this type of ridge is suggested as the original.

10 As mentioned, the house was constructed on request by the count. It is probable that the construction included brick-built fireplace and chimney to obviate fire. Relatedly, the scribe of Ribe county authorities notes in his report of 1663 that the Swedish soldiers have burnt the plank walls of many post-and-plank dwellings so that only the load-bearing timber frames and the chimneys (fireplaces) remain (Overby, 1997).

11 This dendrochronological sample was cut from a beam in the stable. The beam had no traces of the inner braces of the post-and-plank construction and subsequently, was considered as newer. This beam had both heartwood and sapwood and hence, the cutting year was dated to 1783 with a certainty of 99,769% (Slots- og Kulturstyrelsen, 2020, p. 40-45).

12 A carving on the mantel-tree says 'Jens Jørrensen Thielbrenner 1783' (last name: brick-baker) and very likely the then resident responsible for the brick-built Agerskov House (Overby, 1997).

13 Amount of bricks calculated as follows: height multiplied width of each façade/ gable minus areas of holes for doors/ windows etcetera equals the area of the outer walls. Area multiplied with 131 bricks (standard measure for applied bricks per square meter in a one-brick wall) equals 18,078 bricks. Subsequently, the number was rounded off to 18,500 bricks due to waste etcetera. The authors stress that it is a rough estimate.

The modified building (1880–1997)

In this phase, the building was subject to several small alterations,[14] yet the layout and exterior only changed little. The stable was given cast iron windows and a hatch. Moreover, a beam was removed in the stable to make room for a Jutland horse (the 1950s) as well as five collar beams. Only a few changes happened to the layout such as the rebuilding of the fireplace in 1972, celotex insulation boards to improve the thermal comfort and fitting in a bathroom. Moreover, it is likely that the front door was changed (at least) twice (Slots- og Kulturstyrelsen, 2020, p. 142).[15]

The listed building (1997–)

Subsequent to the listing in 1997 and now a subject to the the Act of Building Preservation, major conservation works comprising all parts of the building began. The roof was rethatched, including new reed, laths and straw rope. The roof construction was repaired with reused oak timber (repairs comprising a rotten beam at the east gable, the removed beam in the stable and five missing collar beams). Regarding the outer walls, emulsion paint and many layers of lime wash were cleaned off and they were repaired, plastered and whitewashed. On the inside, the outer walls were padded with ¼ moler brick to improve the thermal performance and then covered with paneling in keeping with West Schleswig vernacular architecture. Furthermore, the windows and their fittings (hinges etcetera) were repaired, two cast iron windows replaced with other ones and, new doors and hatches made.

It is interesting to note that the owner made great efforts to discover and apply used building materials and components to support the identity of the building. Besides the reused oak timber, examples include a number of baroque doors and fittings from contemporary, now demolished buildings, reused cast iron windows, the paving of the kitchen and scullery with reused quarry tiles and paving of the entrance room with reused Oland floor tiles from the former pharmacy in Gram (Slots- og Kulturstyrelsen, 2020, p. 81).

4.3 Findings of the case study

Findings of the analysis are summed up in figure 3. Supporting presumptions are developed in the endnotes. Despite that the house is well documented, it was not possible to establish the age of all materials and components.

First, the roof construction of the Agerskov House originated from 1682 with minor repairs in 1783 and 1997, thus being 341 years old. Second, the roof was rethatched in 1997 equalling a present lifetime of 26 years. Since 1682, the roof must have been renewed/ repaired regularly due to the durability of such materials. Theoretically and following current practice, the roof would probably have been renewed around every 40th year equal to eight to ten times. With the knowledge of preindustrial

14 The delimitation of 1880 is grounded in the historical context. In the last part of the 19th century, many changes took place that also affected buildings. First, Denmark was industrialized rather quickly after 1850 and shortly after, the co-operative movement started, improving the financial situation of the farmers. New materials were introduced in building such as cast iron for e.g. windows, range cookers and stoves. The railway network facilitated easy transport of building materials and fuel, leading to the decline of vernacular building. Consequently, the process that lead to modern housing started in the late 19th century and thus, this delimitation.

15 Slots- og Kulturstyrelsen (2020, p. 142): picture showing the former front door and its predessor.

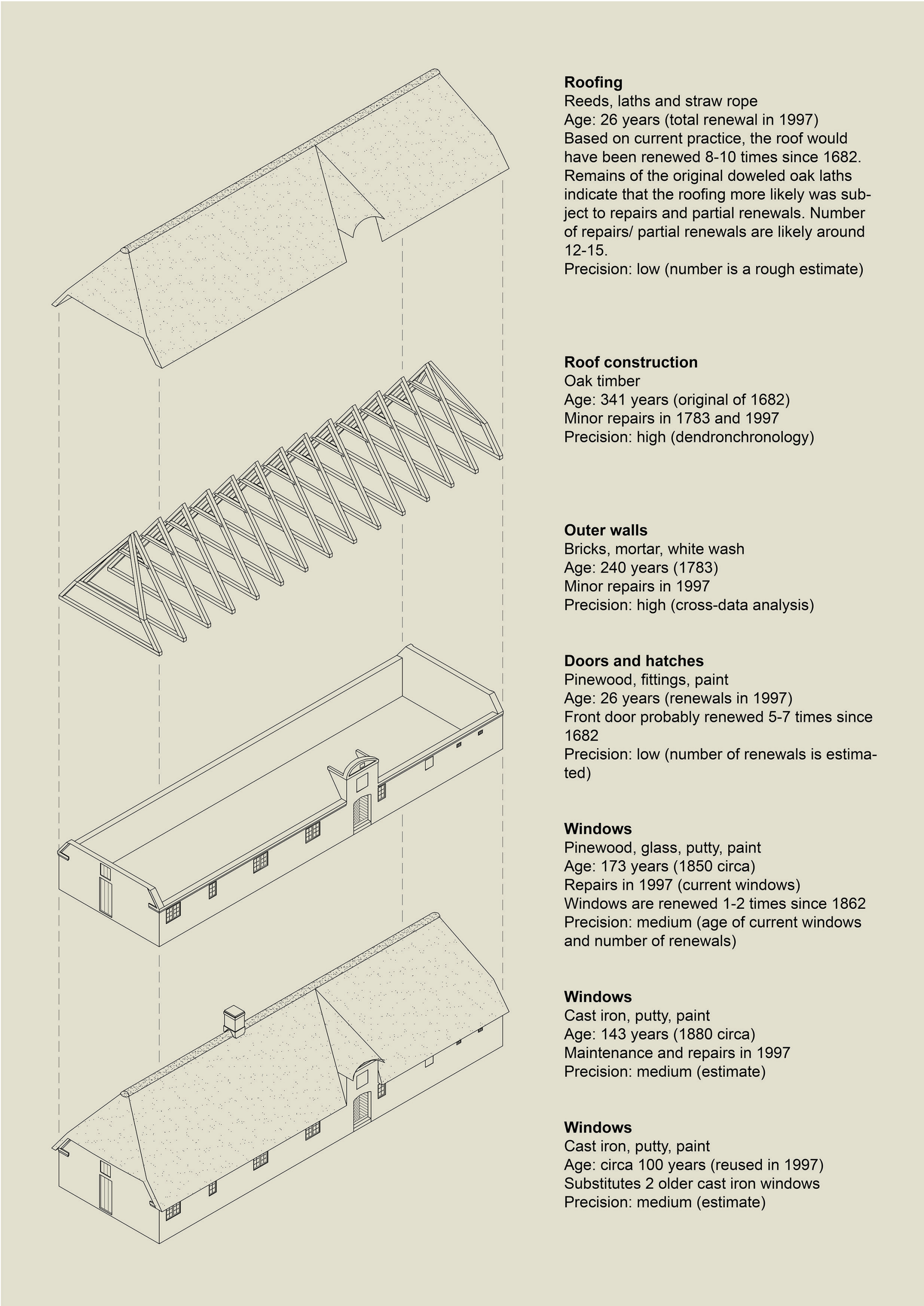

Figure 3
Axonometry of the Agerskov House showing the findings of the case study analysis. Each element is described with regard to materials, age, possible interventions such as repairs and finally, the precision of the dating. FIGURE BY BIRGITTE EYBYE.

vernacular building in mind, it is, however, very likely that the roof only was partially renewed/ repaired in the main part of the lifetime of the building (Eybye, 2016, p. 104-105). Such conclusion is supported by the discovery of original oak laths during the total renewal in 1997. Third, the brick walls date from 1783 with minor repairs in 1997, and they are now 240 years old. Fourth, the four exterior doors were manufactured in relation to the conservation works and are now 26 years old. It is not possible to determine the number of doors since 1682. A qualified guess will be that the house had five to seven front doors since 1682 along with a number of other exterior doors.[16] Finally, the windows of the dwelling date from 1850 circa equaling 173 years old. It is not possible to establish whether they are the second or third group of windows in the dwelling.[17] The cast iron windows of the stable are respectively around 130 years and 100 years old, of which the latter substitute two older cast iron windows.[18]

5. Discussion

The main objective of this study was to examine methods from the field of conservation as a means to discuss and qualify material lifespan in relation to the B- and C-stages of LCA. In doing so, a case study was executed. Hence, this discussion initiates relating to the applied methods and their limitations.

BHI is a mainly non-destructive empirical investigation method based on analogies between the physical components and archive sources, and conclusions on the age of the building components can have a greater or lesser reliability but also change if new data occurs. Several biases of a general sort can be pointed out in regard to the BHI. For instance, the knowledge and documentation of this generic accessible method can be attained by both professionals and laymen. Thus, the accuracy and credibility of the result depend on the skills of those performing the BHI as well as the time available for investigation. Moreover, the determination of age and origin of building components are only as plausible as the source material. Even though tools for exact validation, such as dendrochronology and radiocarbon dating are widely used in e.g. archaeology, they are only employed in rarer cases of architectural conservation.

In this research, the dendrochronological datings of the Agerskov House is a key element, for which reason it is elaborated separately from BHI. Initially, it is important to state that dendrochronological dating is only as certain as the samples made.[19] In the Agerskov dendrochronological investigations, the two samples were carefully selected. Ideally, more samples would confirm the two datings of the Agerskov House. The year 1682 is, however, considered as certain, since this year for a post-and-plank construction is rather late, as they at this time had been prohibited for more than a century and, the location of the building is west of the

16 The post-and-plank construction probably had two doors, see figure 2, which may or may not have been renewed within the first century of the lifetime of the building. In connection to the transition into bricks, the house may have been given a new front door. At the same time, a new door was fitted into each gable. The best room was given a so-called *ligdør*. The *ligdør* was only used when carrying the deceased out of the building, and as it was not otherwise opened, the dead could not return to the house and haunt the living inhabitants. The other door made access to the stable.

17 The number of window renewals is puzzling. The first group of windows in the dwelling relates to the post-and-plank construction and they were most likely small and leaded. The current windows date from 1850 circa based on the shape of the mullion, the profiles and fitting. It is possible that the leaded windows were reused in the brick building. Yet, studies of the cleaned facade bear no evidence of fitting in larger windows. It is also possible that the house had new windows in 1783 and again around 1850. Such a short lifetime (circa 67 years) of the second group of windows is unlikely given the careful maintenance of the roof.

18 It is probable that the stable had no windows or perhaps just one or two hatches before the cast iron windows.

19 For instance, reuse of building materials and components were common in heritage building (Jessen et al., 1975, p. 18; Eybye , 2016, p. 102-103) and a sample from reused timber or timber used for repair causes an erroneous dating. A large number of samples with coinciding dates arguably strengthens the result. Moreover, a sample may be difficult to date if only heartwood and no sapwood is seen. Finally, dendrochronological reference curves continuously improve and older, then non-datable samples may now be dated (Jensen, 2022).

'typical' area of such buildings (Overby, 1997). Furthermore, the year of 1783 converges with the dating on the mantel tree and consequently, is considered as reliable.

To conclude on the methodical aspects of the case study on the Agerskov House, it shows that the building is well-documented with an extensive and rather precise source material such as the records of the Agency for Culture and Palaces, the dendrochronological datings and other central datings based on cross-examinations. Hence, some of the findings (the age of the roof construction and the walls) are accurate and considered to be highly credible, whereas it proved difficult to establish how many times the doors and windows had been replaced and the roof rethatched.

It is interesting to note that the findings of the case study are consistent with the assumptions of Brand and van Reeth regarding the lifetime of structure and skin. The load bearing structure of the roof of the Agerskov House is – with a few moderations – from its origin in 1682, thus confirming the assumption that *structures* in relation to Brands terminology, are rarely changed. The load-bearing structure of the walls seems to have a slightly higher metabolism, than the roof construction. The building was erected as a post-and-plank construction, but the walls were converted into a brick construction in 1783. Regarding the *skin* (understood as roof cladding, wall plasters, doors and windows) of the Agerskov House, an even higher metabolism can be observed as maintenance and replacement of plaster and white wash of the walls have been executed an unknown number of times during the centuries. In addition, lifetimes of the doors and windows were inconclusive, showing that the metabolism of such might be somewhat higher than the outer walls. The different components and their metabolisms may also indicate how variated LCA scenarios in B-D stages could be described and formulated, since structures are more likely to have a long lifespan and low frequency of maintenance, whereas windows and doors seem likely to be changed more often and have a higher frequency of maintenance, in particular historic windows (Vadstrup, 2004, p. 261-295).

Continuing on the findings, the above case study demonstrates that the age of several of the materials and components by far exceed the general study reference period of LCA, such as the roof construction, the outer walls and the windows. It is important to mention that thatched roofs and timber generally are considered to be 'fragile materials' (Brogaard, 1985, p. 29). They need regular maintenance executed in accordance with the existing materials and with a technical understanding of the historic building techniques which may be pivotal to the material lifetimes. Regarding the Agerskov House in particular, BHI shows that maintenance and relevant renewals (e.g. the thatched roof) is a key issue in order to secure a long lifetime of the building. This finding highlights the challenges in relation to assumption-making on B-stages of LCA. From this derives the suggestion that the LCA should be considered as a dyadic tool comprising the concrete assessments of A-stages and the following stages as assumption-based scenarios describing multiple outcomes depending on building technical detailing, usage, maintenance etcetera.

Another outcome of the study relates to the use of BHI and its future potential with regard to LCA. It seems that BHI could be relevant and useful generally for the construction industry, as renovations seemingly make up the increasing amount of the resort area (Kongebro et al., 2012). But BHI is a complex area of knowledge, consisting of several skills, which raises the question whether the methodology should be taught more widely than it is today? Moreover, it is possible that extensive research into the method in combination with LCA could develop an intuitive and widely applicable tool that made the assessments on B–D stages more plausible or survey useable materials and components of buildings condemned to demolition. In relation to EOL scenarios, multiple case studies on BHI as an informant to life time might also document general EOL scenarios of different materials and components.

Methodically, the Agerskov House was selected as a 'typical' case due to its common materials and components. Yet, it can be argued to be a 'critical' case. Critical cases permit logical deduction of this kind: "If it is (not) valid for this case, then it applies to all (no) cases." (Flyvbjerg, 2006, p. 230). If the Agerskov House with its fragile building materials (see above) has lasted for 341 years due to maintenance, then more houses are most likely to last longer if correctly maintained. In this context, it is also noticeable that the layout of the Agerskov House have changed multiple times during the centuries within the original structures. In the light of climate change and considering the findings of this study, it thus seems reasonable to reconsider whether the usual study reference period of 50 to 80 years in LCA is equitable, in particular when it comes to buildings constructed of materials with high CO_2 emissions such as metal, concrete and bricks (CINARK/ Det Kgl. Akademi og Vandkunsten). The notion that future generations should not inherit the emissions of our time is noble, yet the need for longer lifespans of buildings must be addressed. Currently, it is estimated that circa 11 per cent of global emissions are related to building materials and construction. With the growing population, new building will increase and consequently, emissions from upfront carbon are expected to make up half the carbon footprint of new construction until 2050 and hence, becomes a large part of the emissions (Adams et al., 2019, p. 7). This study's findings and the initial retrievals of Statbank Denmark support the potential of maintaining and renovating the existing building stock. In doing so, extensive CO_2 reductions are likely be achieved by decreasing upfront carbon of e.g. virgin materials used in load bearing structures. This approach is in line with what architects and researchers Simon Guy and Graham Farmer characterise as 'the eco-centric logic' (Guy & Farmer, 2001) and the idea put forward by e.g. Professor Richard Ingersoll that we have built all we need already and have to reuse (Ingersoll, 2019). This subject matter is now generally discussed among architects, e.g. the exhibition 'Die Schweiz: Ein Abriss' that highlights the enormous amounts of waste generated by building (Lundberg, 2022). Within architectural conservation, reuse of materials and components have become more prevalent. In the conservation of the Agerskov House of 1997–2000, reuse was highly likely due to the identity of the building and architectural whole (Eybye , 2022, p. 120-121), whereas the conservation of Ørslev Kloster substantiates reuse with reference to sustainability and thus, ethics.[20] Moreover, several works of the Danish architect studio Lendager Group concern extensive reuse such as Upcycle Studios, Resource Rows and The Swan and, Belgian Rotor DC organize reuse of building materials.

20 Site visit at Ørslev Kloster in relation to FORUM 2022 (seminar and site visits regarding architectural conservation 23.–24. September 2022).

Conclusion

Initially, this article problematized the structure of LCA especially the assumptions on general lifespans of 50–80 years of building materials. Subsequently, the question how knowledge of materials and components in heritage buildings may qualify the standardisation of material lifespan in LCA was put forth. This thesis was investigated through the methodology of BHI in the carefully selected case study of the Agerskov House. The study examined the building and various literature, of which the documents of a right of access regarding the conservation works turned out to be an important source of information. The well documented building showed that most building components exceeded the assumed lifespan in LCA, for instance the load-bearing construction more than 4 times, if the study reference period is 80 years. Furthermore, the study indicated that the different architectural components such as the load-bearing structures of roof and walls, doors and windows have different metabolisms and as a consequence, have different levels of substantiated documentations. E.g. the windows, which have had a high metabolism has been more difficult to make definite conclusions on, than the load-bearing structures validate trough both observations and documentations.

To answer the research question, the result of this investigation shows, that the assumed EOLs presented in LCAs might diverge substantially from reality, if building components go through regular maintenance. Ergo, more knowledge is needed on general usage and maintenance and its influence on the lifespan of building components. Consequently, these scenarios will be suggestive, as the user will have tremendous influence on the actual lifespan on building components transforming the B–D stages to different scenarios regarding if the user are honouring regular maintenance (long lifespan) or acting in relation to a more consumer-based culture (short lifespan). The method of BHI have a possibility to give estimates into this subject, and qualify knowledge on long term and short-term maintenance. In this context, the authors recommend that a critical mass of results is collected, by centralized data collection of results from other studies of BHI on historic/existing buildings. This data could substantiate the LCA and subsidize assessments of different scenarios in the B–D stages of a building.

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Biographical information

Birgitte Tanderup Eybye
Aarhus School of Architecture
Address: Exners Plads 7, DK 8000 Aarhus C, Denmark
Phone: +45 8936 0242
E-mail: bte@aarch.dk

Birgitte Tanderup Eybye is an assistant professor at the Aarhus School of Architecture, Denmark. She has a master in architectural conservation and did her doctoral thesis within the field of preindustrial vernacular architecture and sustainability. Her special fields of interest are architectural conservation, connections between sustainability and existing (heritage) buildings, and architectural heritage, in particular vernacular architecture and earthen building. She teaches architectural conservation and adaptive reuse.

Biographical information

Henriette Ejstrup
Royal Danish academy Institute of Technology
Address: Philip De Langes Allé 10,
DK-1435 København K, Denmark
Phone: +45 29439516
E-mail: hejs@kglakademi.dk

Henriette Ejstrup is educated as an architect from Aarhus School of Architecture with a specialization I architectural heritage. In 2019 she obtained her Ph.D. degree in affiliation with Center for Industrial Architecture at the Royal Danish Academy focusing on the tectonics of insulation in Danish vernacular buildings. She possesses an Assistant professorship at the Royal Danish academy Institute of Technology focusing on artistic research, historic buildings, vernacular traditions and their relations to the industrialised architecture as well as she is teaching and co-running masterclasses in sustainable building culture.