Nordisk Arkitekturforskning
The Nordic Association of Architectural Research

Proceedings Series 2023-1

CONCEPTS OF TRANSFORMATION

Editors: Anne Elisabeth Toft and Magnus Rönn

NAF/
NAAR

Nordisk Arkitekturforskning
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PUBLISHER
Nordic Academic Press of Architectural Research
http://arkitekturforskning.net/na/issue/publishing

EDITORS
Anne Elisabeth Toft and Magnus Rönn

GRAPHIC DESIGN
Sølvi Delbekk

COPY-EDITING
Dawn Michelle d'Atri, Amy Klement and John Wheelwright

PRINTING
Aksell AS

ISBN 978-91-983797-7-8

FINANCIAL SUPPORT
Dreyers Fond, Brandförsäkringsverkets Stiftelse för bebyggelsehistorisk forskning, Stiftelsen Arkitekt Agnar August Palmérs Minne and Stiftelsen Elna Bengtssons Fond för Vetenskaplig Forskning

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FOREWORD

Anne Elisabeth Toft and Magnus Rönn

The Nordic Association of Architectural Research (NAF/NAAR) is an independent association of architectural researchers from universities and schools of architecture in the Nordic countries. It has been in existence since 1987.

The present book is the proceedings publication from the 2021 NAF/NAAR symposium by the name of *Concepts of Transformation*. NAF/NAAR symposia are held once a year. They are important platforms for critical reflection on architecture and architectural research in the Nordic countries. To ensure their dynamic and democratic format, the events are conceptualized and organized in collaboration with various partners and each year hosted by a different university or school of architecture. True to tradition, the symposium focuses its discussions on a topic or theoretical framework representing the current research interests of NAF/NAAR and its collaborators.

Fifty researchers from the Nordic countries and abroad attended *Concepts of Transformation*, which took place on 3–4 November 2021 in Aarhus, Denmark. It was the result of a close collaboration between NAF/NAAR and colleagues from Research Lab 1: *Transformation* at the Aarhus School of Architecture. Twenty-nine paper presentations were given during the symposium. In addition, three keynote speeches were held by distinguished scholars, whose interesting lectures contextualized the discussions of the event, along with welcome addresses by NAF/NAAR president Anne Elisabeth Toft and by Mogens A. Morgen and Tom Nielsen, professors at Research Lab 1: *Transformation*.

Critically pursuing different concepts of transformation, how they have emerged—why and when—the symposium set the stage for discussions about the role of transformation and transformation processes within architecture, landscape architecture, and urbanism.

All eleven articles in this proceedings publication—except those by the invited keynote speakers Sven-Olov Wallenstein, professor at Södertörn University in Stockholm, Sweden, and Mo Michelsen Stochholm Krag, associate professor at Aarhus School of Architecture, Denmark[1]—were submitted to a double-blind peer-review process conducted by NAF/NAAR. The publication also includes a not-peer-reviewed written contribution by Mogens A. Morgen and Tom Nielsen. At the request of NAF/NAAR, they have kindly authored an introduction to Research Lab 1: *Transformation's* focused engagement with transformation.

As president and vice-president of NAF/NAAR, we extend our sincere gratitude to the many colleagues who kindly contributed to the symposium and/or to the present book. Thanks go to our collaborators at the Aarhus School of Architecture: professor Mogens A. Morgen, professor Tom Nielsen, research coordinator Hanne Foged Gjelstrup, and research assistant Sidse Martens Gudmand-Høyer for successfully co-organizing the symposium. Equally, on behalf of the association, we wish to thank the many researchers from Research Lab 1 who participated as moderators during the symposium.

We are very grateful to the individual authors who submitted articles to the publication and to the many peer reviewers who have supported NAF/NAAR and its work by offering their time and professional expertise in reviewing the articles. We would like to express our appreciation to all of these people.

Last but not least, we address our gratitude to our financial benefactors. The publication of the present book was made possible thanks to the generous support of Dreyers Fond, Brandförsäkringsverkets Stiftelse för bebyggelsehistorisk forskning, Stiftelsen Arkitekt Agnar August Palmérs Minne and Stiftelsen Elna Bengtssons Fond för Vetenskaplig Forskning.

Anne Elisabeth Toft
President of NAF/NAAR

Magnus Rönn
Vice-President of NAF/NAAR

NOTES

[1] The three keynote speakers at the symposium were: Sven-Olov Wallenstein, professor at Södertörn University in Stockholm, Sweden, Mo Michelsen Stochholm Krag, associate professor at Aarhus School of Architecture, Denmark, and Ellen Braae, professor at Copenhagen University, Denmark. The latter did not develop her keynote lecture into an article for this publication.

LIFE-CYCLE ASSESSMENT OF TRANSFORMATION SCENARIOS OF A TRADITIONAL DANISH HOUSE

Teddy Serrano, Thomas H. Kampmann, and Morten W. Ryberg

ABSTRACT

Renovation is usually seen as more environmentally friendly than restoration, but little information can be found in the relevant literature on the subject. The 'Apprentices' House' is a small, neglected, half-timbered house from 1887, located on the island of Bornholm in Denmark. To make the house suitable for dwelling again, a restoration or renovation must be carried out. An environmental life-cycle assessment (LCA) was conducted to quantify the environmental impacts pertaining to those transformation scenarios, so as to identify the most environmentally friendly way to make the building inhabitable again. The influence of relevant parameters on the output results, that is, the assessment period of the study (fifty or one hundred years were considered) and the dataset used to estimate building materials lifetimes (two were considered), was also studied. The results show that for most environmental impact categories, restoration performs as good or better than renovation. This conclusion is robust regarding the choice of the assessment period. When changing the material lifetime data, restoration shows similar impacts, but results for renovation expose substantial variations. The LCA results were finally compared with LCAs on new single-family residential homes to assess the climate performance of restoring or renovating as an alternative to demolishing the existing house and building a new one. The comparison indicates that transforming an existing building appears to be preferable to the construction of a building and, thus, the most climate-friendly solution.

KEYWORDS

Restoration, traditional building materials, building archeology, sustainable houses

INTRODUCTION

Background

When reusing an existing historical building, there are mainly two approaches, either to restore or to renovate. The difference between both practices can be defined as follows. Restoration means to repair existing building parts using materials and techniques that were used for the construction of the building in the first place. In Denmark, this can for instance involve abiding by the requirements and recommendations from the Danish Agency for Culture and Palaces, Culture Heritage (SLKS), in case the building is listed.[1] The restoration of a building also entails the maintenance of its cultural heritage, with, for example, regional traditional building practices that make it easier to repair and maintain the building. This requires that the architects, engineers, and especially craftsmen working with the building have the necessary restoration skills and experience.[2] It is for example very important that traditional materials (e.g. paint and mortar) are not too dense to prevent condensation formation, or that stronger materials (e.g. concrete) are not applied to weaker materials (e.g. burnt bricks), in order not to damage them.[3] In the case of a renovation of a historical building, in turn, building parts are replaced by contemporary ones using modern materials and with the intention of meeting the requirements of the building legislation in the country where the building is located. Contemporary techniques are usually widely known and do not require special restoration knowledge. As to the building materials, they can be purchased easily in most places. In this article, the 'transformation' of a building is used as an umbrella term to refer to the restoration or the renovation of this building.

Among architects working with transformation of the existing building stock, there is a widespread perception that it is more sustainable to restore existing buildings using traditional techniques and materials, rather than to renovate them using cutting-edge contemporary materials. Concrete knowledge on this subject is, however, missing, as only a few studies have quantified the environmental impacts of restoration, especially with regard to other transformation options, or to the construction of new buildings.[4] Moreover, the existing studies do generally not propose detailed sensitivity analyses to estimate the influence of the modification of input parameters (e.g. the lifetime of building materials considered) on the overall environmental performance of the transformation options studied.

Object of Study

The master's programme in Cultural Heritage, Transformation and Conservation (KTR) at the Royal Danish Academy focuses on limiting the climate impacts of buildings by transforming the existing building stock, while preserving both the valuable aesthetic expression and cultural heritage of existing buildings. In 2017, KTR came in contact with Dansk Håndværk (Danish Craftsmanship), which had just bought an old house on the Danish island of Bornholm, 'The Apprentices' House' (fig. 1), with the purpose of transforming the building into a place where young people could come and be introduced to various crafts. The building, from 1887, had undergone a number of questionable renovations and appeared to be in a rather neglected condition with many alterations, while some of the original building elements had been preserved. This house, which is about to be restored, is a

Figure 1. 'The Apprentices' House' as it looked when the project started in 2018 with a raised Eternit slate roof, plastic-painted walls, plinth, and half-timbering. Photo: Thomas Kampmann.

good example of many other similar traditional single-storey half-timbered houses in the countryside. Moreover, the measurements of the different building elements and the large quantitative data gathered by the previous archeological and architectural studies conducted (cf. Appendix, Figures A.6–A.8) gave an extensive overview of the material composition of the house. This case study was therefore seen as a good opportunity to perform an environmental assessment of different building transformations and to contribute to addressing the identified knowledge gaps.

Research Objectives

The purpose of this study was to find out which transformation scenario for the house had the lowest environmental impacts, with a focus on climate change, due to its relative importance in the eyes of decision makers in the building sector. Calculations of the environmental impacts associated with each transformation option were carried out to determine which option would be the most environmentally friendly. The assessment was performed using life-cycle assessment, a widespread and standardized tool for assessing the environmental performance of products and systems. The study also included relevant parameter variations, such as the source of the lifetime of the building materials considered or the choice of the assessment period. Finally, a comparison between the selected transformation scenarios and the construction of a new standard building of a similar size was carried out.

THEORETICAL FRAMEWORK: QUANTIFYING ENVIRONMENTAL IMPACTS WITH LIFE-CYCLE ASSESSMENT

Life-cycle assessment (LCA) is a standardized[5] tool for quantifying the possible environmental impacts of different solution alternatives. LCA can thus be used to support decisions by identifying the alternative with the lowest potential environmental impact.[6] The primary strength of LCA is that it considers the full life cycle of the alternatives and all potentially relevant environmental impacts. By including all life-cycle stages and environmental impacts that may be relevant, LCA can avoid possibly overlooking important aspects that might otherwise have led to a shifting of burdens.[7] For instance, a reduced use of insulation might improve environmental impact performance related to material production. However, the associated increase of heat loss over the building lifetime may create an even larger environmental impact. Likewise, options for reducing global warming by use of biomaterials might give rise to other impacts due to increased land use from biomaterial production. Such potential trade-offs can be highlighted in an LCA and provide decision-makers with an informed basis for making the best possible decision from an environmental perspective.

An LCA consists of four main phases,[8] as illustrated in Figure 2: 1) Goal and scope; 2) Life-cycle inventory (LCI); 3) Life-cycle impact assessment (LCIA); and 4) Interpretation. An LCA is an iterative process. It is thus common to go back and revise the scope or the LCI after interpretation, in case the results are not fully in line with what was described in the goal of the LCA study.

In the Goal and scope phase, the objectives of the LCA are defined. The scoping of the LCA is done by specifying exactly what the LCA should assess and by defining the scope and principles on which the LCI and LCIA should be performed. In the LCI, the product system of a solution alternative, for example a building, is modelled across its full life cycle starting from raw material production, through production and manufacture, over use, until final disposal and waste treatment. The modelled LCI consists of several activity-specific processes that include information on the resource use and emissions of chemicals (collectively called 'elementary flows') into the environment from each process. In the LCI, all elementary flows from all

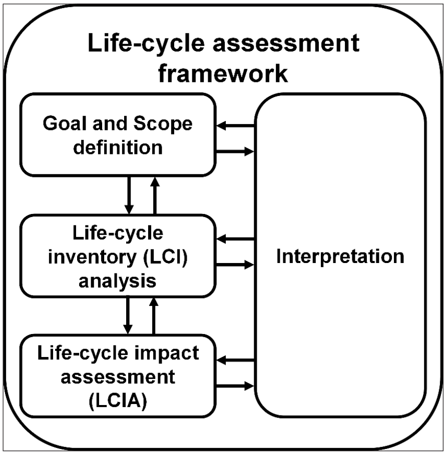

Figure 2. The overall theoretical framework for an LCA, consisting of the four phases in an LCA. Model by Morten W. Ryberg.

processes that are part of the alternatives' life cycle are aggregated to provide a full inventory of all the resources uses and chemical emissions related to the alternative. In the LCIA phase, the inventory of elementary flows from the LCI are translated into potential environmental impacts, such as climate change, land use, water use, resource depletion, ecotoxicity, et cetera. Finally, the results of the LCIA are evaluated in the Interpretation phase to identify which of the alternatives has the overall lowest environmental impact.[9]

LCA is often used to quantify the environmental impact of buildings or building components, for instance as part of building certification schemes. While LCA is mainly applied to new buildings, it is also used for identifying the most environmentally friendly options for renovating existing buildings. Here LCA can be used for answering two types of questions. 1) What were or are the environmental consequences of renovating using one approach compared to an alternative approach? 2) What are the environmental savings from reusing the materials that are kept during the renovation compared to production of new, comparable materials? LCA can thus be utilized for identifying the best alternative, environmentally speaking, or can indicate the impact savings of renovating compared to new construction. The solution to be selected in an LCA on renovation depends on the overall goal of the LCA and the decision (or types of decisions) that the LCA is intended to support. Indeed, LCA is the best method for quantifying and showing the potential environmental impacts of an activity, such as the renovation of a house.[10] However, LCA cannot provide information about any of the other aspects that are important to consider during a decision-making process. Thus, it is not advised to base decisions solely on LCA results or on other tools for evaluating; for instance, economic and social factors (such as aesthetic, cultural, and historical values) are needed to provide a solid and comprehensive basis for decision-making.

METHODS

Description of the Different Transformation Scenarios

In this study, LCA calculations have been made for four scenarios of transformation of the existing building—three restoration scenarios and one renovation scenario. The former are intended to be carried out as if the building were listed—although it is not the case here. When a building is listed in Denmark, except for carrying out ordinary maintenance, one must first contact SLKS, which is responsible for listed buildings in the country. Based on a description and drawings of the project, they decide if one can get permission for the desired changes. As the considered building in this study is actually not listed, SLKS has not been consulted. It is, however, the authors' belief that the described changes to the building are within the realm of what could realistically be approved.

In the first scenario, Scenario 1 (S1), as many original building parts as possible are preserved, and the building parts added are preferably made up of materials similar to the original materials. No exterior insulation has been considered, as this would heavily alter the appearance of the building and, in this particular case, not be aligned with the guidelines provided by SLKS.[11] A limited re-insulation is therefore carried out (75 mm internal insulation on exterior walls), as probably permitted in a listed house. This allows the proportions of the room to remain almost identical, with only little valuable living space lost.

As it was expected that the heat loss from the building would be of great importance for the overall environmental impact, an additional restoration scenario, which includes a higher insulation thickness in the house, was considered. This scenario is Scenario 1b (S1b). S1b is therefore similar to S1, but the internal wall insulation is increased to 200 mm, and retrofit insulation is fitted to the existing exterior doors with 40 mm insulation.

As SLKS has not confirmed whether the proposed work in Scenario 1 would be approved, a scenario without re-insulation, which, according to the authors, has the greatest probability to be accepted by the agency, was included. This Scenario 1c (S1c) was also relevant as it permitted an assessment of how important re-insulation of an older house will be. In S1c, the building is therefore restored as specified in Scenario 1, but without post-insulation or addition of secondary glazing to the windows. This scenario is therefore the one that entails the least intervention on the building. There are many people—especially architects—who believe that this option is likely to be the most environmentally friendly, as the future development of green energy production means that insulation will be of less relevance in reducing environmental impacts.

Finally, in Scenario 2 (S2), the house is renovated to comply with the Danish building regulations from 2018[12] in relation to energy consumption and with the use of new contemporary building materials. Here, ceilings, walls, and floors are re-insulated and exterior doors and windows replaced with new ones. In this scenario, mineral wool (300 mm) is used to insulate the walls of the building. This requires an additional air gap of 50 millimetres between the insulation and the existing wall, thereby reducing substantially the effective living space.

Scope of the Study

To compare the two renovation options, a functional unit describing the main function provided by the transformation options of the building was defined. In this study, the functional unit was defined as 'use of the building for dwelling during one average year in Bornholm, Denmark'. As the results of this LCA may only involve decisions made to buildings that are in a similar situation to this house, the results are not expected to have large-scale consequences on the building sector. Therefore, the decision context, specifying the intended application of the study, was defined as a micro-level decision support. This is also reported as *Situation A* in the ILCD LCIA methodology, a document providing detailed guidance for LCA applications and recommended by the European Commission.[13] As a result, we modelled the life-cycle inventory (LCI) using an attributional approach, that is, using data on market average suppliers. We used the cut-off methodology[14] for modelling recycling as recommended in the European standard on LCA of construction.[15]

Performing an LCA also requires defining an assessment period, which specifies the time frame of the study. In building LCA, the assessment period is normally defined as equal to the lifetime of the studied building. Fifty years has become the standard lifetime used in building LCA.[16] However, fifty years can be considered a relatively short lifespan, especially for restoration architects that are used to working with buildings that have a much longer lifespan. Extending the assessment period raises problems as to the difficulty of estimating future technological, environmental, and societal developments, on which the LCA is also based—one can just try to see how much the building sector and society in general have developed over the last fifty years. This being said, the restoration scenarios assume that the building is listed and, in this case, that a lifespan of only fifty years is very unlikely—not least considering that the building is now already 134 years old. An assessment period of one hundred years, which considers a house lifetime of one hundred years, was therefore also studied to show how it may affect the environmental performance of the different solutions and the comparison among the four scenarios.

The impact results were estimated for sixteen environmental impact categories based on the European Commission's recommended ILCD LCIA methodology.[17] For one of those sixteen impact categories, however, 'Ionizing radiation E', the results, shown as interim, were not considered mature enough to be used and were therefore left out. The characterized results were then related to the annual impact of an average person in the world in 2010 using the normalization references derived by Sala et al.[18]

The system boundaries for the LCA are indicated in Figure 3. The foreground system consists of processes that are directly involved in the life cycle of the transformation. These processes were directly created in this study based on available data about the building as described in the 'Results' section. The LCI was modelled in the dedicated LCA software OpenLCA 1.10.3. The background system was based on the data in Ecoinvent 3.7, using the 'cut-off' database in accordance with European standards.[19]

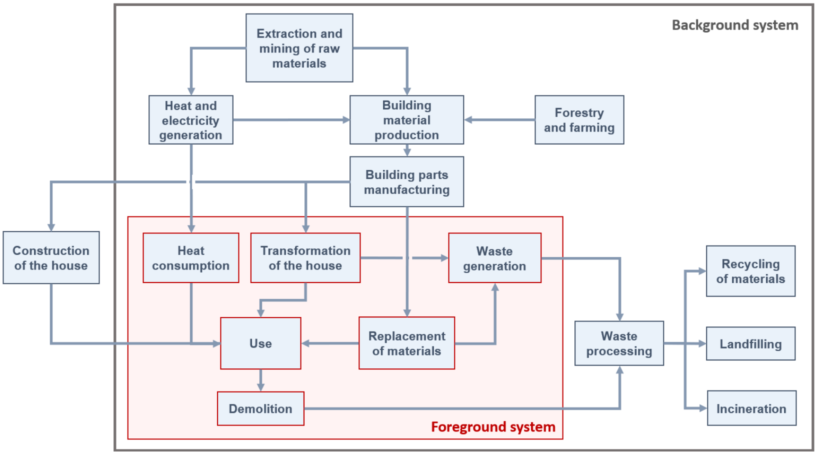

Figure 3. System boundaries of the LCA, applicable to all scenarios. The foreground system consists of processes that are directly involved in the life cycle of the transformation. Modified model by Teddy Serrano based on ISO 14040

Life-Cycle Inventory

In this section, the life-cycle inventory (LCI) is provided with details for each of the following life-cycle stages:

- the transformation stage, accounting for the removal and input of building parts and materials during the restoration or renovation process;
- the replacement stage, standing for the replacement of the building materials whose lifetime is lower than the building lifetime;
- the energy consumption during the use phase;
- the demolition stage, representing the end-of-life treatment of all the house materials at the end of the building lifetime, when the building is torn down.

A description of the LCI for those stages is further detailed in the next subsections, providing details as to which materials were included in the scope of this study, as well as how the quantity of energy consumed in the building was calculated. The description of the LCI of this study is based on that of another study that was carried out on the same building.[20] Regarding the modelling of processes, for many widely used contemporary materials (e.g. clay brick, concrete, wood), equivalent unit processes have been directly adopted from the Ecoinvent database. For specific materials and products (e.g. some insulating materials, windows), new processes were created in order to best account for their composition. The full list of the processes modelled for the LCI is provided in an open online data repository on Zenodo[21] (sheet 'LCI Materials' and 'LCI Building').

Transformation

During this first stage, regardless of the scenarios of restoration or renovation, old building materials are being removed from the house, while others are retained. Some new building materials are also added during this transformation process to rehabilitate the house. Differences are, however, observed regarding the type and quantity of materials removed or added to the house in the different scenarios. As the scenarios S1b and S1c are slight variations of Scenario 1, we now provide details on this phase only for Scenarios 1 and 2 (S1 and S2, respectively).

To estimate the bill of materials under both scenarios, on-site measurements of the building were first performed. This enabled one to make drawings of the house (cf. Appendix, Figures A.1–A.5), from which material geometries were determined in order to make an inventory of the materials present in the house before transformation. Then, in both scenarios, it was considered that the brick and timber structures, oak and pine beams, wooden roof structure, stairs, foundations, and interior doors of the house are kept as far as possible. In S1, all windows and exterior doors are also preserved. It was, however, assumed that 30 per cent of the retained structural timber, 5 per cent of the masonry, and 5 per cent of the wood composing the kept doors and windows needed to be replaced. In both S1 and S2, the modern materials introduced during past renovation attempts, for instance the one that occurred in the late 1960s, are removed (such as mineral wool and gypsum in the walls, or fibre cement on the roof). For the new materials ultimately entering the house, thatching covers around 75 per cent of the surface of the roof in S1, the rest being covered with tiles. In S2, only tiles are used. For the windows, they are considered to be extended by a wooden frame with a layer of energy glass in S1, while in S2, new wood-aluminium windows, of the two-pane energy type, are replacing the old ones. In S1, the new interior walls are generally rebuilt with adobe bricks and covered in clay mortar, whereas gypsum and mineral wool are preferred in S2. In both options, the chimney is rebuilt with burned bricks. Finally, regarding the insulation, in S1 the building envelope (composed of all the surfaces in touch with the exterior) is insulated as thick as possible without altering the original appearance of the surfaces. This thickness has been set to 75 mm, which was assumed to be a balanced compromise. Insulation materials are chosen so that they are comparable to the materials originally used when the house was first built, such as hempcrete,[22] wood fibre,[23] and windproof insulation.[24] The floor is constructed and insulated using wood fibre insulation and Ytong.25 In S2, the building envelope is insulated with mineral wool only to meet the energy requirements of the current standards.26 As to the inside part of the exterior walls, they are modelled as covered with lime mortar in S1, and gypsum in S2.

Table 1 provides an overview of the material inputs and outputs for those two scenarios. For S1b and S1c, the bill of materials is similar to that of S1, except for the insulation. Indeed, in S1c, no insulating materials, or secondary glazing in the windows, are considered to be used during the transformation phase. On the contrary, in S1b additional insulation is used (compared to S1) in the exterior walls and the exterior doors; this results in the input of

19.98 m^3 of hempcrete instead of 9.18 m^3 for the exterior walls, as well as an additional 0.29 m^3 of wood fibre insulation and 0.10 m^3 of plywood for the doors. A full overview of the life-cycle inventory used for modelling the two transformation options, including the specific processes employed to model the full life cycle, is provided in the dedicated data repository.[27]

Table 1. Material input and output for the transformation phase in Scenario 1 (S1) and Scenario 2 (S2). Source: The authors.

		Scenario 1 – Restoration			**Scenario 2 – Renovation**			
	Material	**Kept**	**Removed**	**Added**	**Kept**	**Removed**	**Added**	**Unit**
Beams	Oak wood	1.11	0.48	0.53	1.11	0.48	0.53	m^3
	Pine wood	0.63	0.82	0.71	1.02	0.44	0.44	m^3
Ceiling	Gypsum		0.35			0.35	1.25	m^3
	Mineral wool		0.49			0.49	44.85	m^3
	Timber	4.64		1.05	3.78			m^3
	Lime mortar	2.17	0.11	0.94	0.67	1.61	0.02	m^3
	Wood insulation			44.63				m^3
Exterior doors	Glass (new glazing)						0.02	m^3
	Glass (old glazing)	0.01		0.01		0.01		m^3
	Pine wood	0.51	0.03	0.03		0.54		m^3
	Wood-alu door frame						14.41	m^2
	Plywood							m^3
	Wood fibre insulation							m^3
	Linseed oil			6.51				kg
Exterior walls	Gypsum		0.22			0.22	1.20	m^3
	Lime mortar		0.13	1.50		0.13		m^3
	Brick	15.82	0.83	0.83	15.82	0.83	0.83	m^3
	Timber	0.42	0.11	0.11	0.42	0.11	0.11	m^3
	Hempcrete			9.18				m^3
	Windproof			0.24				m^3
	Mineral wool						29.98	m^3
Floor	Concrete		6.65			6.65		m^3
	Timber	2.44		1.53	2.44		1.53	m^3
	Wood insulation			39.71				m^3
	Aerated concrete			13.24				m^3
	Mineral wool						26.47	m^3

		Scenario 1 – Restoration			Scenario 2 – Renovation			
	Material	**Kept**	**Removed**	**Added**	**Kept**	**Removed**	**Added**	**Unit**
Foundations	Concrete	3.08			3.08			m^3
	Natural stones	7.58			7.58			m^3
Gazebo	Brick	1.98	0.10	2.01	1.98	0.10	2.01	m^3
	Bitumen sheet			10.12			10.12	m^2
	Pine wood			0.87			0.87	m^3
Inner elements	Pine wood	2.58	0.05	0.05	2.52	0.05	0.05	m^3
	Glass (old glazing)	0.00			0.00			m^3
Interior walls	Concrete		0.95			0.95		m^3
	Gypsum		3.32			3.32	1.32	m^3
	Brick	6.63	3.39	1.40	6.63	3.39	1.40	m^3
	Adobe brick		1.15	6.81		1.15		m^3
	Mineral wool		5.92			5.92	8.26	m^3
	Lime mortar	0.08		1.78		0.08		m^3
	Clay mortar			1.65				m^3
Roof	Bitumen sheet			52.36			195.86	m^2
	Pine wood	5.20			5.20			m^3
	Fibre cement		1.63			1.63		m^2
	Thatched roof			171.50				m^2
	Tiles			2.06			7.72	Tonnes
Windows	Glass (new glazing)						0.15	m^3
	Glass (old glazing)	0.06		0.04		0.06		m^3
	Pine wood	1.09	0.06	0.29		1.15		m^3
	Wood-alu window frame						13.85	m^2
	Linseed oil			25.11				kg

Replacement

When the assessment period exceeds the lifetime of the materials, they are considered to be taken down from the building and replaced by the same material input. In the building sector today, there is a strong focus on the durability of different building parts, and the subject is controversial. Lifespans are extremely difficult to predict due to the multitude of unknown factors that affect the actual lifetime of a building material. Therefore, the environmental impacts were estimated based on two sets of building material lifetime estimates. First, material lifetimes (LT1) were based on a study from Statens Byggeforskningsinstitut,[28] which provides estimates of material lifetimes for different uses of the materials in the building. A second set of material lifetimes (LT2) was developed by the authors. This was partly based on building archeological investigations, where the age of the individual building parts was determined from the experience of restoration architects.[29] Depending on the assessment period taken into account (either fifty years, also referred to as AP50 or one hundred years, referred to as AP100), the number of times that materials need to be replaced during the lifetime of the building varies. Those are documented in Table 2, showing the building material lifetimes depending on the lifetime source taken, as well as the corresponding number of replacements for each assessment period.

*Table 2. Material lifetimes used for the study, and their corresponding number of replacements during the building lifetime, depending on the lifetime source (LT1 or LT2) and assessment period (AP50 = fifty years; AP100 = one hundred years) considered. *Only 20 per cent of the linseed oil is assumed to be replaced every ten years. Source: The authors.*

Building material	**Material lifetime source**		**Number of replacements for AP50**		**Number of replacements for AP100**	
	LT1	**LT2**	**LT1**	**LT2**	**LT1**	**LT2**
Bitumen sheet	50	50	-	-	1	1
Brick	300	300	-	-	-	-
Clay mortar	50	50	-	-	1	1
Concrete	200	150	-	-	-	-
Fibre cement	80	80	-	-	1	1
Glass (new glazing, energy panes)	20	20	2	2	4	4
Glass (secondary glazing)	50	100	-	-	1	-
Gypsum	50	40	-	1	1	2
Hempcrete	50	50	-	-	1	1
Lime mortar	60	100	-	-	1	-
Linseed oil*	10	10	4	4	9	9
Natural stones	300	300	-	-	-	-
Plywood	60	60	-	-	1	1

Building material	Material lifetime source		Number of replacements for AP50		Number of replacements for AP100	
	LT1	LT2	LT1	LT2	LT1	LT2
Mineral wool	60	40	-	1	1	2
Adobe brick	100	100	-	-	-	1
Thatching	50	50	-	-	1	2
Tiles	80	80	-	-	1	1
Timber	100	100	-	-	-	-
Wood/alu doors frame	50	40	-	1	1	2
Wood/alu windows frame	50	40	-	1	1	2
Windproof insulation	60	60	-	-	1	1
Wood fibre insulation	60	60	-	-	1	1
Ytong	100	100	-	-	-	-

Energy Consumption for Heating

By definition, the energy consumption for heating is meant to balance the heat lost during the use of the building. In order to estimate the transmission heat loss of the house, an assessment of the insulating performance of the building envelope and the doors/windows under both scenarios was carried out. The assessment was based on the recommendations of the Danish Standard 418:2011 + Till.1:2020.[30] It includes the calculation of transmission heat loss through all the surfaces of the house in contact with the outside during an average year on Bornholm island, Denmark. Heat transfer was also calculated at the junction between those surfaces, in particular between the foundation and the walls and around the doors and windows frames. The calculations used to estimate the yearly transmission heat loss are provided in the aforementioned online repository[31] (sheet 'Heat loss, S1' and 'Heat loss, S2'). Table 3 shows the estimated annual heat loss for the building in all scenarios. The ventilation heat loss related to the renewal of the interior air, has, for the default case, not been studied. The data available to quantify airflow through the building envelope was indeed not deemed sufficient to differentiate the losses across the scenarios. This point is further discussed in the section 'Comparison of Restoration/Renovation Scenarios' below.

*Table 3. Heat loss through the different surfaces of the building envelope, as well as doors and windows, for all scenarios. *Considering a heated floor area of 204 m^2. Source: The authors.*

Results for one year	**Transmission heat loss (MJ)**				**Relative to S1**		
	S1	**S1b**	**S1c**	**S2**	**S1b**	**S1c**	**S2**
Windows	8,847	8,847	14,490	9,329	-	+64%	+5%
Exterior doors	9,301	5,036	12,624	5,705	-46%	+36%	-39%
Ceiling	10,584	10,584	163,675	9,261	-	+1446%	-13%
Floor	7,569	7,569	25,910	8,880	-	+242%	+17%
Exterior walls	22,547	13,463	77,021	6,875	-40%	+242%	-70%
Total	**58,848**	**45,499**	**293,719**	**40,050**	**-23%**	**+399%**	**-32%**
Total per square metre*	288	223	1,440	196	-23%	+399%	-32%

The heat supply is modelled as being provided with a heat pump, which is replacing the old oil boiler that was previously used for heating the building. The electricity input for the heat pump is based on a dynamic electricity grid mix. The grid mix in 2020 was founded on communication with the utility company on Bornholm, which manages the electricity supply. The electricity grid mix in 2035 was founded on the energy strategy of Bornholm, where electricity is assumed to be fossil-free and based on a combination of electricity from wind and photovoltaic energy.[32] A gradual change from the grid mix in 2020 to the mix in 2035 is modelled. The electricity grid mix in 2035 is kept constant until the end of the assessment period. An overview of electricity sources used for modelling the electricity grid mix on Bornholm in 2020, and from 2035 onwards, is shown in Table 4.

Table 4. Overview of the modelled electricity grid mix on Bornholm in 2020 and from 2035 onwards. Source: The authors.

Electricity source	**Percent of total electricity consumption**	
	2020	**from 2035 onwards**
Electricity from Sweden	25.1%	0.0%
Biogas	8.3%	0.0%
Photovoltaic	12.8%	2.3%
Wind	43.5%	97.7%
Wood chips	7.9%	0.0%
Coal/Oil	2.3%	0.0%
Total	100.0%	100.0%

Demolition

At the end of the assessment period, corresponding here to the building lifetime, the building is considered to be demolished. The demolition phase therefore comprises all of the end-of-life processes of the materials that make up the different building parts of the house·

RESULTS

The characterized impact scores, that is, the environmental impact results in absolute values, are shown in Table 5. They provide details for each of the fifteen impact categories, for the lifetime source chosen (LT1 or LT2), and for the assessment period considered (AP50 or AP100). A color code has been added to present internally normalized results, that is, the relative performance of the different scenarios compared to an internal reference. For a given assessment period and impact category, the reference = 1 was taken for S1 and LT1. This allows one to compare the results, and therefore to pinpoint the scenarios with the lowest environmental impacts for a given impact category or to identify the influence of the variation of the source of the lifetime, or the assessment period on the relative performance of the scenarios.

When the calculations are made with an assessment period of fifty years, the results show that for each of the fifteen impact categories, regardless of the lifetime source chosen, S1c seems to perform worse than any other scenario; sometimes up to a factor 4 to 5 compared to S1 (notably for 'Freshwater ecotoxicity', 'Ionizing radiation Human health', 'Mineral fossil & renewable resource depletion', and 'Water resource depletion'). S1b performs slightly better than S1, regardless of the lifetime source considered (results for S1b are on average 10 per cent lower than S1). The renovation scenario (S2) shows impact scores of a similar magnitude compared to S1 in most impact categories when considering the lifetime source LT1. For nine out of fifteen categories, the results' difference between the two scenarios is indeed lower than 20 per cent. Nonetheless, it should be noted that for four impact categories ('Acidification', 'Mineral fossil & renewable resource depletion', 'Particulate matter', 'Photochemical ozone formation'), S2 performs 44 to 68 per cent worse than S1. With LT1, 'Land use' is the only impact category where S2 performs significantly better than S1 (-25 per cent). When considering the lifetime source LT2, a more significant difference between S1 and S2 is observed. Depending on the impact category, impact scores of S2 are indeed either equivalent or up to 2.5 higher than S1 (as it is the case for 'Acidification' or 'Mineral fossil & renewable resource depletion').

Table 5. Characterized results for fifteen impact categories. Details are provided for each scenario (Sx = Scenario x), material lifetime source (LT1 or LT2) and assessment period (AP50 = fifty years; AP100 = one hundred years). The color code shows internally normalized results, that is, the relative performance of the different scenarios compared to an internal reference. For each impact category, the reference = 1 was taken for S1, AP50 and LT1 in this impact category. Source: The authors.

		AP50				**AP100**			
		S1	**S1b**	**S1c**	**S2**	**S1**	**S1b**	**S1c**	**S2**
Acidification	LT1	2.6	2.5	5.6	4.3	1.9	1.8	4.4	3.7
molc H+ eq/year	LT2	2.6	2.4	5.6	6.6	1.8	1.7	4.3	4.8
Climate change	LT1	631	577	1,477	715	430	386	1,129	538
kg CO_2 eq/year	LT2	631	578	1,477	838	408	364	1,108	598
Freshwater ecotoxicity	LT1	48,564	38,444	229,988	40,335	47,337	37,347	226,394	39,506
CTUe/year	LT2	48,564	38,434	229,998	47,581	47,258	37,268	226,324	43,123
Freshwater eutrophication	LT1	0.12	0.11	0.44	0.17	0.11	0.10	0.41	0.16
kg P eq/year	LT2	0.12	0.11	0.44	0.25	0.11	0.10	0.40	0.20
Human toxicity, cancer effects	LT1	0.00018	0.00016	0.00065	0.00017	0.00018	0.00015	0.00065	0.00016
CTUh/year	LT2	0.00018	0.00016	0.00065	0.00023	0.00018	0.00015	0.00065	0.00020
Human toxicity, non-cancer effects	LT1	0.00025	0.00020	0.00088	0.00029	0.00022	0.00017	0.00081	0.00028
CTUh/year	LT2	0.00025	0.00020	0.00088	0.00045	0.00022	0.00017	0.00081	0.00035
Ionizing radiation Human health	LT1	75	63	308	71	44	39	170	50
kBq U235 eq/year	LT2	75	63	308	87	43	37	169	58
Land use	LT1	2,443	2,551	2,536	1,830	1,868	1,956	1,674	1,461
kg C deficit/year	LT2	2,443	2,514	2,572	2,687	1,749	1,837	1,557	1,878
Marine eutrophication	LT1	0.59	0.60	1.15	0.62	0.47	0.47	0.96	0.53
kg N eq/year	LT2	0.59	0.59	1.16	0.88	0.45	0.45	0.94	0.67
Min., fos. & ren. Resource depletion	LT1	0.049	0.039	0.223	0.077	0.047	0.038	0.218	0.076
kg Sb eq/year	LT2	0.049	0.039	0.223	0.120	0.047	0.037	0.218	0.097
Ozone depletion	LT1	0.000044	0.000040	0.000140	0.000049	0.000039	0.000035	0.000131	0.000045
kg CFC-11 eq/year	LT2	0.000044	0.000040	0.000140	0.000061	0.000037	0.000034	0.000130	0.000051
Particulate matter	LT1	0.40	0.38	0.84	0.57	0.29	0.27	0.68	0.48
kg PM2.5 eq/year	LT2	0.40	0.38	0.84	0.84	0.27	0.26	0.67	0.61
Photochemical ozone formation	LT1	1.9	1.9	3.6	2.9	1.6	1.5	3.0	2.7
kg NMVOC eq/year	LT2	1.9	1.9	3.6	3.8	1.5	1.5	2.9	3.1
Terrestrial eutrophication	LT1	6.2	6.1	13.3	7.4	4.8	4.7	10.5	6.4
molc N eq/year	LT2	6.2	6.0	13.4	10.9	4.6	4.4	10.3	8.1
Water ressource depletion	LT1	485	402	2,165	421	299	254	1,313	300
m^3 water eq/year	LT2	485	401	2,165	527	299	254	1,313	353

Impact scale (relative to S1 and LT1)	0.7	0.8	0.9	1	2	3	4+
	🟩	🟩	🟨	🟨	🟧	🟧	🟥

When the assessment period is changed to one hundred years, the scenarios perform on average 20 per cent better compared to when fifty years is considered. For some impact categories, such as 'Freshwater ecotoxicity' or 'Human ecotoxicity (cancer effects)', the difference is less significant (around -5 per cent for AP100 compared to AP50). For some others, for example 'Ionizing radiation human health' or 'Water resource depletion', it is more substantial (around -40 per cent).

In Figure 4, the results are shown for a specific environmental impact, 'Climate change'. Additional information has been added here, providing details on the contribution of the energy use during the use phase of the building to the total climate impact (dark area), as well as that of the production, use, and end-of-life treatment of all building materials (light area). For AP50, regardless of the lifetime source, the impact scores of materials are equal in S1, S1b, and S1c. It is the energy use that determines which scenario performs the best: S1b performs slightly better (-9 per cent) than S1, and S1c substantially worse (+134 per cent) than S1. For S2, when LT2 is considered, the impacts of materials are significantly higher (+22 per cent) than with LT1. Compared to S1, they are around 36 per cent higher with LT1, and

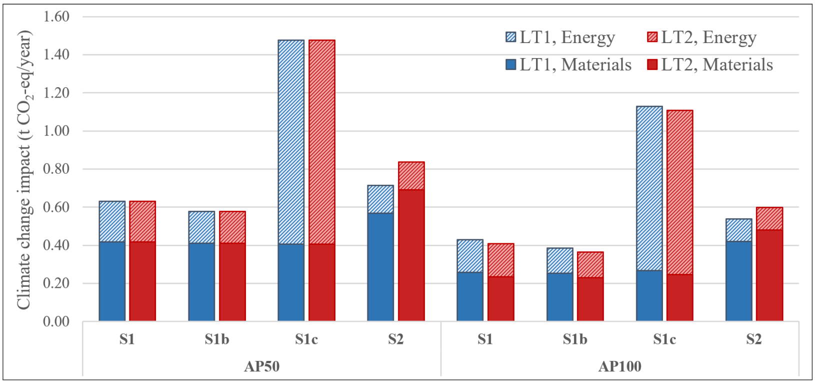

Figure 4. Characterized results for climate change (in t CO^2-eq/year), provided for each scenario (Sx = Scenario x), material lifetime source (LT1 or LT2), and assessment period (AP50 = fifty years; AP100 = one hundred years). Source: The authors.

66 per cent higher with LT2. The impact of energy use of S2 is, however, the lowest of all scenarios, which is consistent with the relative lower heat loss calculated for this scenario in Table 3. When both energy and materials are considered finally, the impacts of S2 are 13 per cent higher than S1.

The conclusions remain similar when switching to an asessment period of one hundred years, although the gaps between the different scenarios are wider. Indeed, although more materials need to be replaced for AP100 (see Table 2), the impacts of the transformation and demolition stages are divided by a factor 2 compared to AP50, which increases the contribution of energy use that is the main differentiating factor between the scenarios. For LT1, for example, S1b still performs slightly better (-10 per cent) than S1, and S1c still substantially worse (+163 per cent) than S1. The difference is ultimately bigger (+25 per cent) between S2 and S1.

DISCUSSION

Comparison of Restoration/Renovation Scenarios

The results of the study show the trade-off between impacts related to the materials and impacts related to the energy use, such as heating, during building operation. It is important to strike the right balance. For instance, no (or very little) utilization of insulation to reduce operational heat use will not be good for the environment at present. This is because the impacts related to the heat generation will exceed the environmental benefits from not producing the additional insulating material. This is perfectly illustrated in S1c, which overall has the worst environmental performance across the 4 scenarios. Indeed, as shown in Figure 4, the climate impact from operational energy use is 1.1 t CO_2-eq / year, which is about 73 per cent of the total climate impact for the fifty-year assessment period. Likewise, S1b, which is designed with the intention to be energy efficient while still maintaining the original appearance of the building, generally performs best across all impact categories (thirteen out of fifteen for both fifty- and hundred-year assessment periods, see Table 5). In S1b, the energy used to heat the building only accounts for about 29 per cent of the total climate impact during a fifty-year period. The best insulated scenario is the renovation scenario S2. Here, the operational energy use only accounts for about 20 per cent of the total climate impact. This is due to the relatively high energy efficiency, which keeps energy use and subsequent impacts low, combined with the increased impacts from additional production and treatment of mineral wool for insulation.

In terms of restoration contra renovation, we see that S1 and S1b perform generally better than S2. This is mainly because the restoration scenarios retain more of the original materials and repair or add small improvements rather than simply replacing them with new materials. This higher degree of material reuse, together with a larger reliance on bio-based materials, such as thatching or wood fibre insulation, means that environmental impacts embodied in the materials can be kept relatively low (also illustrated for climate change in Figure 4). On the other hand, the energy efficiency in the restoration scenarios is slightly lower than that in the renovation scenario. But this does not outweigh the better performance related to materials. Indeed, the heating is based on electricity as a heat source, and the electricity generation is here considered to be increasingly based on renewable energy during the assessment period, especially for one hundred years.

A potentially important parameter for calculating heat loss (and thus energy consumption) that was not considered in this study was the heat lost from ventilation. Quantitative data for estimating the air exchange rate of the building for the different scenarios was not available, making it impossible to differentiate the heat loss in the specific case of building transformation. According to the calculation methodology proposed by Danish standards for heat loss calculation in buildings, the heat lost from ventilation depends on the gradient of temperature between indoor and outdoor air, the heated floor area, and the airflow per heated floor area.[33] For the later parameter, an estimated value of 0.3 $L.s^{-1}.m^{-2}$ of air circulation is proposed for usual rooms. When heat loss from ventilation is included, using the proposed air exchange value in the four scenarios of this study, an additional yearly energy consumption of around 24 MJ is found. This corresponds to between 8 per cent (for Scenario 1c) and 60 per cent (for Scenario 2) of the yearly energy consumption originally calculated. More research is therefore required to assess how a differentiated air exchange rate resulting from the different level of transformation and the choice of different materials can affect the impact results of transformation scenarios.

Importance of Materials Lifetime Estimates

The importance of the material lifetime estimates was in general found to be larger for the fifty-year assessment period compared to the one-hundred-year assessment period. This is because the two material lifetime sets in our study vary around the fifty-year mark (see Table 2). Thus, for a fifty-year period, an additional material replacement is needed depending on the selected material lifetime set. For instance, the new window and door frames need to be replaced after forty years according to LT2 even though the building only has a total lifetime of fifty years. This type of variation is less frequent with the one-hundred-year assessment period, where the actual difference between LT1 and LT2 is less pronounced. An option for extending the lifetime of the replacement beyond ten years could be to perform selective demolition followed by reuse of the materials. In this situation, the relatively new materials should be carefully removed from the building and then be reused as part of new construction.

The overall conclusions about the two scenarios were not found to change substantially as a result of the two sets of lifetime estimates used in this study, for the results generally remain in the same order of magnitude. However, the gap between the renovation and the restoration scenarios is generally wider with LT2. Indeed, considering LT2 gives an advantage to traditional materials, which have a similar or higher lifetime compared to LT1 (e.g. lime mortar or secondary glazing glass), whereas it is the opposite for new materials (e.g. wood/aluminium frames, gypsum, mineral wool). It is therefore quite possible that the selection of material lifetimes could affect conclusions and subsequent decision-making. This holds especially true for cases with materials that have a large environmental footprint and that involve large uncertainty about the actual material lifetime. This aspect is also expected to become even more important in the future as the decarbonization of the heat and electricity use during building operation implies that the impacts embodied in materials become increasingly important.

The estimation of material lifetimes is inherently uncertain since the actual time a particular material is in use depends on a multitude of factors, such as material properties, production quality, handling, exposure to weather and climate, user behavior, or wishes and ability to maintain and repair. One method to improve these estimates is to apply different approaches for determining material lifetimes based on various sources of expertise. Different results can then be calculated using the lifetime sets to get the range in which the actual results are expected to lie. Here it would be relevant to consult different expert groups within the building sector, such as engineers, architects, construction workers, and waste handlers, to get their opinion about the lifetimes of the different materials and to provide the final decision-makers with comprehensive and reliable information.

Building Transformation Compared to New Build

Restoration and renovation are generally seen as an environmentally preferable alternative to demolition and construction of new buildings. This is because the reuse of the existing building and the kept materials avoids the production of new materials, which would need additional resources and lead to emissions of additional substances into the environment. Based on a recent LCA study by the engineering group Rambøll,[34] the results for four renovation scenarios were compared with results for a newly built single-family home. Two new houses were used, one based on contemporary materials (called the 'Brick house'), such as light concrete, bricks, and tiles, and one based on timber materials (called the 'Timber house'), which is seen to perform better climate wise. The climate impacts pertaining to the materials as calculated by Rambøll were used. Based on the energy calculation provided in the report, the heat use for the two buildings over a fifty-year period with the same heat source as in our transformation scenarios was estimated. It should be noted that the heat use for the new houses is only based on energy calculations for the exterior wall and roof. Hence, it does not take into account heat losses through the ground, doors, and windows, which account for 12 per cent and 13 per cent of the total climate impact in S1 and S2, respectively. Thus, the actual heat loss will most likely be substantially larger for the new houses. However, data on the complete heat loss was not available.

The total climate impact for the Brick and Timber houses was found to be 318 and 253 kg CO_2-eq/m^2 over a fifty-year assessment period, respectively. In comparison, the results for S1 and S2 using LT1 with a fifty-year assessment period were found to be 216 and 250 kgCO_2eq/m^2, respectively. Those results indicate that restoration and renovation are therefore climate wise preferable compared to building a new house, even if the house is constructed using more climate friendly materials, such as timber. Again, it should be noted that the impacts of the new buildings are likely to be larger if energy use during operation is fully taken into account. Moreover, the results from Rambøll do not include any initial demolition, removal, and treatment of the old building that would be needed before the construction of a new house. These processes will also impact the climate, further driving up the impact related to demolition of old buildings and the construction of new ones.

In this sense, our results are in line with other studies that show the benefits of restoration or renovation instead of building new.35 Indeed, the restoration or renovation of an existing building is an obvious way to increase circularity and use circular economy principles to provide new economic value to old buildings, while reducing impacts on climate and the environment in general. In particular, the results of this study show that restoration where the original appearance of the historical building is retained can be also preferable in terms of protecting the climate. Thus, the restoration of historically important buildings could be a focus area as this is likely to help maintain aesthetical and cultural value while reducing impacts on the climate. However, the findings of this study can not be generalized to all traditional buildings before more research is carried out: although the study of similar buildings in Denmark are likely to lead to similar conclusions, this LCA was indeed specific to the situation of this building. More studies on building transformation should therefore be done to corroborate—or not—the present conclusions.

CONCLUSION

In this study, we conducted a full LCA on four different scenarios for restoring an old historical house with the intention of making it suitable as a single-family home. Three scenarios were, on different levels of restoration, taking different approaches with regard to the extent of the restoration and the maintaining of the original appearance of the house. In a fourth scenario, a renovation was modelled using modern contemporary materials and in line with current standards for energy efficiency in project renovation. The evaluation of the building was undertaken using different assessment periods (i.e. fifty and one hundred years) and different material lifetime estimates. The results show that the two restoration scenarios which combine restoration and energy efficiency (S1 and S1b) generally perform best. In fact, S1b was found to perform best in thirteen out of fifteen impact categories. Overall, we find that the change in material lifetime estates affects the results and has a noteworthy effect on materials with medium-long lifetimes (e.g. around fifty years) and especially on the renovation scenario. Indeed, the impacts of the latter scenario were seen to change by 30 per cent on average across all impact categories depending on the material lifetime determination. Finally, we compared our results with similar findings for the construction of new buildings. Here, restoration and renovation were found to perform better than the construction of new buildings. This aligns with other studies in showing that the reuse of existing buildings and materials, via restoration or renovation, is likely to be environmentally preferable compared to demolition and construction of new buildings. Thus, this study recommends more focus on the restoration of historical buildings as a means of maintaining aesthetics and cultural heritage without increasing environmental, especially climate, impacts. However, more research on the transformation of similar buildings is needed to corroborate the findings on this specific house.

ACKNOWLEDGEMENTS

This study was funded by the Royal Danish Academy, as part of a research collaboration between the Royal Danish Academy and the Technical University of Denmark.

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APPENDIX

Examples of scale 1:50 drawings

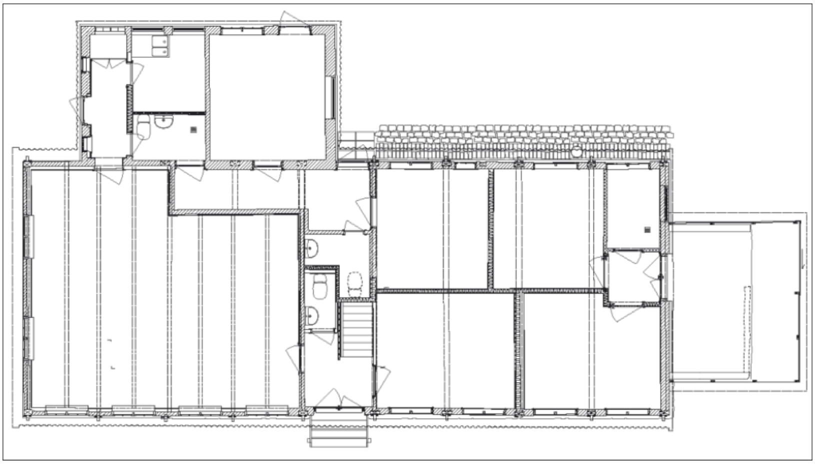

Figure A.1. Plan of ground floor, measured by Kristin Groos Kilen, Katrine Frølich Kristensen, Anna Elizabeth Rosendahl and Mia Baltzer Nielsen

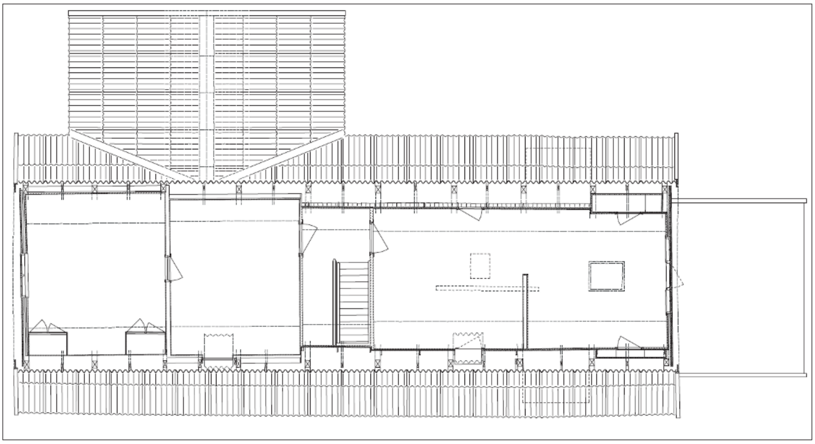

Figure A.2. Plan of first floor, measured by Kristin Groos Kilen, Katrine Frølich Kristensen, Anna Elizabeth Rosendahl and Mia Baltzer Nielsen

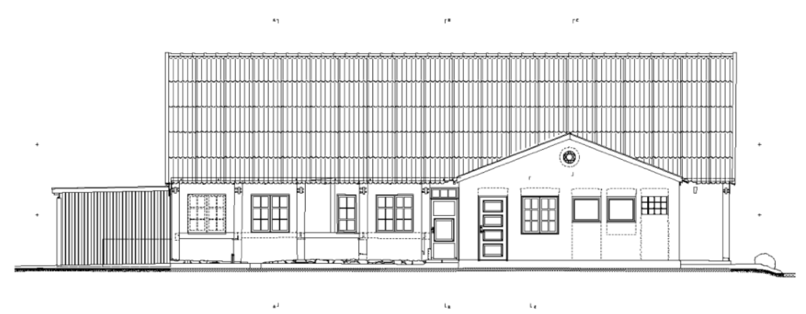

Figure A.3. Southwest elevation, measured by Freja Bang Dahl and Nanna Dahl

Figure A.4. Cross section BB, measured by Maria Vang, Caroline Crüger Ahm

Examples of scale 1:10 drawings

Figure A.5. Measured by Kristin Groos Kilen and Katrine Frølich Kristensen

Figure A.6. Historical picture of the house viewed from the west. Private photo from Martin Silbersteins archive on Bornholms Ø-arkiv, BØA 1980-20-2.

Figure A.7. Historical picture of the house viewed from the north. Private photo from Martin Silbersteins archive on Bornholms Ø-arkiv, BØA 1980-20-2.

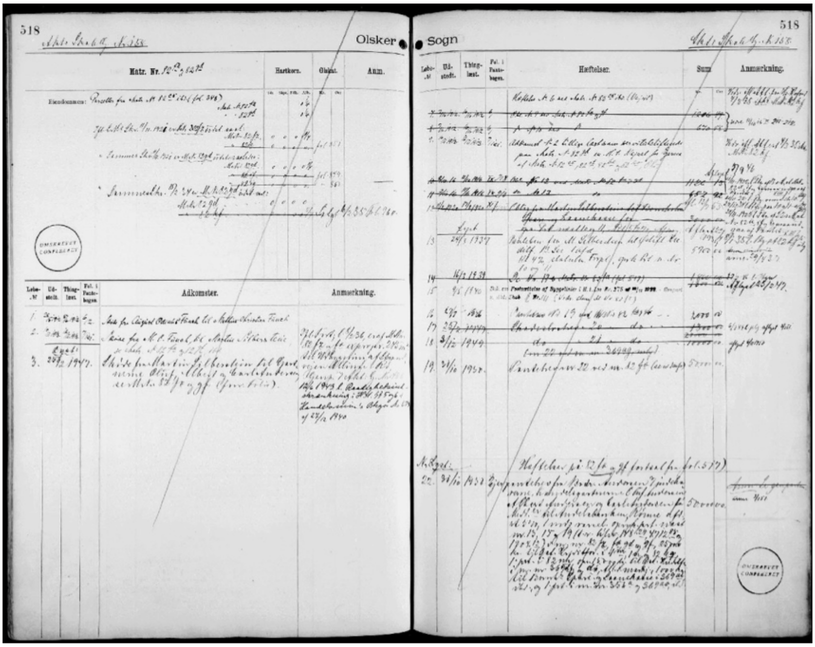

Figure A.8. Example of a notarial deed. Source: The National Archives, Denmark. Realregister til Skødeprotokol for Olsker, tinglysningsprotokol, Rigsarkivet.

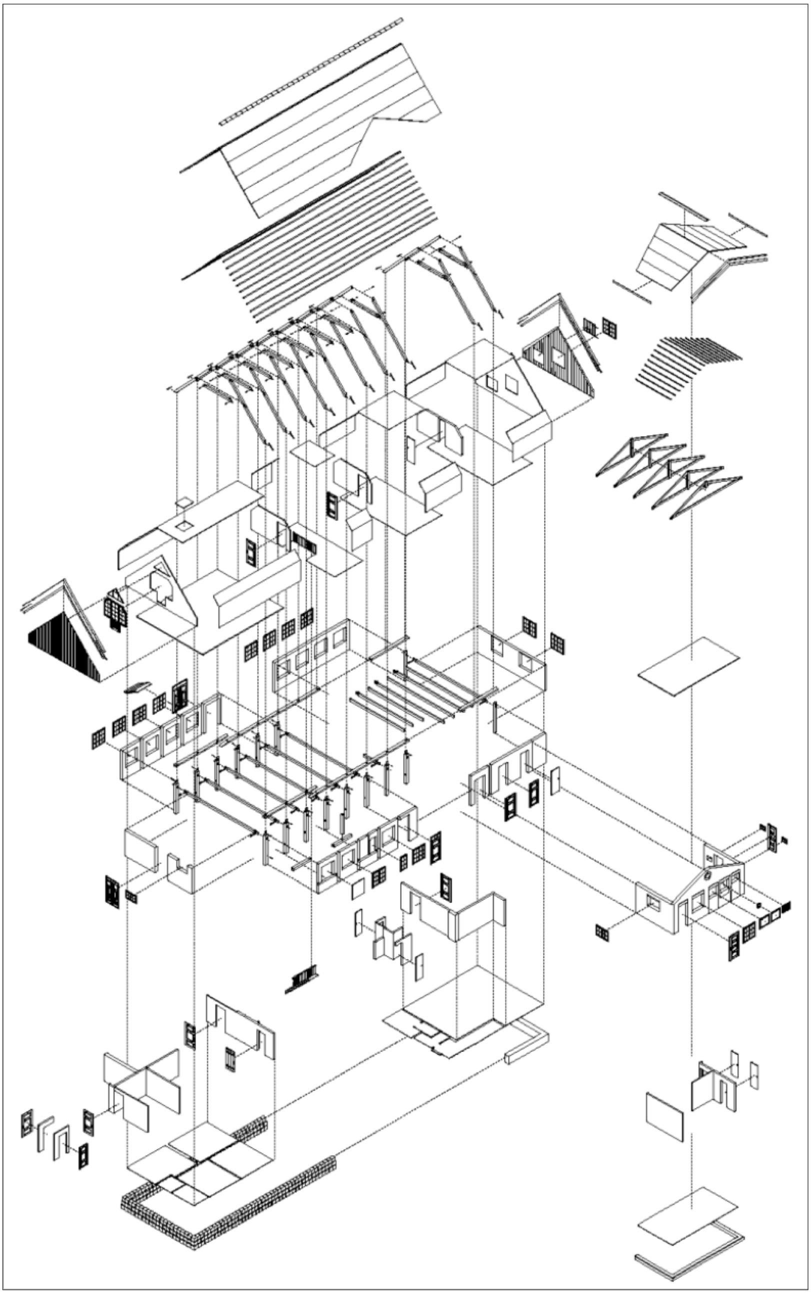

Figure A.9. Exploded axonometric viewed from the west showing the house in 2019. Drawing by Rasmus Helleskov Weileman