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SUMMARY

This study aimed to enhance the knowledge in the environmental assessment of heritage buildings and circulars economy. The study of environmental assessment for heritage buildings is still not sufficient. In this thesis, the environmental impact of adaptive reuse of an industrial heritage building (PM5) was examined by comparing it with other scenarios. The assessments were performed based on the Life Cycle Analysis (LCA) and modified according to the scenarios. This study found that the adaptive reuse scenario, which considers the balance between the building's socio-cultural value and energy efficiency, results in the lowest environmental impacts. This scenario achieved the green deal target, 60% carbon reduction in 2050. Moreover, the recommendation for further research has been presented.

3 KEYWORDS
Heritage building
Environmental impacts assessment
Adaptive reuse

Title: Investigate the Environmental Impacts of Adaptive Reuse Industrial Heritage Building and Compare with Other Scenarios: Demolition and New Construction

Acknowledgment

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I would like to thanks Associate Professor Dimitrios Kaniotis and Co-supervisor Ms. Selamawit Mamo Fufa, for their guidance. This master thesis has helped me to understand more about environmental impacts and sustainability. Moreover, I will do further research on this topic.

Oslo Metropolitan University

June 09, 2021

Khin SuSu Kyaw

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Khin Su Su Kyaw

Abstract

Nowadays, the environmental impact assessment is improved for new construction buildings. The European Commission targeted to achieve the 55% of carbon reduction in 2030 and 60% in 2050 compared to the 1990 carbon emission level. In the building and construction industry, constructing new buildings and manufacturing construction materials dominate the industries' total carbon emissions. There is also a large amount of building stock that is getting old, and most of the buildings have significant values in culture and society. Some of them are titled heritage buildings and must be preserved.

Furthermore, the heritage buildings are critical to preserve and rehabilitate due to there are a significant amount of heritage building and culturally valuable buildings which were built within the industrial revolution time. Most of the non-residential buildings are not possible to use the original purpose. Then, the rehabilitation of the building must be carried out. However, since the heritage buildings have a high value in culture and society, the professional bodies are considering carefully. On the other hand, the environmental consideration for the heritage building is also critical. The heritage building always has had a long service life; precisely, the service life is longer than expected. Therefore, the environmental impacts of the building use must be studied. Life cycle stages and the building's lifespan are the influencing factors for the building's environmental impacts. The life cycle analysis method is used for the new construction, but environmental impacts assessment of the heritage building has not been established yet. The author believed that the environmental assessment for the heritage building could be carried out by modifying the life cycle assessment.

This research aims for a broader insight study in environmental assessment and circular economy. The outcomes of the study enhanced the knowledge of environmental assessment for heritage buildings. The objective is to investigate the rehabilitation of an industrial heritage building (PM5) in Skien, Norway, comparing it with other scenarios. Life cycle assessment analysis was used as a based method for this heritage infrastructure and modified according to the scenarios' system boundary. The adaptive reuse scenario without considering the energy performance was the most favorable scenario among all the scenarios.

Moreover, the aspects to determine the environmental assessment of heritage buildings were studied. One-Click LCA is used as an assessment tool to evaluate the environmental impacts. Heritage building's components and materials have heritage value and socio-cultural values same as the whole heritage building. Therefore, each component of the building also must be preserved. This study found that the most suitable way to rehabilitate a heritage building is to reuse it as a non-heated public building. Moreover, the recommendation of reusing the replaced components and further studies are presented.

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Definitions

Cast Iron
The term is used to describe a method of manufacturing iron parts or certain building elements. The iron is heated and poured into molds.

Plaster
Plaster applied to the entire façade of the building, both exterior and interior.

Mortar
Soft cementitious material was applied between bricklayers.

Dormer
A structure built upon a sloping roof to provide a window into the attic story

Façade
A building façade is an outer wall of a structure.

Finish materials
Any smooth surface wood painted, brick or stone are finish materials.

Masonry
Masonry is the group of materials that use stone, brick, ceramic, or concrete block units, usually separated by mortar beds and joints. Exterior stucco is included in the masonry group.

Retaining wall
A wall is constructed to withstand the pressure of the ground from one side of the wall.

Visible
The term 'visible' refers to the condition of being seen from the public area.

1. Introduction

1.1. Background Information

Climate change created extreme weather, storm, drought, ice caps melting, and sea levels rising in many parts of the world. Since the ecological and biological are connected, these changes become critical to human society and other species on the planet. Therefore, international organizations such as United Nations and European Commission have started establishing the United Nations Framework Convention on Climate Change (UNFCCC) to stabilize greenhouse gas concentration, and it has been practiced since 1994.

The European Union prioritized the UNFCCC and invested in preventing and adapting the climate change. The 2030 climate and energy framework of the European Union (E.U.)[1] includes the EU-wide targets and policy objectives from 2021 to 2030. E.U. targets to cut off 40% of the GHG (Green House Gases) emission compared to the 1990 level by improving renewable energy by 32% and energy efficiency by 32.5%.[1]. Moreover, according to European Green Deal [2], the E.U. will be climate neutral by 2050 and aim that Europe will be the first climate-neutral continent in the world.

The environmental assessment of different sectors and industries had been introduced. The building construction industry is a primary sector for sustainable development. It is considered an enormous contribution in using primary resources both by land use and material extraction. Buildings and construction together account for 36% of global final energy use and 39% of energy-related carbon dioxide (CO2) emissions when upstream power generation is included. [3]

Therefore, the professional of the construction industry established different assessments to reduce the carbon footprint/emission. On the other hand, the life cycle assessment is the most comprehensive method to access and evaluate emissions and final environmental impacts. There are also materials databases for EPD (environmental product declaration) used in life cycle assessment. However, these databases and methodology of the life cycle assessment are focus on recent construction. The methodologies to assess the heritage buildings and old buildings have not been established yet due to insufficient research and research projects.

The life cycle assessment is an essential method to measure the building's environmental impacts. Life cycle assessment can be performed based on the materials and service lives for new constructions and existing buildings with adequate project information. Moreover, the adaptive reuse of the existing old building becomes more attractive to stakeholders. The growing demand for greener buildings has been partly facilitated by an emerging generation of builders and architects with firm resource

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[1] E.U. European Union

efficiency beliefs. [4] Furthermore, the holistic research approach for heritage buildings is not developed well due to the lack of historical information and the building components' data. Moreover, there is not enough study about industrial heritage buildings for adaptive reuse purposes.

In this research, the environmental assessment of reuse industrial heritage buildings was performed using the life cycle assessment method. Nevertheless, the past service life of the buildings was not considered. This research's outcomes will enhance the knowledge of environmental assessment of heritage buildings in a more holistic way. In Norway, 80% of existing building stock will still be used beyond 2050 [5]. The rehabilitation of the existing building, including heritage buildings and heritage infrastructures, becomes vital. However, due to several factors, the original purpose of the building could not be retrieved. Therefore, the rehabilitation of these buildings must consider an adaptive reuse purpose.

The overall aim is to study broader insight into holistic environmental impact assessment and circular economy by investigating the study case, an adaptive reuse industrial heritage building. The life cycle analysis of the study case-building will be performed by different scenarios, including after the end-of-life scenarios. An industrial heritage building PM5, in Skien, Norway, is used as a research project or study case. The PM5 building was built in 1883 with brick and masonry. The original purpose of the PM5 building is a paper mill. Norwegian Directorate for Cultural Heritage (Riksantikvaren) has protected this building.

This research is part of the ADAPT (Sustainable Adaptation Resilience in Urban Regeneration), a research project financed by the Norwegian Research Council through the Miljøforsk program. The ADAPT project focuses on resilience in the industrial transformation, cultural heritage structures, and the urban transformation process. The research project develops new knowledge about employing environmental, cultural, social, and economic sustainability in the existing industrial building stock. The ADAPT project is performed closely between SINTEF and NIKU (Norwegian Institute for Cultural Heritage Research), NMBU – Department of Landscape Architecture, and TØI (Planning of Transportation). In addition, the author is engaged in research on this topic and project in close collaboration with the project's owner, research institutes, and the university.

1.2. History of case study

In this research, a case study of an industrial heritage building (PM5) built in 1883 in Skien, Norway, was explored. The inspiration building was built with stone, brick, and masonry during the second industrial revolution. There are two islands in Skien, Klosterøya and Smieøya. Both the islands have solid historical inspirations for the people living in Skien. Gimsøy Monastery and the PM5 building (study case) are located on Smeiøya. Gimsøy Monastery was built before 1150 and played an important role in religion. This island is protected as a cultural monument area of early industrial history in Norway.PM5 building reflected the first industrial revolution time, and the architecture of the building is still in good condition. However, the building was abandoned for about 50 years (according to the property owner) and allowed public access with no specific purpose. After changing the land ownership to Steinar Moe Property, the new urban city has been established on Klosterøya and Smieøya. The rehabilitation of the PM5 building will help the sustainable society and increase the building stock of the public area in Skien.

Figure 1-1:Telemarks Canal and PM5- Building[6]

Telemark canal, built in 1892, is one of the national tourist attractions. Telemark canal connects Skien to Dalen by linking several long lakes through a series of 18 locks. The Skien lock (Skien Sluse) of the canal is beside the PM5 building. There will include an overbridge across over canal and a new building for mechanical and electrical service for the PM5 building. The critical consideration for the adaptive reuse of this building is water splashing from the canal chamber to the PM5. Since Smieøya is crucial for the people living in Skien, the whole island will be adapted as a heritage city garden. Moreover, the owner of the PM5 building plans to have a maker space where everyone can be creative and explore their interest after the rehabilitation. PM5 will become a memorial building for the people around. Moreover, the graffiti artwork around/inside the building reflects the subcultural of the Skien. The interior renovation work will be carried out the way these artworks can remain and visible.

PM5 building was completed between 1882-1883. The building's original purpose was to produce wood pulp (cellulose) and eventually be used for paper production. According to Vestfold and Telemark municipal, PM5 means Paper Machine No.5 [7]. Although it was not big enough to run a paper factory, it was used as a cellulose-making machine. In 1958, the paper machine was removed due to more extensive and advanced machines in the production industry. Then, the building became a warehouse for paper production. Due to the building condition (decay), Skien municipal council decided to demolish it. However, the preservation of PM5 was submitted by Fortidsminneforeningen and Telemark Arkitektforening in 1981. Then the municipal changed the decision to conserve the building, and now the PM5 has been preserved by Norwegian Directorate for Cultural Heritage (Riksantikvaren) under the heritage act: kulturminneloven §§16-20 [8].

It is a technical-industrial cultural monument for the years of the modern wood products industry. It is also the oldest conserved building in the factory industry in Norway. Steinar Moe Eiendom (property) owns the islands, and Tømmerkaia's project has been establishing currently. Tømmerkia will be a new residential area with all amenities and public areas for social activities. Steinar Moe Eiendom decided PM5 building to adapt for today's use and protected for the future. Steinar Moe Eiendom provides the data and information of the PM5 building for this study.

The social-cultural values of the Skien must be accounted into the adaptive reuse of the PM5 building. The Vestfold and Telemark County have been planning for a new bridge with walking and cycling trails across the islands and Skien. It will increase the urban development of the Skien as well as the historical value of the area. The new expected service life of the PM5 building is 100 years, and the area's socio-cultural value will remain until then. Moreover, the intention of the adaptive reuse of PM5 building are:

1. To use the space of the outdated structures in new ways and get the new spatial experiences
2. To contribute to the diversity of architecture in the neighborhood
3. To remain the identity and history of the area and preserve as the industrial heritage infrastructure
4. To be active the PM5 with new activities
5. To develop as a facility of the Telemark Canal and Tømmerkia

1.3. Research approach

The data of the study case-building (industrial heritage) ’s components and materials were collected from the owner of the building who is implementing the adaptive reuse of the PM5 building. One-Click L.C.A. was used as an assessment tool and performed the comparative assessment of the different scenarios. Although most heritage buildings are not allowed to be demolished, this study included demolition as a comparative assessment scenario. As a result, the study outcomes will benefit another existing building or old building that is not entitled as a heritage building. Figure 1-2 demonstrates the research approach of this study.

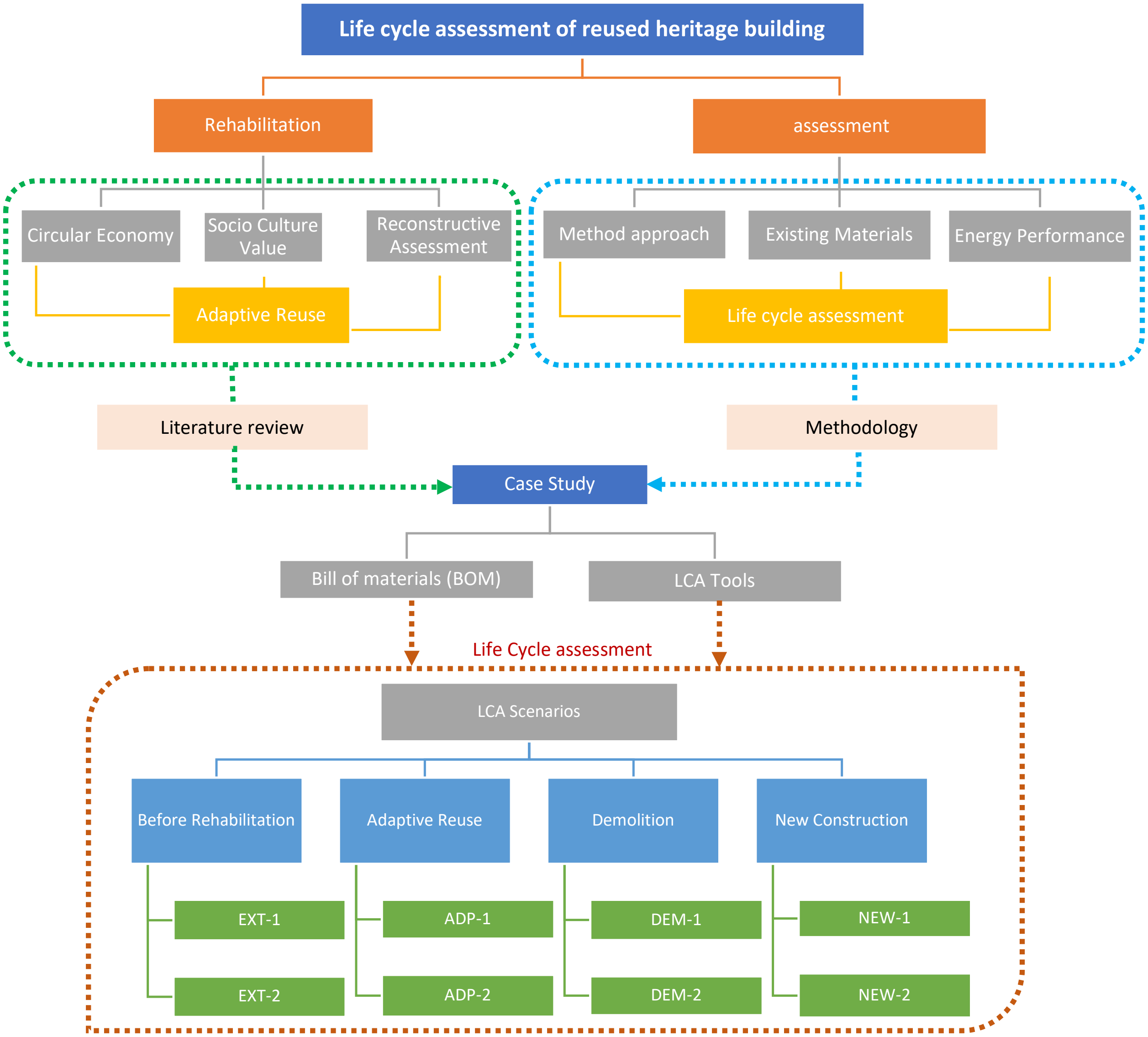

Figure 1-2:Research approach flow chart

The primary aim of this study is a broader insight study in environmental impact assessment and circular economy to strengthen the knowledge of the environmental assessment for the heritage building. The objective is to investigate an adaptive reuse heritage building by comparing it with other scenarios. First, the literature study about heritage building's life cycle assessments is carried out before evaluating the environmental impacts of the PM5 building. Several methods can be applied to carry out a literature review in research studying, and choosing the appropriate one is a delicate process.

In this study, systematic literature review and state-of-the-art analysis were used for literature research. Literature review showed that due to lack of knowledge about heritage building's environmental impacts studies, establishing the holistic approach of environmental assessment is vital. Therefore, the target audiences are construction companies, environmental consultants, municipalities, policymakers, engineering, researchers within the field, architects, media, and other parts of society affected by the topics. The outcomes of this study are how to reuse the heritage building and materials, prove that the heritage building must be reused, highlighting the gaps of the recent study, and recommend future research.

1.4. Research Organization

This thesis paper is divided into six chapters to achieve the research goals. The chapters are as figure 1-3. Chapter 1, the introduction, included the research and study project's background information and research approach. Chapter 2, literature review, included the current study's systematic literature review and state of the art. Chapter 3 included the method approach and data collection. Then, chapter 4 is the result, and chapter 5 is the discussion. Finally, chapter 6 is the conclusion.

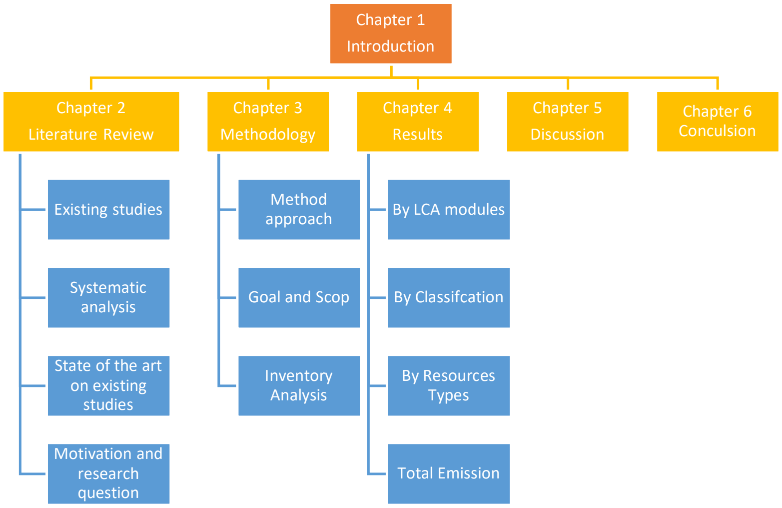

Figure 1-3:Organization Chart for Research

2. Literature Review

Protecting the cultural and historical heritage building has long been a matter of sustainability. The literature research about the environmental impact assessment of the heritage building is minimal due to the lack of research articles and less interest in the environmental assessment of the existing buildings. Existing buildings are complicated to perform the environmental assessment, and significant problems are found for existing buildings such as heritage buildings or historic buildings. Therefore, the author believes that studying the environmental impacts of heritage buildings will significantly help the building and construction industry.

In this section, the literature research for environmental impacts of the reuse of heritage buildings is carried out before studying the case study. State of the art on the research of heritage building environmental impact assessment is provided in Section 2.2. The most relevant parts of literature and documents are prioritized. Figure 2-1. shows the main disciplines of the literature research. Those disciplines are 1) heritage value or cultural-socio value, 2) adaptive reuse, 3) Existing Materials Data, and 4) service life prediction. All disciplines are focus on the existing buildings or different heritage buildings.

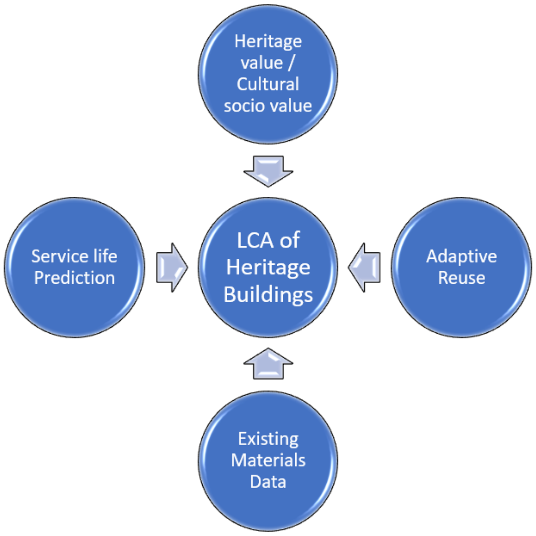

Figure 2-1:Disciplines for the literature research

2.1. Existing studies

The existing studies of the environmental assessment of heritage buildings will be present in this section. The primary research question is “Which aspects to consider evaluating environmental impacts of adaptive reuse of industrial heritage buildings?”. This study will benefit the building stock for determining an existing building should be preserved or reconstructed, especially for the existing building with extended service life. However, this study focuses only the heritage buildings as it is used as a study case.

Firstly, the relevant publications were selected by using two reliable databases. The Systematic Literature Review (SLR.) method was used for this literature research. SLR is a systematic way of collecting, critically evaluating, integrating, and presenting findings from multiple research studies on a research question or topic of interest [9]. Figure 2-2 demonstrates the sequential graphic of the literature research approach.

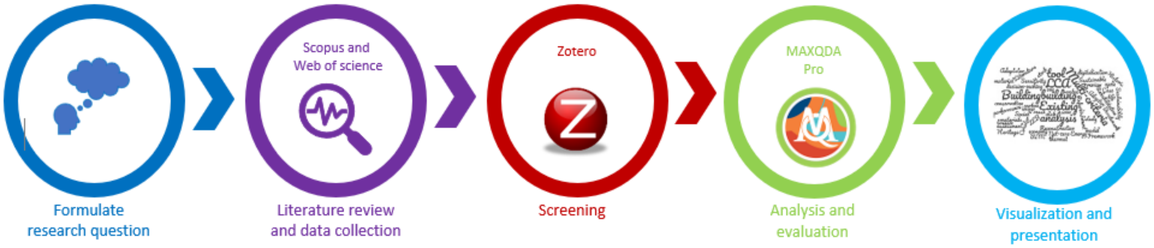

Figure 2-2:The sequential graphic of the literature research approach

Identifying and counting existing research publications in the environmental assessment of heritage buildings was made using the ‘Web of Science database’ and ‘ScienceDirect database.’ Web of Science (previously known as Web of knowledge) is a website that provides subscription-based access to multiple databases that provide comprehensive citation data from many different academic disciplines. It covers more than 8500 journals encompassing 150 disciplines. (“Web of Science” 2021). ScienceDirect is a website that provides access to an extensive bibliographic database of scientific publications. It hosts over 18 million pieces of content from more than 4,000 academic journals and 30,000 e-books of this publisher. [11] ScienceDirect database is also called Scopus.

Then, the selected documents are screened and filtered with Zotero. Then, analyzing with MAXQDA to evaluate the data analysis and content analysis. MAXQDA is a world-leading (Quantitative Data Analysis) Q.D.A software package for qualitative and mixed methods research. It is one of the most comprehensive programs in the field and is used by thousands of researchers in more than 150 countries worldwide.[12] Finally, state-of-the-art based on the existing study is presented in section 2.2 with comprehensive visualizations such as graphs and charts.

2.2. Selection of research articles

The primary research interests involved 1) environmental assessment, 2) life cycle assessment, 3) adaptive reuse, and 4) heritage buildings. The keywords are written keeping the roof of the word and adding the asterisk symbol (*) after it to include all the grammar forms of the word. The keyword for the research is (“Environmental assessment” OR “Life cycle assessment” OR “Adaptive reuse”) AND “heritage building.”

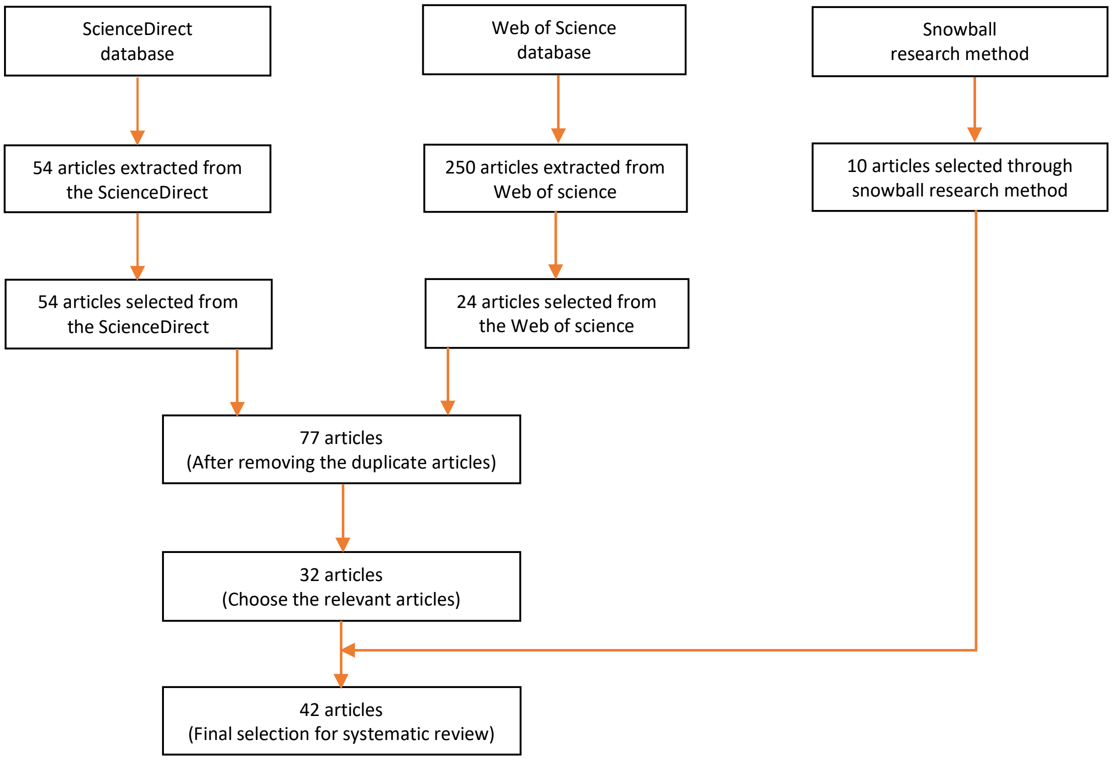

Figure 2-3:Prisma diagram for selecting the relevant articles

The Prisma Diagram for selecting the research articles is presented in Figure 2-3. The keywords were used to extract the relevant articles from databases, ScienceDirect (54 articles) and Web of Science (250 articles). Then, these articles were read thoroughly to ensure that they contained lessons-learn to the environmental assessment of reuse heritage buildings. Many of these papers are not accessible and not written in English. Some articles were removed from the list due to the lack of information and repeating. After reconsidering the selection of research articles, a total number of 77 articles are extracted.

The extracted articles are published from different regions worldwide and include Africa, Asia Pacific, Europe, Middle East, North America, and South America. By screening the entire list of publications, about three-quarters of the documents, 74% (n=57) are published in Europe, over one-third 33.8% (n=26) are in Asian Pacific regions, 10% (n=8) are in the Middle East region, and the other regions are less than 5% of total publications. These results reflect the financial availability of the European Commission. European Commission has invested in the Framework Programme (F.P.) for Research and Technological Development to develop innovative and effective ways to preserve the region’s cultural heritage. The geographical distribution bar graph is shown in Figure 2-4.

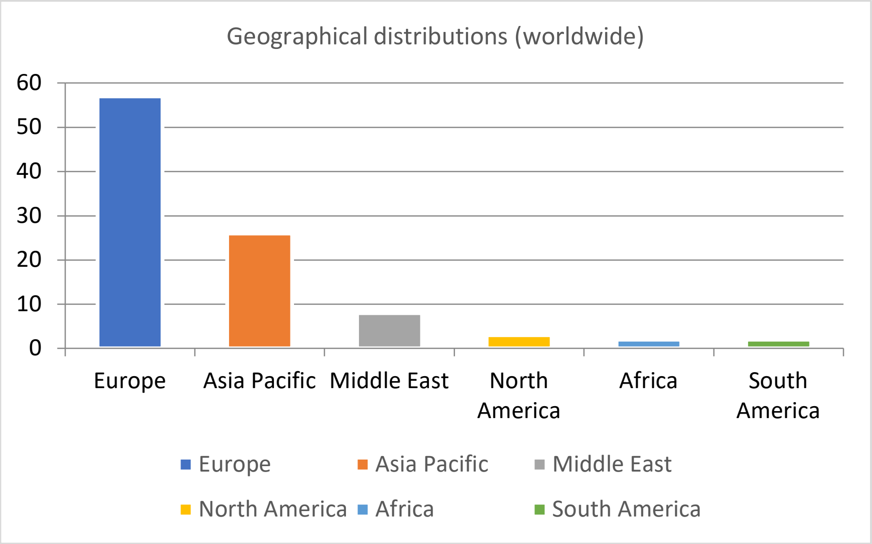

Figure 2-4:Geographical distribution by region

The research articles of this study are selected according to the exclusion criteria. The extracted 77 articles are categorized into four groups, and Figure 2-5 shows the exclusion criteria of this study. The articles related directly to the topic are classified as Group 1 and Group 2. The articles were published in Europe, Australia, and America are in Group 1, and the articles were published in the other countries are Group 2. Similarly, Group 3 and Group 4 are indirectly relevant to the topic. Group 3 is for Europe, Australia, and American, and Group 4 is for other countries. Group 1 articles (n=32) are selected for the current studies' literature reviews and methodology approach. Finally, ten articles extracted from the snowball research method are added to the selection of research articles. The total number of articles for the study is 42. The written language of 95% (n=40) is in English, and the rest 5% (n=2) is in Norwegian.

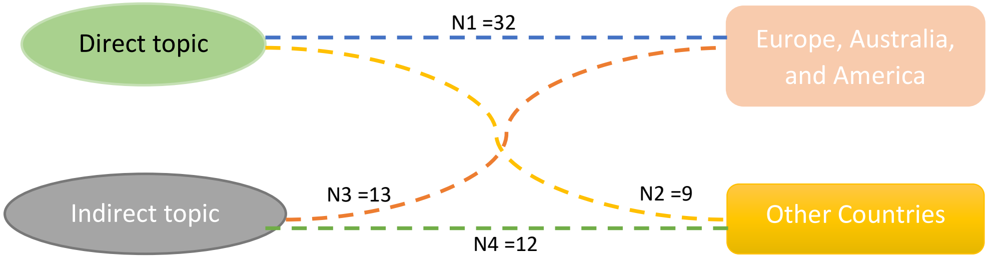

Figure 2-5:Exclusion criteria for the article's selection

Then, Data were extracted for specific variables of interest, author's name, including the year of publication and locations. The final selection of publications (42) will be conducted through the systematic literature analysis. A systematic analysis literature review is conducted to identify the pattern and meaning of the text. MAXQAD is software designed for qualitative and mixed-method data, text, and multimedia analysis. The data analysis will be performed with this software.

2.3. Systematic analysis of selected articles

For systematic analysis, data was retrieved by reading the abstract for the following analysis of the selected literature: -

1) Geographical distribution,
2) Chronological sequence, and
3) Progression in the field of the study

Geographical distribution

The geographical distribution of the documents is defined, considering the published articles within European countries, American countries, and Australia. Norway is the highest number of research articles due to the additional articles from the snowball research method. Other than Norway, Italy, and United Kingdom have published about 12% (n=5). The research articles from the other countries are less than 10% (n=4). Figure 2-6 represents the distribution by country of this study.

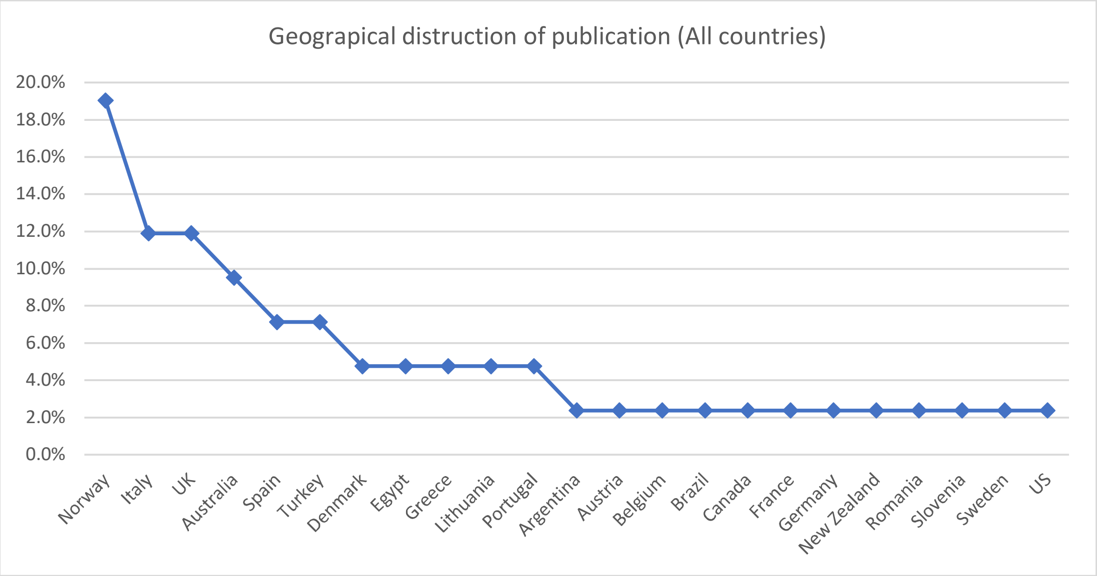

Figure 2-6:Geographical distribution of research articles

Chronological sequence

The environmental assessment of heritage buildings has gotten much attention among researchers in recent years. The scientific articles were written actively after 2012, although a few articles were published before. The graphic Figure 2-7 shows that the number of publications increased drastically over the past years. The total number of publications reached 14, as highest in 2019. This chronological research is based on the selected 42 articles.

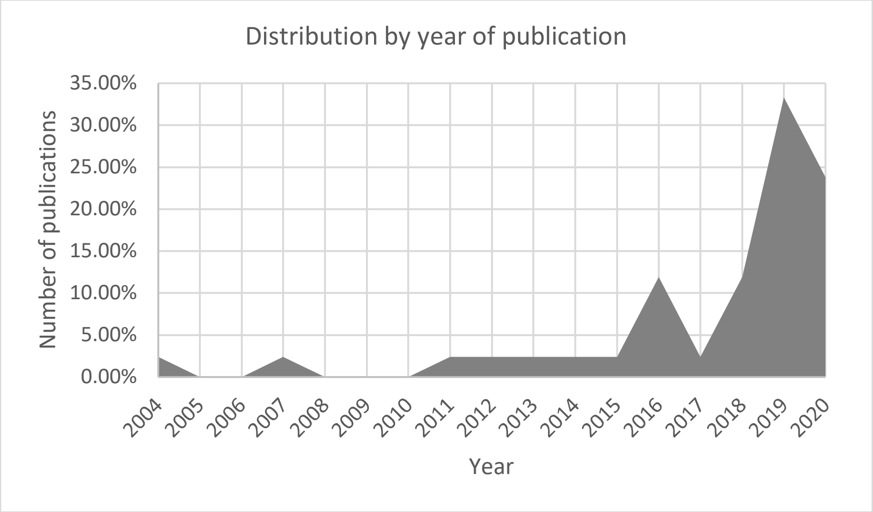

Figure 2-7:Distribution of documents by year of publication

Progression in the field of study

This literature research shows that scientific papers were written majority as journal articles, 67% (n=28). The percentage of selected articles related to the review is not significant, with less than 21% (n=9). The other types of publications are less than 5%. Figure 2-8 represents the distribution of documents by type of publication.

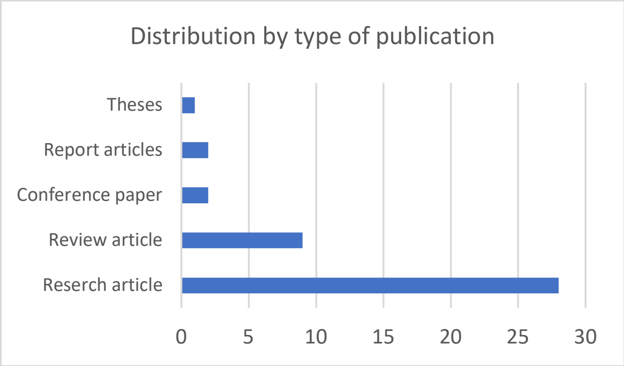

Figure 2-8:Distribution by types of publication

This content analysis includes only one level with explicit content relevant to the interest in Europe and America region. When one document was judged to belong to more than one category, it was assigned to the authors' most relevant field. The qualitative content analysis result is demonstrated in Figure 2-9. The summative quantitative content analysis involves interconnected steps-reading, coding, displaying, reducing, and interpreting the data. After reading all the publications, the coding process began by classifying the cluster of analysis. A code expresses an idea in text or text segments. Next, text within and between the codes was analyzed to identify the common observation, relationships, and patterns in the data. The screening process resulted in 13 clusters for the analysis.

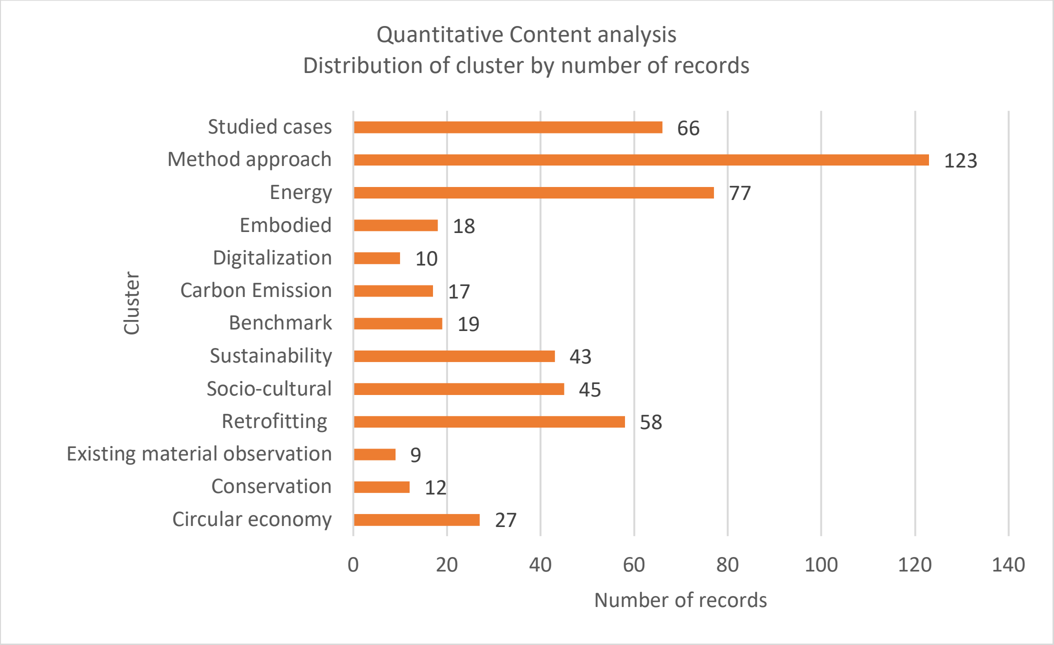

Figure 2-9:Distribution of clusters by number of records

2.4. State of the art based on existing studies

In this section, the state-of-the-art (SOTA) literature review is conducted to study as closely as possible state of the art in current methodology regarding the adaptive reuse LCA of the heritage building. The following specific goals will be studied as SOTA:

1- The focus of the articles
2- Studied method of the articles
3- The main finding and gaps of the articles

The life cycle assessment (LCA) of adaptive reused or reused heritage buildings is performed and studied in different study methods and concepts.

Focus

Among selected articles, [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32] and [33] focused on **adaptive reused design strategies or assessment methodology** of historic and heritage buildings. In [34], the researcher studied the sustainable building renovation to improve the quality of life for the society. The facilities management for heritage building rehabilitation is explore in [13]. [4], [34], [35], focused on the **soft values** such as social value, heritage value, cultural value. [28], [36], [37], [38], and [39] supported for the **decision making** concept how to reuse the building or whether the building should be reused or not. Moreover, the application of BIM technology in heritage buildings' adaptation are studied in [39]. Additionally, [40], [41], [42], [43], [44], [45] are focused **the energy refurbishment** aspects such as energy flexibility and energy quality. **<u>Build environment and circular economy</u>** are researched in [46], [47], [48], [49] and [50]. The important factor of LCA, building lifespan , are studied in [51].

Method

In preservation and adaptive reused of heritage buildings, the most important step is defining the **decision-making tool** for the use of buildings. The **multi-criteria decision-making method (MCDM)** are used in [28] and [36] , and **field observation with interviews** are performed in [52]. The about 40% of the selected articles used literature survey method ([4], [15], [16], [17], [19], [21], [22], [25], [29], [30], [32], [34], [42], [46], [48], [49]) and state of the art literature survey, literature review, systematic literature review and academic investigating research are included in these literature survey research. The other types of research methods are **filed observation and interviews** ([13], [52], [16], [46] and [19]), **Multicriteria analysis or data analysis** ([36], [37], [18] and [29]) , **assessment approach or case study approach** ([14], [20], [21], [22], [41], [24], [38], [26], [43], [31], [33], [45], [23]) are the dominant methodology. However, There is only one article [40] that studied about GIS[2]-based methodology of building renovation, and it focused on energy flexibility.

Finding and gaps

Here the finding which has the significant effect only will be studied. During the initial stage of the heritage building's renovation, a pre-renovation evaluation for the heritage building with existing structural integrity and energy performance. A project of building rehabilitation should start with the **pre-evaluation** for use as a baseline of post-evaluation. [34] Therefore, the pre-renovation evaluation plan will be performed as a scenario (EXT) in this study to carry out the comparative assessment. Heritage building reuse and preservation were studied in different methodology approaches.

Deciding on the reuse purpose and method of the heritage building is vital for all the stakeholders. In order to gain a holistic life cycle assessment, all the stakeholders are equally important. All parties (for example; policymakers, designers) must involve in the life cycle assessment model. [44] Every project must carry out a decision-making analysis or assessment before the project started. Although the **Multi-criteria decision-making (MCDM)** method is popular in other research fields and academic studies, this approach is not widely used to reuse and preserve heritage buildings. [36] D. Misirlisoy et al. [16] provide a comprehensive review of adaptive issues and factors' effect on decision-making. This study will reference this approach to investigate the environmental impact of the adaptive reuse heritage building.

The building's renovation was measured using **different aspects** like environmental, social, economic life cycle assessment and building certification systems [34]. A **holistic approach** taking soft values and

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[2] GIS: Geographic information system framework

socio-cultural factors into consideration will gain the society and increase the awareness and understanding of how sustainable resources are embedded in the historic building stock.[4] Most of the life cycle assessment considers the Heritage, Social and Environmental aspects. A robust, holistic approach to sustainability impacts should include social, economic, and environmental aspects. [34] However, Kagan G and Damla M, [19] suggested considering five main assessment dimensions called HEEPS -Heritage, Environmental, Economical, Social, and Process) for a holistic approach of heritage building adaptive reuse methodology. In the article [4], the authors indicated a possibility of obtaining a **holistic approach** to the cultural heritage building's socio-cultural, technical, and environmental impact. Life cycle analysis combined with environmental product declarations (EPD) and preserving the heritage value and socio-economic values. However, the concept of value evaluation must be simplified.

Adaptive reuse strategies should be developed as owned for each project, and this adaptive reuse method should be carried out without harming the architectural identity of the building [19]. A built cultural environment should be included in the environmental assessment procedure for achieving a more integrated view of the environmental and social dimension [46]. Moreover, a comprehensive framework and practical tools for the project team must be created to support the circular economy strategies. [48] Cost optimal methodology may be robust, but it requires sensitivity and expertise. [23] The energy-efficiency measure is a multi-objective optimization problem, though energy-saving is available. [41]

The building service life (or) lifespan is a vital factor in evaluating the total emission of the building per year per square area. The longer **lifespan** of the building components reduces the total emission of the building and should not use the shorter lifespan of materials for building components. [51] Most of the previous studies of reused building life cycle assessment considered production stage (A1-A3) and replacement stage (B4) but recycle or reuse **module** (D) was considered less than 50% [32]. According to the article [22], the environmental impact for the use phase is dominant for overall environmental impacts. Also, the construction and demolition phases impacts are significant.

In the article [33], Vaclav Hasik proved that 53-75% of **the total emission of the building had been reduced** in the reused building compared to the new construction. It is a motive to investigate the different scenarios of the adaptively reused building in a case study. Overall, the reused building results in **more sustainability** in environmental, social, economic [34]. The case study approach of a refurbishment building from the 1930s, [45] highlighted that materials used of the building and user behavior have **crucial impacts** on the greenhouse gas (GHG) emission of the building.

Adaptive reuse is a concept of converting an existing building to undertake according to the user requirement. The existing building can be reused for the same purpose or adaptive purpose. Renovation and refurbishing are involved in the adaptive reuse concept. Existing buildings need to be reused to develop a sustainable society. The existing building includes newly completed buildings and old buildings with extended service lives. There are many heritage buildings to be accounted as reusable heritage buildings. The most significant amount of heritage buildings that can be reused are industrial heritage buildings. Industrials heritage buildings are the building which was built in Industrial Revolution through to the onset of the World War 1 (in 1914). [53] However, the Industrial Revolution started in the 18th Century, and many industrial buildings can be reused with a new or adaptive purpose.

The interest in the circular economy and environmental assessment concepts of heritage buildings are increasing over the years. It will increase furthermore. The descriptive analysis shows the several methods to evaluate the environmental impacts of the existing heritage building are the most significant. It is about one-fourth of the total content coding. However, these studies are not efficient in evaluating a complete environmental assessment of existing heritage buildings due to not consistent analysis, especially in establishing a comprehensive framework. More research on actual existing buildings needs to be performed. On the other hand, the building information modeling study (BIM) of heritage buildings and the heritage building’s materials observation is still insufficient. The specifications of heritage building materials must be standardized and documented. It is vital for reusing heritage buildings. Regarding the study case of the heritage buildings, just a paper out of all the publications is written about reuse industrial heritage buildings.

During the revitalization of the heritage building, there are often conflicts between public and private interests, especially in public projects. The main challenge of the rehabilitation of heritage buildings is balancing these conflicts between public and private. In this case, facilities management plays an essential role in handling the project [13]. Moreover, every project should have transparent documents of methodology choices for each sustainability assessment [25]. Further research about facilities management of the adaptive reuse heritage building needs to be performed. Table 2-1 shows the study’s method, focus, and findings of the selected articles.

Table 2-1:Literature survey matrix for the selected articles

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding
Literature review (State of the art)	[34]	To improve the quality of life-social sustainability.	Sustainable building renovation. (social value)	-	Common overview of SBR[3]: - 1- SBR can be grouped into main factors (durability/ building physics, economy, environment, and comfort) 2- More sustainable in terms of environmental, social, economic (or) at least two of these. 3- Demand-side: owners, users Supply-side: providers of design and construction service. 4- A pre-evaluation of the building for post-evaluation baseline 5- High transaction costs but can overcome with “Relational contracting.” 6- Sophisticated strategic partnerships: 2 decades in U.K. and spread to several other countries. 7- Not many tools and systems for decision support dedicated to building renovation 8- SBR is measured through a combination of different parameters. (environmental, social, economic LCA, building certification systems.) 9- Regulation and policymaking play a central role (incentive schemes, building codes, certification schemes) and inhibiting factors: handling cultural heritage building. 10- The sophistication of building materials, technical installation, and services have escalated in the past decade. A. heating and cooling demand reduction, B. energy-efficient equipment and low energy technology, C. renewable energy supply (digital tools), and D. diagnostic method. But all are still in the lab.
Bibliometric data analysis	[36]	To reveal the knowledge domain of MCDM approaches in heritage buildings’ reuse and preservation	Multicriteria decision-making method (MCDM) approaches in heritage buildings’ reuse and preservation.	-	MCDM methods are widely used in many other areas; their usage in cultural heritage buildings is weak.

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[3] SBR: Sustainable building renovation

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding
Field observation and interviews	[13]	To explore the conditions and challenges in the heritage revitalization project, especially how FM-related professional services offer value-added opportunities.	Facilities management for Heritage building revitalization	HRB[4]- Former Central police station compound (Hong Kong)	Reveal the role of F.M.[5] in coordinating the HBR[6] process to benefit stakeholders and the general community. • The main challenge for a successful HBR is the ability to balance the often-conflicting public and private interests. • F.M. plays a critical strategic role in community development and urban renewal.
Geographic Information System (GIS) with bottom-up methodology	[40]	To provide a methodology for sustainable retrofitting plans based on GIS[7] data selection of building clusters to assess energy flexibility.	Energy flexibility in building cluster (through deep renovation)	HRB[8]-Spain-Hermandades neighborhood	• The building cluster hourly load profile for heating and cooling and thermal comfort indexes. • This GIS-based methodology will become part of a more comprehensive spatial decision support tool for environmental public policies contributing to building stock transformation through deep renovation and renewable energy use.
Case Study approach	[14]	Analyzing the existing building safety factor and response of the structural masonry–steel system after rehabilitation.	Sustainable design strategy for the restoration of historical buildings	HRB-Greece-neoclassical buildings in Veria	• Structural resistance for upgraded operating loads during seismic events can be appropriately defined so that integrity of the historical building is high. • A steel structure including decking and fire protection will typically cost 5% to 7% less than a concrete framing system. • Steel structures can be easily modified to accommodate the new requirements (design flexibility). • Both life safety and recoverability of the structure after a seismic event are likely the most critical factors that need thorough investigation.

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[4] HRB: Heritage reused building
[5] FM: Facilities Management
[6] HBR: Heritage building revitalization
[7] GIS: Geographic information system
[8] HRB: Heritage reused building

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding
Systematic Literature Review	[15]	to assess the potential of Multi-objective optimization (MOO) using a Genetic algorithm (G.A.) for supporting the development of retrofitting strategies and their D.M.[9] process.	Building retrofitting strategies towards energy efficiency	-	Strong suitability for solving a wide range of building retrofit MOO[10] problems, based on robust outcomes with significant objectives improvement *Gaps: -* • Yielding optimal retrofit solutions may require G.A.[11]-mixed techniques or modified G.A. due to time-consuming and effectiveness issues. • Lack of standard systematic approach; complex switch between modeling and optimization environment; high expertise needed to perform MOO and manage software; and lack of confidence in results.
Literature review and semi-structured interviews	[52]	To highlights, criticism causes through the examination of essential aspects associated with any adaptive reuse decision making.	adaptive reuse decision making for heritage buildings	Privately owned Diyarbakir Hassan Pasha Khan in Turkey and publicly owned Limassol University buildings in Cyprus	• Urges to cautious revision of adaptive reuse legislation and regulations of the targeted building • Developing a standard for adaptive reuse decision making sound practice
literature survey, content analysis, and field study	[16]	To evaluate the appropriateness of the re-functioned heritage buildings To define the problems in the decision-making	Adaptive reused strategies (holistic approach)	6 re-functioned heritage buildings from different countries (include industrial heritage building)	• To decide the most appropriate adaptive reuse strategy for the heritage buildings, all the factors must be considered holistically • A qualitative approach and the adaptive reuse strategies can be developed according to the decision-makers and policy issues of the related context • Proposes a comprehensive methodology for the development of adaptive reuse strategies for heritage buildings • Provides a comprehensive review on the adaptive reuse issues and the factors that affect decision-making • A universal model that can be applied to heritage building located in any context

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[9] DM: Decision making

[10] Multi-objective optimization

[11] Genetic algorithm

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding
Literature review	[17]	to explore possible applicable assessment themes for heritage building refurbishment	Refurbishment assessment themes for heritage buildings	Non-domestic building	• Identification of five main assessment dimensions called HEEPS- Heritage, Environmental, Economic, Social, Process • Integrating all dimensions into a single assessment framework is crucial. • Suggest that relevant policy makers and decision-makers develop a comprehensive, strategic, integrated, and effective approach to best assess these buildings by integrating the five assessment dimensions as suggested to achieve sustainability
Multicriteria analysis	[37]	to propose an integrated evaluation model based on multicriteria analysis and a financial model to support the choice of alternative reuse to define a "shared strategy" based on a "bottom-up" approach.	Integrated decision support system for sustainability reused of the heritage building, with economic and financial feasibility	Italy- Ex Ritiro del Carmine (Unused monastery)	• the model proposed can be a useful decision support tool in environments characterized by high complexity, such as cultural heritage sites. • The solution found is not sustainable from a financial point of view considering the high investment costs; so, the financial analysis showed the need for access to public funding to cover investment costs. • Future research in this field can be oriented toward the search for new circular financing models, particularly in the field of impact financing, as well as new circular governance models
Data Analysis	[18]	Investigating LCA method of restoration concerning cleaning technologies and materials	Applicability of life cycle assessment methodology (cleaning technologies and materials)- after service life	-	• LCA applies to conservation works concerning cleaning, although some limitations still exist, such as the limited data availability in the databases • For some cleaning methods, the impacts related to manufacturing and disposal are very similar, which emphasizes the importance of performing LCA, including the end-of-life scenarios Gap: • the short-comings and proxies arising from the lack of a specific database. (some materials are not present in the database.)

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
Field observation, Literature survey	[19]	To measure and compare the success of the adaptive reuse practices through user experiences.	Assessment of adaptive reuse practices through user experience	Twelve case studies (six from the north and six from the south) in the walled city of Nicosia	- heritage buildings that are re-functioned with the public use, such as commercial, cultural, and educational use, are more successful in contributing to the socio-cultural and economic development of the city - For the continuity of the heritage buildings, socio-cultural, economic, and physical aspects should be taken into consideration with a holistic approach - Adaptive reuse strategies should be developed to use traditional houses with their original functions or appropriate functions with the authenticity of the original function - Adaptive reuse should be carried out without harming the architectural identity of the buildings
Interview/ Literature survey	[46]	to examine the role that built cultural heritage can play within sustainable urban development.	Built cultural heritage or built environment contributing to the satisfaction of human needs	Victoria Square Belfast- Former civic marketplace	- Including built cultural heritage within the assessment procedures for sustainable development would mark progress towards a more integrated view of the environmental and social dimensions. - The lack of understanding interactions between people and the built environment is reflected in the absence of legislation to address this heritage by appropriation
Systematic literature review / Synthesis method	[48]	To reduce lifecycle environmental impact of buildings with a circular product supply chain approach.	Circular economy strategies	-	- A new and comprehensive framework for circularity strategies for existing buildings - A practical tool for project teams
Assessment approach	[20]	calculates and combines embodied energy and operational energy, proposing a methodology for assessing building components' life-cycle energy, suitable for the assessment of repairing and replacing scenarios.	Refurbishment assessment: Comparing walls repair or replacement and considering different scenarios of users' requirement and thermal comfort	H.B.- pre-industrial Lisbon	- the advantages of preserving building components and materials in terms of whole life cycle energy demand. - framework involving the main stages of energy in buildings (product stage, operational stage, and end of life stage) proposing a methodology and testing. - a comparative assessment of buildings refurbishment options combined with different thermal comfort users' requirements scenarios. - lower operational energy results do not always compensate a significant material and energy loss in replacement scenarios and this loss

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
Literature review/assessment approach	[21]	To provide some clarification by reflecting on the different approaches described in the literature as forms of sustainability assessment and evaluating them in terms of their potential contributions to sustainability.	to clarify what the term ‘sustainability assessment’ should mean if it is to fulfill its potential as a tool for promoting sustainability	-	• Principles-based approaches to developing such sustainability criteria, concluding is more appropriate since they avoid many of the inherent limitations of the triple-bottom-line as a conception of sustainability. • Assessment for sustainability requires a clear definition of sustainability and corresponding criteria against which the assessment can be conducted. • Assessment for sustainability does not replace all applications of EIA[12]-driven impact assessment or objectives-led processes of decision-making. It is an additional tool that can be effectively applied within a decision-making framework to ensure that decisions are sustainable.
Literature review/assessment approach	[22]	Updating an existing tool that enables to carry out the life cycle assessment of buildings by considering demolition and construction phases.	Life cycle assessment (cradle to grave) within the built environment	E.B.- a public office building in Brussels	• The main findings confirm the huge impact of the use phase, highlight the impact (energy and CO2 emissions) of the construction and demolition phases, and show that the in-depth renovation of this building leads to lower environmental indicators compared to its full reconstruction. • Support the development of policies of retrofitting of the existing building stock and highlight the importance of including the whole life cycle of the building in the analysis
Case study approach	[23]	To provide a holistic scheme for the design of the Energy refurbishment of a historic building, capable of integrating suitable standards and methodologies.	Refurbishment of the historic building (cost-optimal methodology)	HB- Italy -Palazzo Penne- XV century	• The selection of input parameters is highly influential. • The cost-optimal methodology may be a powerful tool of sustainability, but it requires sensitivity and expertise. • Refurbishment of historic buildings, aimed at lowering energy demand and greenhouse emissions, is possible and economically feasible.

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[12] EIA : environmental impact assessment

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
meta-analysis	[35]	To identify common drivers of the economic value of cultural and historical heritage by conducting a meta-analysis of heritage valuation studies.	Driver of heritage value (economic value / monetary valuation)	-	• Heritage sites in areas with higher population density holds higher value, and conservation that supports adaptive reuse of sites generates higher values than passive protection. • Identify a need for more economical and interdisciplinary research on the value of non-built heritage to improve understanding of the composition and drivers of heritage value.
Assessment approach/ case study approach	[41]	Integrated design of energy refurbishment of existing buildings, with reference to historical architectures	Energy retrofit (respect of the historical value)	H.B.- Educational building of the University of Sannio, located in the ancient center of Benevento (Southern Italian city)	The selection of the energy efficiency measures is a multi-objective optimization problem, and – even if heritage buildings require respect of several constraints – however, satisfactory energy savings are available.
Assessment approach	[24]	An integrated life cycle framework developed by combining life cycle modeling with building energy efficiency simulation software	Life cycle assessment of heritage building (whole building)	eight residential heritage buildings in Victoria, Australia	Lower life cycle primary energy consumption does not necessarily lead to lower carbon emissions as carbon reduction depends on a combination of primary energy consumption, the magnitude of heating and cooling, fuel mix profile, and efficiency of the conventional grid.
Systematic Literature Review	[25]	Explores and synthesizes the sustainable potential of maintenance and repair methods using concrete and cement-based composite materials.	Sustainability assessment of maintenance strategies (concrete)	-	• Stimulated scholarly discussion on further methodological progress to align with the good practices identified in our review. • Scientific practices to assess sustainability for 'maintenance' measures with cement-based materials. • It is required for transparent documentation of methodological choices within each sustainability assessment for purposes of comparison.

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
Assessment approach	[38]	a method based on life cycle assessment (LCA) as a useful decision-making tool for analyzing the most suitable building system for intervention in heritage sites.	Life cycle assessment as a decision-making tool	Roman Theatre heritage site in Italica (Spain)	indicate that LCA can be of assistance in selecting the most suitable option for intervention at a heritage site.
Assessment approach	[26]	To achieve the net-zero carbon emissions building through the reuse of existing materials and structures.	Life cycle assessment of building restoration	Don Valley Brick Works' Kiln Building, in Toronto, Canada)	Insights for assessments of future projects as such refurbishments become more commonplace. The methods and recommendations regarding data sources, data collection, and approach to uncertainty evaluation will be useful for the LCA of any construction project.
Review and Analysis	[42]	A review and analysis of previous life cycle energy analysis were conducted reexamining this conclusion	Life cycle energy of building	-	Highlights that a more holistic approach is needed to achieve low life cycle energy buildings in the future
complex methodology merges the ecosystemic approach	[27]	to analyze the preservation and capitalization of technical and industrial heritage.	Preservation and adaptive reuse of heritage building	Different phases of urban regeneration projects (the cities of Bucharest, Timisoara, Calan, Resita)	Highlights the importance of identifying and analyzing the directions pursued by the various functionally restructured areas, as well as current challenges in implementing alternative development policies To reuse the technical and industrial heritage has to be materialized and converted into an instrument that is absolutely necessary for the reassertion of under-privileged industrial areas
Multicriteria analysis	[28] 56	to introduce an appropriate evaluation tool to support the efficiency in selecting the optimum solution.	Adaptive reuse of heritage building	Aziza Fahmy Palace, Alexandria, Egypt	The best use is mixed uses with the highest value, which is 0.30 (30%), followed in sequential order by the museum, office building, and hotel.

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
(Literature review and analysis) Academic investigation and design response	[29]	The transformation of an industrial heritage building into a new place or stage. To promote and experience the adaptive reuse approach for the already-built urban environment.	Adaptive reuse and experience design of heritage building	an old oil and olive oil soap factory in Ayvalik	Old buildings, carefully re-designed in line with the principles of the experience economy model, enable the transformation of historically built environments into up-to-date attractive urban centers while ensuring social and economic development.
MCDM and BIM application	[30]	Enhancing sustainable development, of course, three main sub-systems of sustainability are evaluated: the economic value of changes, impacts on natural environments, and influence on the social environment.	Heritage building's Conversion alternative with BIM and MCDM of	Sapieha Palace, built in the Baroque style in 1689–1691 in Vilnius, Lithuania	The suggested integration of modern digital technologies and decision-making models helps to assure the rational conversion decision of built cultural heritage based on high accuracy data and contributes to the sustainable development of engineering processes.
Assessment approach (Simplified assessment method)	[43]	A simplified evaluation method for assessing and comparing the environmental and energy quality (EEQ) of museum buildings.	Environmental and energy quality (compare environmental and energy performance and identify the most common problems)	Fifty European museums	A strategic and repeatable approach for conserving and enhancing cultural heritage recognizes that the project is not limited to the design of the building, but it requires maintenance and updating over time.
Literature review	[30]	to provide a comprehensive overview of the refurbishment of heritage buildings.	Refurbishment of a heritage building (Sustainability and universal design)	-	The current research related to heritage building renovation and reuse does not comprehensively address sustainability and universal design issues. Typically, in research, the topics of heritage, sustainability, and inclusiveness are considered separately. It is essential to consider these topics not only separately but also in an interrelated way.

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
Literature review	[49]	to provide state-of-the-art on C.E.[13] research through a literature review.	Circular economy in the built environment	-	- Research gaps and a theoretical framework were proposed to guide future research - The need for more explanations about CE and circular business models is highlighted - Government support (such as subsidies, laws, and tax incentives) is crucial to the strategic performance of Decision Maker to introduce circular principles and make buildings and the built environment more sustainable
Literature review (State of the art)	[4]	To pursue a more holistic picture of the total footprint of existing buildings by including historical, architectural, and aesthetic arguments when establishing the value.	Life cycle analysis of historic building (socio-cultural values)	-	- A holistic approach, taking soft values and social factors into consideration, will gain the society and increase awareness and understanding - Further, sustainable resources in the form of soft values embedded in the historic building stock can contribute to and encourage future sustainable society
Case study analysis	[31]	to establish scientifically robust benchmark values for different Norwegian building typologies.	material emission reduction strategies (ZEN Pilot case)	Sampled study cases from Norwegian programs and research centers such as Futurebuilt, Framtidens Byer, the research center on zero-emission buildings.	The results show a decrease in emission after introducing the standardized data sources (e.g., EPD) and focus on material emission reduction strategies
Literature review, methodology analysis	[32]	establishing the state of the art of building rehabilitation LCA methodology used in case studies.	LCA Methodology: building rehabilitation	41 LCA studies	Three methodological challenges (definition of the functional unit/functional equivalent and the building scenarios, determination of the RSP/ReqSL, and modeling of operational energy) were pointed out, and recommendations for methodological improvements were proposed

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[13] C.E.: Circular Economy

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
Statistical analysis	[51]	to explore how the environmental impact from building components is affected by building lifespans of 50, 80, 100, and 120 years in a Danish context.	Effect of building lifespan	The choice of 7 primary building components	If construction professionals and policymakers use short building lifespans, then resource allocation to reduce environmental impact during procurement may become disproportionately focused on the construction contra operational phases of the lifecycle
Meta-analysis	[44]	to explore the impact of contextual factors at both policy and project level in significantly reducing the embodied environmental impacts of buildings.	Energy refurbishment- Low embodied impact buildings	Eleven refurbishment projects as case studies	• Planning authorities, major clients, developers, and individual designers can all play an essential role in reducing embodied impacts by encouraging innovation • Recommendations for policy makers, designers, and LCA modelers who will support and effect real reductions in the whole life embodied impacts of buildings
	[50]	a first approximation towards how resource use is allocated across Norway's sectors and societal needs and wants.	Circularity gap		In terms of societal needs and wants, Nutrition and Housing, and Infrastructure are the most significant contributors to the material footprint.
Ph.D. thesis	[47]	to overcome the collaboration difficulties among different communities associated with heritage conservation by defining a framework that includes all the necessary steps from study to practice in a methodologic way.	Zero-emission refurbishment (ZER): Built environment	A block of building in Trondheim	• the carbon footprint of intervention measures, linked with the energy improvement of the buildings after the completion of the works • A sustainable approach for reducing greenhouse gas emissions while at the same time ensuring the best possible preservation strategies is a challenge that needs to be faced for the present and future generations. • A district-scale enables the intervention works to be implemented through largescale projects, thus ensuring their uniformity and reduction of time and cost of the actions.

Method Use	Author/Ref: no	Aim/Objective	The focus of the study	Case Study	Main Finding/ Gap
Assessment approach	[33] good article to reference	Compare LCA of new construction and renovation LCA approach for renovation projects LCA approach for adaptive reuse case study	Life cycle assessment of new and existing buildings		The case study showed 53–75% reductions across six different environmental impact categories when the renovation was compared to a new construction scenario. The reuse of the structural and envelope components provided the most reductions, as most of the renovation was of the interior components and finishes.
Assessment approach	[45] good article	presents and the results of a Norwegian life cycle assessment comparing the net climate benefits.	Life cycle assessment: energy refurbishment	a residential building from the 1930s	Material use and user behavior have a crucial impact on greenhouse gas emissions from a life cycle perspective and should advocate in building codes and environmental policies.

2.5. Motivation and Research Questions

There is a lot of research and development which focus on the life cycle assessment of the new building to assess the sustainable impacts. However, there is much less research on reused building's life cycle assessment methods to investigate heritage buildings or historic buildings. There are few methods to prove how the heritage buildings are more sustainable than the new construction and how the heritage building's social value can be remained by conservating the building. Assessment methods considering socio-cultural resources exist hardly. Such a method will enable assessing the holistic sustainability in historic buildings and urban settings for establishing the total green footprint. [4] In this study, environmental impacts assessment of a reused industrial heritage building is investigated and compared with new construction.

The life cycle assessment method will be used as a based method and improve according to the adaptive reuse purpose. This study will support establishing the holistic assessment method to investigate the sustainable impacts of the heritage building. This work offers insight into the state of knowledge on existing buildings' environmental assessment and reports how these topics are being explored. This systematic review shows that the topics are incorporated actively into the research agenda since 2014, although the researchers' interests started at the end of the 20th Century.

The interest is growing with the increased production of research articles. However, the current research is minimal, and most of the publications are in Europe. Moreover, the environmental assessment of heritage buildings still lacks the knowledge to evaluate holistically. The results show that the topic has not been exploited enough, and more research should be studied with a broader insight into holistic environmental assessment and circular economy. The study of the environmental assessment of existing buildings should be improved. The following research questions have been explored to carry out this study after performing the literature survey and background information.

The existing heritage buildings' blueprint may not be available. Even though it is available, the information may not be enough to perform refurbishment or repair. In order to perform a satisfactory refurbishment of the heritage building, the existing materials must be explored whether the structure is strong enough for the building function. The existing building and its components can be tested for material deterioration, such as moisture tests for building performance. The building can be improved based on the results of simulation and testing.

Moreover, the reconstruction assessment for structure aspects also must be done before any refurbishing or retrofitting. The conversional conservation of heritage buildings was conducted for the last several years. However, construction technology is improving nowadays. Therefore, the heritage buildings must be digitalized and monitored for robust and resilient buildings. Digitalization can be established new applications, tools, and features in existing tools of the environmental assessment of Heritage Buildings.

Q1: What are the different impacts between adaptive reuse of the existing building, demolition, and new construction?

The current comparative assessment of adaptive reuse heritage buildings compared only existing design and adaptive reuse design. Therefore, the demolition scenario will be included in this study. Some heritage buildings, such as industrial heritage buildings, are allowed to remove under particular conditions.

Q2: Are existing tools relevant to evaluate the environmental impact of adaptive reuse of existing buildings? What are the particular challenges for heritage buildings?

The well-known life cycle assessment tools are ZEB tools and OneClick LCA in Norway. However, these tools have used the database for the new materials and new construction. For the heritage building, the existing materials are different and complicated due to the different construction techniques. The construction technique is also different based on the age of the building or building's built year. Therefore, the database of outdated materials of the ancient construction method must be established. However, the current assessment tools will be tested to evaluate the life cycle assessment of the heritage building.

Q3: How to evaluate the environmental impacts of adaptive reuse of industrial heritage buildings?

Several heritage buildings conducted the life cycle assessment for adaptive reuse, but one article studied the industrial heritage building. Therefore, little research about the industrial heritage buildings' adaptive reuse currently needs more research. Therefore, an industrial heritage building (Paper Factory - PM5 building in Skien) is used as a studied case in this study. The author believes that the assessment method of industrial heritage buildings will different from the cultural heritage building.

3. Methodology

3.1. Method approach

This study aimed to compare the environmental assessment of industrial heritage buildings based on the life cycle assessment method. However, the life cycle assessment method was modified to suit the industrial heritage building. In this study, the methodology was structured in four steps. The fundamental phases in the LCA include **goal and scope definition**, **inventory analysis**, **impact assessment**, and **interpretation** [54]. The LCA method for heritage building was carried out as the flow chart in Figure 3-1.

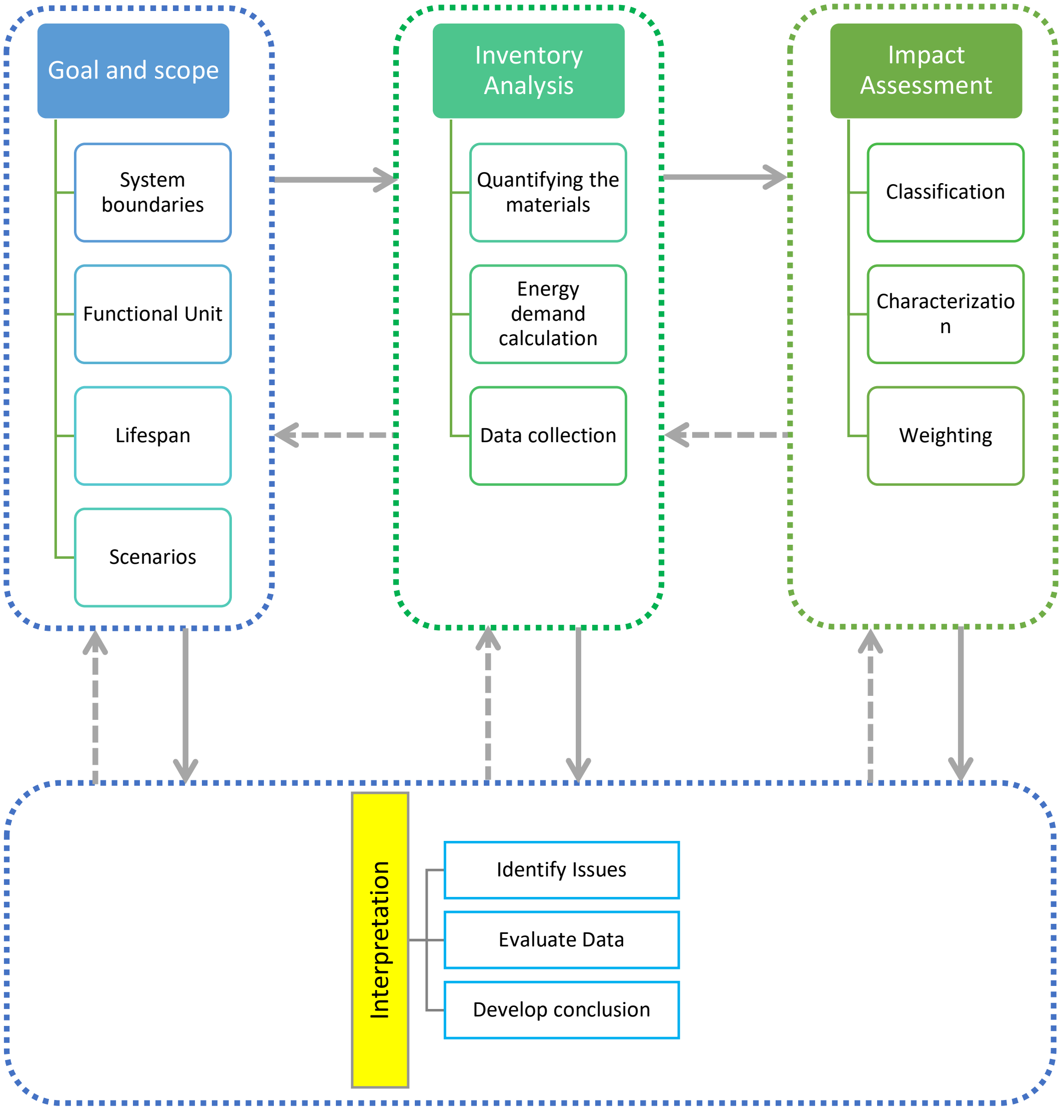
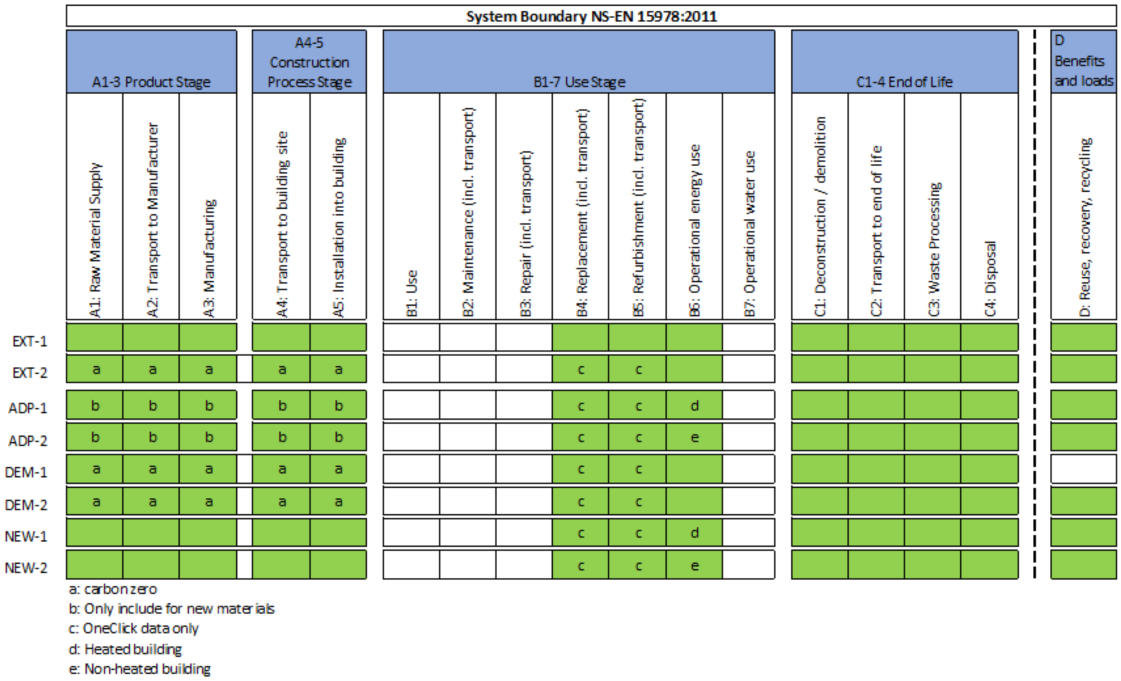


Figure 3-1:Fundamental phases in the LCA

3.2. Goal and Scope

The goal of the LCA for the industrial heritage building is to prove that the emission of an adaptive reuse heritage building is significantly lower than the new construction and demolition. The purpose of this study is described in the previous Chapter. The primary purpose of the LCA[14] result is considered from the beginning while defining the goal and scope. [18] The scope of the LCA will be defined according to ISO standard 14044 [55].

3.2.1. System boundary



System Boundary NS-EN 15978:2011

	A1-3 Product Stage			A4-5 Construction Process Stage		B1-7 Use Stage							C1-4 End of Life				D Benefits and loads
	A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	D: Reuse, recovery, recycling
EXT-1	🟩	🟩	🟩	🟩	🟩				🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩
EXT-2	a	a	a	a	a				c	c	🟩		🟩	🟩	🟩	🟩	🟩
ADP-1	b	b	b	b	b				c	c	d		🟩	🟩	🟩	🟩	🟩
ADP-2	b	b	b	b	b				c	c	e		🟩	🟩	🟩	🟩	🟩
DEM-1	a	a	a	a	a				c	c	🟩		🟩	🟩	🟩	🟩	
DEM-2	a	a	a	a	a				c	c	🟩		🟩	🟩	🟩	🟩	🟩
NEW-1	🟩	🟩	🟩	🟩	🟩				c	c	d		🟩	🟩	🟩	🟩	🟩
NEW-2	🟩	🟩	🟩	🟩	🟩				c	c	e		🟩	🟩	🟩	🟩	🟩

a: carbon zero
b: Only include for new materials
c: OneClick data only
d: Heated building
e: Non-heated building

Figure 3-2:System boundary of LCA Scenarios[56]

The LCA of PM5 considered the emission of product and construction (A1-A5) as zero by assuming embodied emission had been offset. The PM5 building was an in-use stage in this study. Although the building was abandoned for several years, some subcultural societies entered the building and performed some activities. Therefore, maintenance (B2), replacement (B4), refurbishment (B5), and operational energy (B6) are considered. However, the data input was only materials, and the emission result is according to One Click LCA. Windows were replaced with aluminum frame windows, and this replacement (B4) also was regarded in the adaptive reuse scenario. The system boundaries of each scenario are shown in Figure 3-2. The system boundaries were slightly different between scenarios. Then, the interpretation of the life cycle assessment is carried out. The results obtained are presented synthetically, presenting the critical sources of impacts and the options to reduce these impacts.

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[14] LCA: Life Cycle Assessment

Finally, compared the outcomes of all scenarios and the most efficient design was highlighted. However, there were many challenges due to uncertainty and lack of information

3.2.2. Functional units

All the replaced components of the building were studied in adaptive reuse scenarios. However, the whole building materials and components were examined in the other scenarios. The materials data was extracted by analyzing the construction technique of the 18th Century. The functional units of study are ton-CO_2 e/m^2 or ton-CO_2 e. The dominant replaced building component is windows.

3.2.3. Building lifespan

The owner (Steinar Moe Eiendom) has established a residential area, and the national monument park will be provided for the residents. This residential area was presumed for 100 years of lifespan. Therefore, the LCA of the PM5 building was also evaluated based on 100 years of service life. The replaced materials lifespan followed the EPD data of the products. However, the demolition scenarios used one-year service life due to the assumption that the building will be demolished within a year.

3.2.4. Scenarios

The scenario analysis for this study was grouped into four- before rehabilitation, adaptive reuse, demolition, and new construction. Each scenario has two sub-scenarios depends on the assessments' purpose. Table 3-1 shows the different scenarios and sub-scenarios for the LCA assessments of the industrial heritage building.

Table 3-1:Assessment scenarios description

Scenario	Description	Materials/component	Energy demand	Site Operation	Lifespan
EXT-1	Before rehabilitation – Normal Assessment	A1-A5 is considered as a new construction	Lighting (only)	-	100 years (Until 2120)
EXT-2	Before rehabilitation - Neutralized	A1-A5 is carbon zero.	Lighting (only)	NA	100 years (Until 2120)
ADP-1	Adaptive reuse - improved	Materials are improved to achieve the standard U-value	Energy demand (Table 3-4)	Rehabilitation	100 years (Until 2120)
ADP-2	Adaptive reuse – not improved	Materials are not improved and used the same materials.	Energy demand (Table 3-4)	Rehabilitation	100 years (Until 2120)
DEM-1	Demolished – not reuse the deconstructive materials	Existing materials but not reuse any materials.	Deconstruction (only)	Deconstruction	Demolish within a year
DEM-2	Reuse- reuse the deconstructive materials	Existing materials – reused according to One Click LCA	Deconstruction and recycle/reuse (only)	Deconstruction	Demolish within a year
NEW- 1	New construction – heated building	Complete materials (existing + addition)	Energy demand – PH (Table 3-4)	New Construction	100 years (Until 2120)
NEW- 2	New construction – non-heated building	Complete materials (existing + addition)	Energy demand – TEK (Table 3-4)	New Construction	100 years (Until 2120)

Before rehabilitation: EXT-1 and EXT-2

The carbon emission of the before rehabilitation scenarios (existing buildings) were evaluated in the EXT-1 and EXT-2. The building was abandoned for approximately 50 years. Since the building envelope was not used for energy performance, regulations on technical requirements for buildings were not considered. EXT-1 was performed as the whole building evaluation but not considered the carbon offset for the existing materials. Thus, the bill of quantity for EXT-1 included Manufacturing and Construction (A1-A5). EXT-2 considers carbon offset of the material and only included replaced (B4), refurbished (B5), and operational energy use (B6). The operational energy use (B6) included only the lighting in both scenarios.

Adaptive reuse: ADT-2, and ADP-2

These cases included the whole life cycle of the building. However, according to [57], new-building typically take between 10 and 80 years to offset the environmental impacts of the initial construction process. Since the PM5 building's life is more than 135 years, it assumed that the environmental impacts of the initial construction process were offset. Therefore, the existing materials were considered only for B4-B5 and B6. B4-B5 was according to the One Click LCA database, and that database could not be edited. However, the additional materials were considered for all the stages. Doors and Windows were the major replaced components, reflecting the significant impacts. Moreover, energy demand for B6 was calculated by adapting the indoor thermal comfortability, refer to Table 3-3 and Figure 3.4.

In ADP1, the building components such as walls are upgraded to achieve the standard thermal transmittance (U-value). On the other hand, ADP-2 was rehabilitated for heritage and social value. ADP-2's outer walls were not improved to achieve the energy budget because the inner sider of the walls is not appropriate to cover. Thus, heating and cooling of the building were according to the component's U-value and interior temperature only. Therefore, this scenario is appreciated highly in the cultural values of the building. However, ADP-1's energy demand 127357 (kWh/year) is more significant than ADP2's 110814 (kWh/year).

Demolition: DEM-1 and DEM-2

Assumption makes in these cases that PM5 building was demolished for a sufficient reason. The heritage values and cultural values are neglected in these scenarios to study the environmental impacts after building service life. Therefore, the existing building materials were included at the end of service life (C1-C4). However, the reuse of deconstruction building materials (D) was considered only for the DEM-2 but not considered in the DEM-1. The transportation of reuse materials will be neglected in DEM-2. The materials considered to reuse are brick, cast-iron columns, concrete blocks/walls, and demolishing/deconstruction waste for Case DEM-2. However, the reuse/ recycling energy use was added per the OneClick LCA database because the data input for the energy use of demolition is not allowed to edit in One Click LCA.

New Construction: NEW-1 and NEW-2

The new buildings were assumed to build the same as the existing building size and materials. There are two cases of new construction scenarios that were based on the energy use of the building. However, the new construction was assumed to build the same building's size and materials as the PM5 building. Therefore, the energy consumptions were also the same as the adaptive reuse scenarios.

Furthermore, the European Green Deal is a set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral in 2050. European Commission encourages to deduct 55% of the carbon emission in 2030 and 60% in 2050, compared with the carbon level in 1990. In this study, Assessment results of all scenarios were studied to select the most favorable scenario/case and investigate the emission profile with ten-year intervals of the selected adaptive reuse scenario.

3.3. Inventory analysis

A critical point in performing Life Cycle Assessments is precise information and the consistency between inventory data and databases. [18] LCA analysis has two key aspects: 1) collecting data (can be measured, calculated, or estimated) and 2) calculating data to attain results for the system being studied [54]. The inventory analysis is a technical process of collecting data to quantify the inputs and outputs of the system, as defined in the scope. [59]

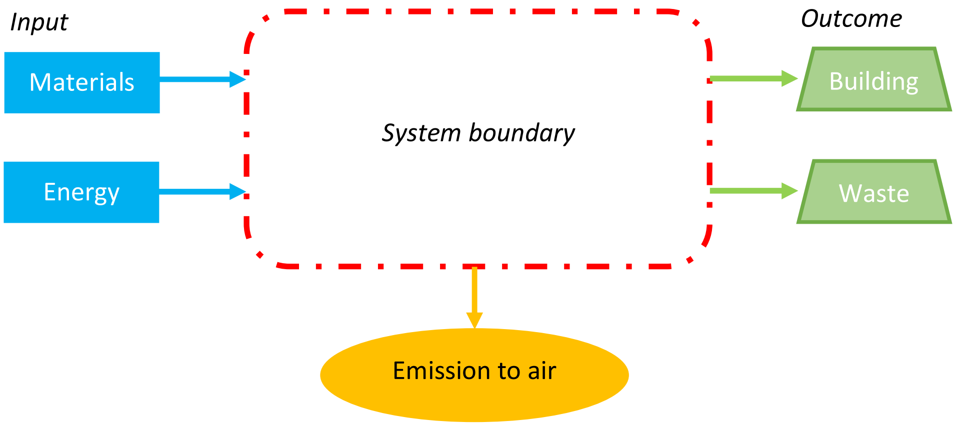


Figure 3-3:Classification of Life cycle inventory analysis

The classification of life cycle inventory analysis is shown in Figure 3-3. The four categories of inventory data are: -

1- Input: Materials and energy
2- Products: The whole building and waste product
3- Emission: emission to air
4- Environmental impacts: Greenhouse gases: GHG (CO_2)

The quantities of materials and energy used in each process and life cycle stage must be quantified (for example, the amount of concrete and kilowatts of electricity consumed). Then the emission relevant to each process must be quantified (for example, CO2 released per kilowatt of electricity). The result of an inventory analysis is a list of the total inputs from nature (resource materials or energy) and emissions to air for the study system. The result of the LCA can be included hundreds of different emissions. However, GHG emissions are considered for this study. The primary data are collected using different methods and tools. The project developer provided the project information.

The assemblies of the buildings need to verify for constructive study. Firstly, the construction techniques of the 19th Century were studies as the PM5 building was built in the 19th Century. Due to the lack of information, determining the building components' assemblies was challenging. After studying the possibility of assemblies and materials, the Bill of Materials (BOM) was calculated conventionally by using the developer's drawing (APPENDIX E). The building material is affected and deteriorated to some extent. However, for the PM5 building, the developer confirmed that the building's integrity is entirely stable. Therefore, no structural assessment of the PM5 building was considered.

3.3.1. Materials

The data were calculated from the PM5 building drawings and images provided by the developer. During the 19th Century, concrete was widely used for industrial buildings. The first concrete building with steel rods reinforced was built in England in mid-19th Century. [60] The PM5 building was constructed in the 1880s. There are concrete beams across the short span of the building with 450mm intervals. Based on these facts, the assumption was made that the PM5 building was built with Portland cement concrete with aggregate reinforcement. The concrete cement ratio is 60% of aggregates and 15% of Portland cement [61]. The presumption made for the materials used and energy demand for all the scenarios is described in Table 3-2.

Therefore, the additional products of the **adaptive reuse** scenarios are:

(1) The outer wall's plastering is replaced and repainted on the outer side (all adaptive cases),
(2) Outer walls' insulation (inner side) was added to achieve the requirement (Only ADP-1)
(3) Floor screeding was repaired,
(4) Doors and windows were replaced with new products, and
(5) A new elevator was installed.

Table 3-2:Materials and energy presumption for all scenarios

Before rehabilitation: EXT-1 , EXT-2	
Foundation	Double dry-stone walls with filling materials in between are the typical foundation in 1870-1930. However, the foundations' depth varied according to circumstances, but generally, the foundations were shallower than the modern foundation. In this study, the drystone wall foundation (0.7 m (T) x 1 m (H)) was used under the outer walls.
Outer walls	Outer walls are load-bearing for the building. The inner side of the outer wall was concrete masonry walls, and the outer part was the brick wall. The brick walls were quantified as 20% of Portland cement and 80 % of bricks. In addition, there are two dormers on the roof and accounted into the assessment
Slab	All the floor screeding (top layer of the slab) has deteriorated.
Column	Outer walls, columns, and beams are the load-bearing of PM5. There are 30 numbers of cast-iron columns on each floor. The outer walls are not supported to remove or repair to maintain the building's integrity. The thickness of the circular column varied between 23.5 mm and 33 mm along the column perimeter. [62] For this reason, the assumption of the columns is the grey cast-iron column with 25mm thickness.
Beam	Grey cast iron ground beams were built across the building span to prevent the building from spreading. The primary cast-iron beams are sitting on top of the columns. Secondary concrete beams are across the building with 400 mm spacing center to center.
Roof	According to the photo and research, the PM5 building's roof had been refurbished before the building was abandoned. The roofing cover is not clay roof tiles. Moreover, the bricklayer under the roof membrane is in excellent condition.
Doors & Windows	The building was abandoned for several years. The wooden frame of the doors and windows have deteriorated, and eventually, the doors and windows must be replaced.
Stair	There is a ladder to access the upper floor and ceiling. However, this is just a ladder and not suitable for the public. Instead, the developer proposed to install an elevator for public use. It is not included in the evaluation.
Energy demand	The average energy consumption is obtained from energy calculation. Therefore, lighting is the only contribution to the energy consumption of the PM5 building before rehabilitation.
Adaptive reuse: ADP-1, ADP-2	
Foundation	Same as the before rehabilitation scenarios.
Outer walls	The walls are still in good condition to reuse. ADP-1 considers achieving better energy performance with additional materials. In ADP-2, the exterior plastering and painting were only added due to not concerning heating demand.
Slab	The concrete slabs were suitable to reuse, but the screeding was repaired.
Column	The cast-iron columns are strong enough to remain.
Beam	Beams are also the same as the column above.
Roof	Same as the before rehabilitation scenarios.
Doors & Windows	The doors and windows are replaced with aluminum frames.
Stair	An elevator was installed to access the upper floors.
Energy demand	The energy demand was calculated by considering the energy use of heating, cooling, technical equipment, lighting, and hot water.
Demolition: DEM-1, DEM-2	
Foundation, outer walls, Slab, column, beam, roof, door & windows, stair	Same as the before rehabilitation scenarios.
Energy demand	Only included the lighting for 1-year service life. However, the deconstruction energy used is considered only in One Click LCA. It is not transparent.
New Construction: NEW-1, NEW-2	
Foundation	Same as the before rehabilitation scenarios.
Outer walls	Complete building; existing walls + addition for energy performance
Slab	Complete building: existing slab + screed
Column	Complete building: existing columns
Beam	Complete building: existing beams
Roof	Same as the before rehabilitation scenarios.
Doors & Windows	Use the same doors and windows of adaptive reuse scenarios
Stair	Same as adaptive reuse scenarios
Energy demand	Same as adaptive reuse scenarios

3.3.2. Energy Demand

The energy demand is a critical contributor to building emissions in the long term. Although the PM5 building was abandoned for more than 50 years, subcultural societies had access to the building. Therefore, the **EXT-1 and EXT-2 scenarios’** energy consumption is assumed as electricity for lighting.

Table 3-3:Energy Consumption for Adaptive Reuse scenario and NEW Construction Scenario

	ADP-1			ADP-2		
	Energy req	Area	Energy demand	Energy req	Area	Energy demand
	kWh/m2-yr	m2	kWh/yr	kWh/m2-yr	m2	kWh/yr
Heating demand			47508			52509
Cooling demand			40789			19246
Lighting	17.2	1550	26660	17.2	1550	26660
Equipment	3	1550	4650	3	1550	4650
Hot water	5	1550	7750	5	1550	7750
Total Energy Demand			**127357**			**110814**

The static heat balance was calculated for both ADP-1 and ADP-2 by using NS EN3031-2020 and NS-EN 3031-2014 as the standard data. The thermal conductivity (λ) of the construction materials was taken from Table 3- NS-EN 10456:2007. The heat gain calculation included heat from equipment, person/ human and lighting, and the solar gain. The heat loss was calculated with each building component's thermal transmittance (U-value) in different circumstances. According to the standards ' criteria, the existing building component’s U-value was inefficient. Therefore, the adaptive reuse scenario ADP-1 was improved to achieve the criteria by adding insulation and the air layer. Those changes result in a significant effect on the environmental impacts. On the other hand, the energy demand of the ADP-1 scenario has calculated the energy based on the existing U-value and indoor temperature (21 ° in operation hours and 19 ° in non-operation hours). The energy consumption input data for adaptive reuse scenario and new construction scenario are shown in Table 3-4 and calculation in Appendix D.

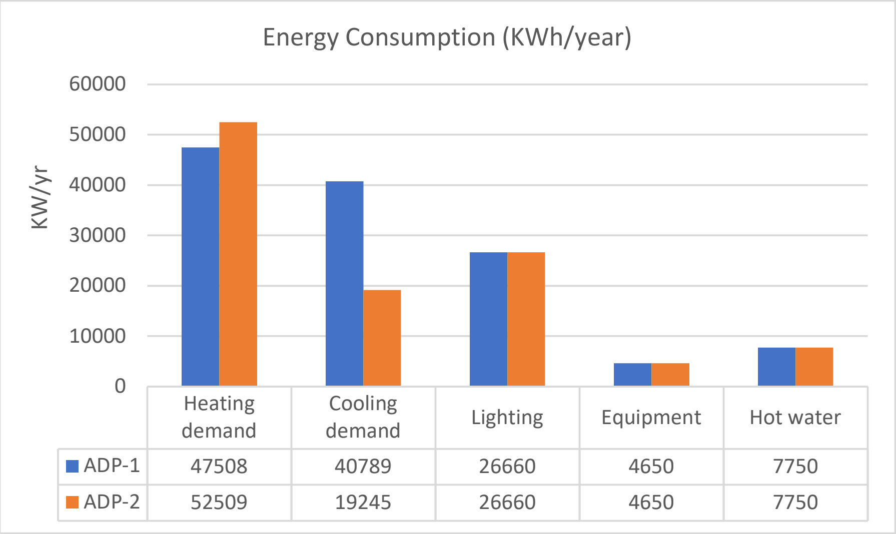


Figure 3-4:Energy Consumption of ADP-1 and ADP-2

The operational energy use (B6) between ADP-1 and ADP-2 was not significantly different, and both the scenarios needed energy for heating and cooling. Figure 3-4 represents the data input of energy consumption of ADP-1 and ADP-2. These data were used for the life cycle assessment of the studied project.

3.3.3. Data Input for materials and energy consumption

Materials' quantities, energy consumption, and service life are needed to perform a life cycle assessment. The input data of materials and energy consumption are shown in Appendix B-1. The data are based on the AutoCAD drawings (Appendix E) and traditionally calculated quantities of materials. The bill of material (BOM) calculation is presented in Appendix A-2, and the energy calculation is shown in Appendix D.

3.3.4. Environmental Product Declaration Data

The environmental impact assessments of defined scenarios were performed by using the OneClick LCA webtool. There is an option of the building typology: heritage monuments, cultural buildings, and industrial buildings in OneClick LCA. Heritage monument building option was used for this study. The data sources were based on the environmental product declaration (EPDs) provided in the assessment tool. This tool integrates data from nearly all the available EPD platforms around the world. (OneClick L.C.A., 2020) All E.U. databases are included in OneClick LCA. It is easy to evaluate environmental impacts. This tool does not need the exact project information to perform a simplified materials LCA. Also, it is handy to use for the project do not know the specific/exact building product. OneClick L.C.A. has country-specific average data. This study used average data from OneClick L.C.A. The used materials' EDP are shown in Appendix B-2.

3.4. Ethics in Research

The thesis was following the LCA standard to carry out the environmental assessment. Since it is a SINTEF project, the author follows the SINTEF's morals and ethics. The author gains knowledge about the topic and achieves a master's degree, while SINTEF achieves the outcome of the thesis as the organization's research. The SINTEF will include this thesis as part of their project in publication. An interview meeting with the owner of the project was conducted. The data of the developer will not be published without their acknowledgment.

4. Results

The environmental impact of the rehabilitation of the industrial heritage building design was investigated by comparing it with other scenarios. The results of all the scenarios are divided into four sections: -

1) Life cycle assessment results by life cycle modules
2) Life cycle assessment results by components' classification
3) Life cycle assessment results by resources
4) Total carbon footprints and total embodied carbon footprints

4.1. Life Cycle Assessment Results by Life Cycle Modules

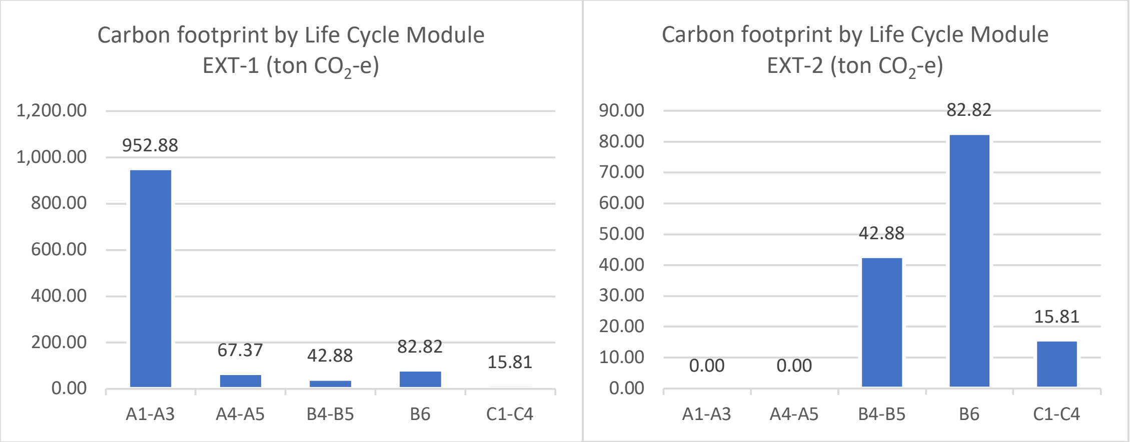
Table 4-1 shows the carbon footprint of each case by life cycle module. The results are extracted from OneClick LCA. The carbon footprint of each case will be presented separately. There are six Modules of the life cycle stage: Module A1-A3 (product), Module A4-A5 (construction), and Module B4-B5 (use and maintenance), Module B6 (operational energy use), Module C1-C4 (end of life), and Module D (after the service life).

Table 4-1:Life Cycle Assessment Results by Life Cycle Modules

Module	EXT-1	EXT-2	ADP-1	ADP-2	DEM-1	DEM-2	NEW-1	NEW-2
A1-A3	952.88	0.00	97.65	95.60	0	0	1,038.90	1,036.85
A4-A5	67.37	0.00	4.92	4.62	0	0	72.59	72.29
B4-B5	42.88	42.88	114.19	109.78	0	0	119.11	114.69
B6	82.82	82.82	395.66	344.27	0.83	0.83	395.66	344.27
C1-C4	15.81	15.81	15.19	15.03	15.81	15.81	20.14	19.98
D	-572.53	-572.53	-602.47	-602.15	0	-567.03	-602.47	-602.15
Total excl D	1161.75	141.51	627.60	569.28	16.63	16.63	1,646.40	1588.08
Total incl D	589.23	-431.02	25.14	-32.87	16.63	-550.39	1043.93	985.93

4.1.1. Before Rehabilitation

In this section, the LCA result within the system boundary will be presented. Figure 4-1(a) shows the results of EXT-1. The most significant impact is in Module A1-A3, 952.88 (ton CO₂e), and the lowest impact is 15.81 (ton CO₂e) in module C1-C4. There is a significant setback of Module D, -572.53 (ton CO₂e) (Table 4.1). This case is not considering carbon neutralization.

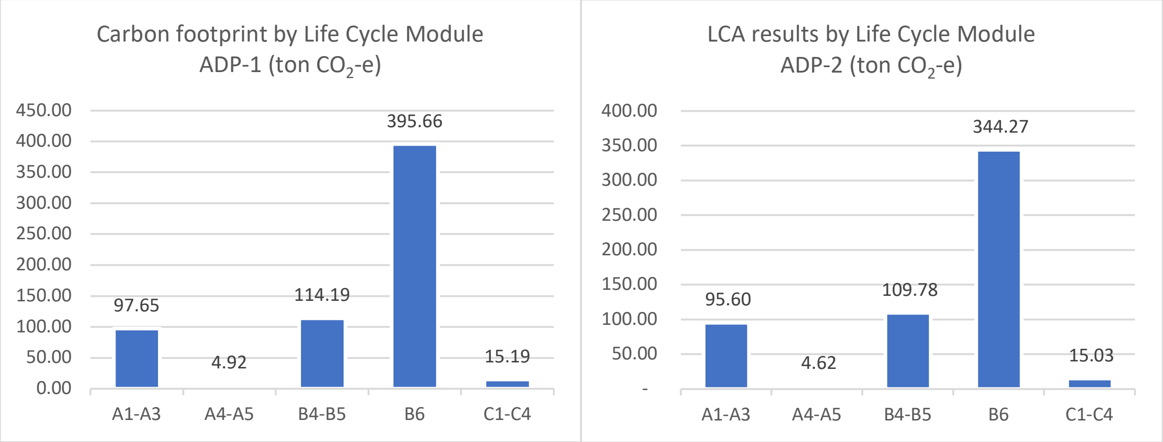


a) Case EXT-1 *(b)Case EXT-2*

Figure 4-1:LCA results by life cycle modules of Before rehabilitation Scenarios

The results of EXT-2, in which the carbon was offset, would be according to Figure 4-1(b). Module A1-A3 and A4-A5 are zero due to carbon setbacks of the entire building's materials. Module B6 has 82.82 (ton CO_2e). However. Module B4-B5, 42.88 (ton CO_2e), module C1-C4, 15.81 (ton CO_2e) and module D, -572.53 (ton CO_2e) are equivalent to EXT-1. The total results show the building has shallow impacts after carbon have been offset. Module B6, operational energy use, is the dominant impact after the carbon neutralization.

4.1.2. Adaptive reuse



a) Case ADP-1 *(b) Case ADP-2*

Figure 4-2:LCA results by life cycle modules of Adaptive Reuse Scenarios

The LCA results of adaptive reuse scenarios are shown in Figure 4-2, ADP-1 in Figure 4-2(a), and ADP-2 in Figure 4-2(b). In these cases, the operational energy uses, Module B6 is the highest impact with 395.66 (ton CO_2e) and 344.27 (ton CO_2e), respectively. The reason is that building materials are considered as zero-emission for the existing materials and total energy consumption after rehabilitation. However, there are significant impacts on the additional materials and energy demand. Both cases have reflected the additional materials and replacement components such as doors and windows in Module A1-A5 and energy demand in Module B6 compared to before the rehabilitation scenario. The results of Module A1-A3 are 97.65 (ton CO_2e) in ADP-1 and 95.60 (ton CO_2e) in ADP-2. All the results are slightly higher in ADP-1, which is considered achieving the U-Value criteria compared to ADP-2

4.1.3. Demolition

The demolition scenario is presented in Figure 4-4. Both DEM-1 and DEM-2 have the same impacts in modules C1-C4, 15.81 (ton CO2 e), and module B6, 0.83 (ton CO2e). However, the consideration of reusing the deconstructive materials, Module D -567.03 (ton CO2 e), is accounted only for DEM-2. Therefore, it is undeniable that the DEM-2 is more environmentally friendly than the DEM-1. These scenarios ignored the socio-cultural values and heritage values for studying how the demolition of the old building affects the environment.

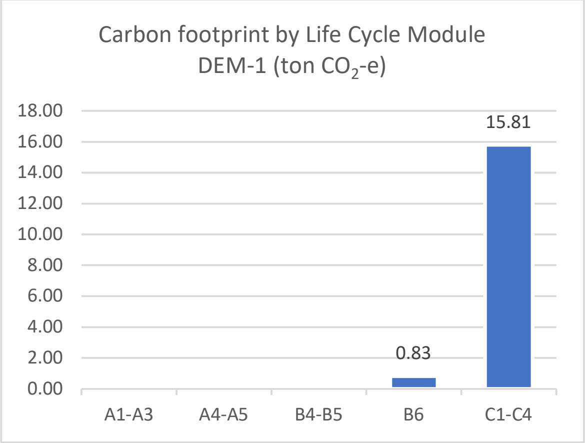
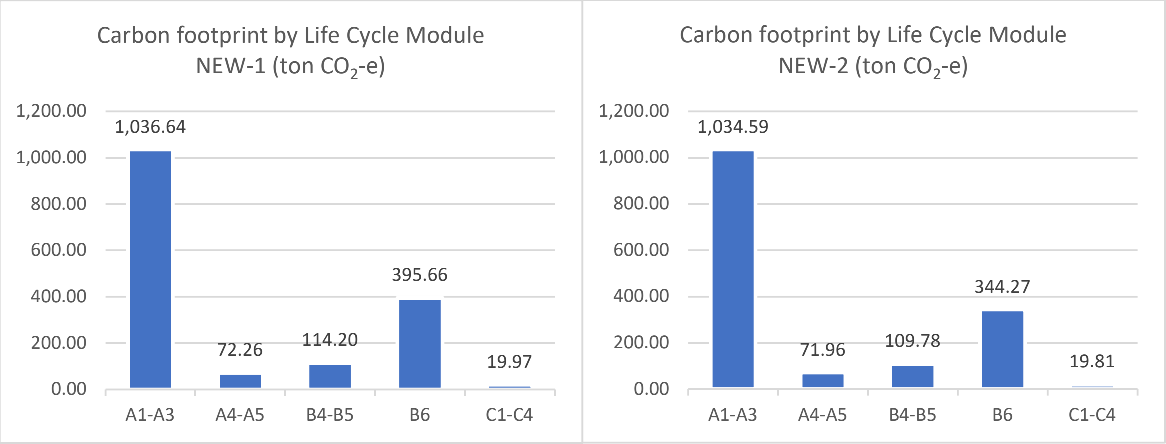


Figure 4-3:LCA results by life cycle modules of Demolition Scenarios

4.1.4. New Construction

The LCA results of new construction scenarios are represented in Figure 4-5(a) and Figure 4-5(b). The bill of materials for these cases is the combination of before rehabilitation and adaptive reuse scenarios. The results are similar to the adaptive reuse scenario, but complete life cycle stages are accounted for in both cases. Again, Module A1-A3 is the dominant contributor, 1038.90 (ton CO_2 e) in NEW-1 and 1036.85 (ton CO_2 e) in NEW-2.



a) Case NEW-1 *(b) Case NEW-2*

Figure 4-4:LCA results by life cycle modules of New Construction Scenarios

On the other hand, module B4-B5 results are 114.20 (ton CO_2e) and 109.78 (ton CO_2e). Module A4-A5 and C1-C4 are not differing much between the two scenarios. Module B6 and Module D are the same as the adaptive reuse scenarios. However, these scenarios are not practical to rebuild the existing building's same materials and construction techniques.

4.1.5. Comparison

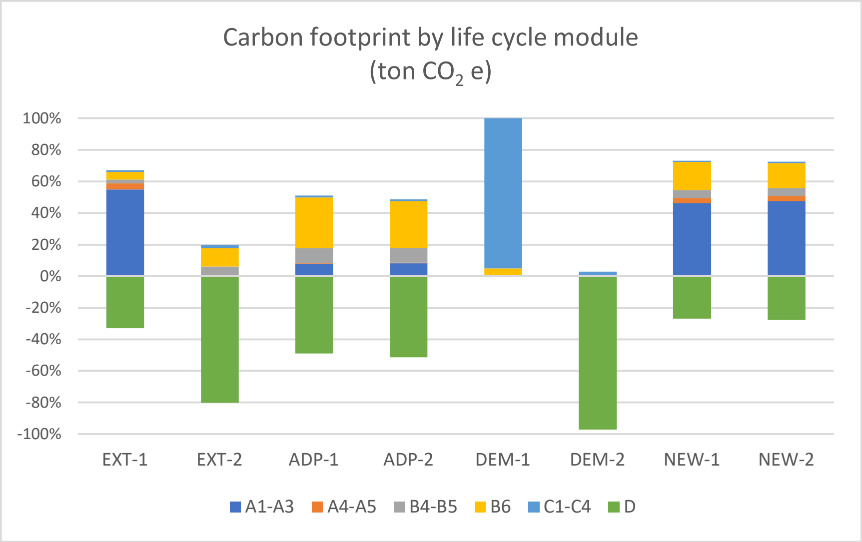


Figure 4-5:Comparison of LCA results by life cycle module

In this section, the LCA results of all the scenarios are compared. Figure 4-5 represents the comparison of LCA results by life cycle modules, and Figure 4-6 represents the total carbon footprint with and without module D. Based on the comparison, ADP-2 has the superlative among all the scenarios. Module D is the carbon deduction for reusing and recycling the deconstructive materials. It has significant impacts on the total carbon emissions after the service life. The carbon footprints, including Module D, are consistently less than excluding Module D. Although Module D is included, the carbon footprint of EXT-1, 589.23 (ton CO$_2$e), is much higher than EXT-2, -431.02 (ton CO$_2$e), which is considering the carbon have been offset.

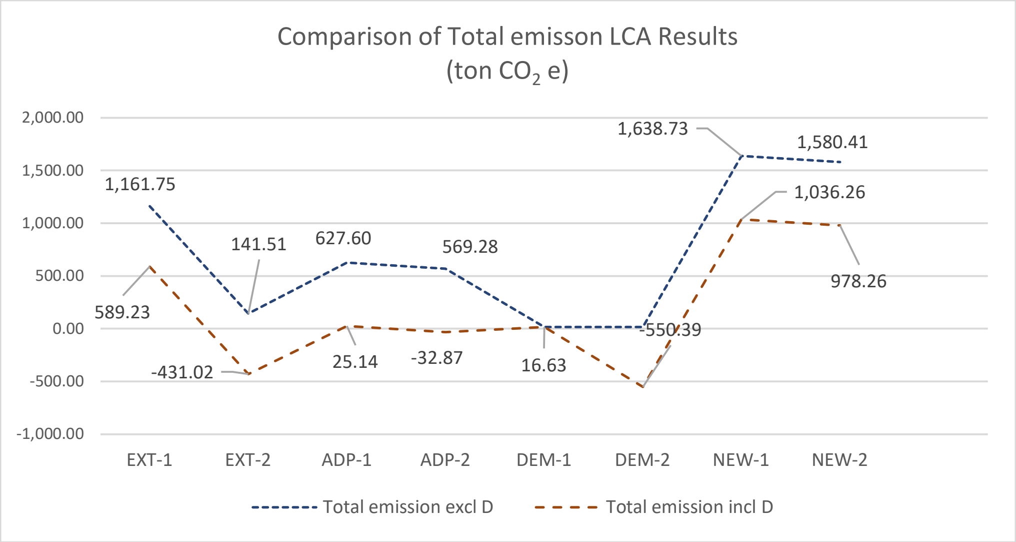


Figure 4-6:Comparison of Total LCA results

On the other hand, Module D was neglected in DEM-1. Therefore, the carbon footprint of DEM-1, 16.63 (ton CO_2e), is the same in both emissions. However, DEM-2 is lower than DEM-1 after including module D.

4.2. Life Cycle Assessment Results by Components' Classification

Here, the LCA results by the classification are explored. The classification of the building components is according to the NS3720-2018 (Method for greenhouse gas calculation for buildings). Figure 4-7 represents the LCA results of all the scenarios by classification. The classification of building parts which were included in this study are: -

1) 21- Foundation
2) 222- Columns
3) 223- Beams
4) 23- Outer walls
5) 234- Windows and door
6) 25- Floor
7) 26- Roof
8) 28- Stair and balcony
9) Electricity.

	EXT-1	EXT--2	ADP-1	ADP-2	DEM-1	DEM-2	NEW-1	NEW-2
🟩 Electricity	82.82	82.82	395.66	344.27	0.83	0.83	395.66	344.27
🟨 28-Stair and balcony	0.00	0.00	38.27	38.27	0.00	0.00	38.27	38.27
🟧 26- Roof	349.38	20.72	20.71	20.71	8.27	8.27	349.38	349.38
🟩 25- Floor	151.39	1.91	29.63	29.62	1.91	1.91	181.01	181.01
🟫 234- Window & Doors	45.66	31.75	50.63	50.63	1.31	1.31	50.63	50.63
🟫 23- Outer walls	176.44	2.88	91.27	84.35	2.88	2.88	267.71	260.79
🟩 223- Beams	268.13	1.02	1.02	1.02	1.02	1.02	268.13	268.13
🟨 222- Columns	60.24	0.07	0.07	0.07	0.07	0.07	60.24	60.24
🟧 21- Foundation	27.70	0.35	0.35	0.35	0.35	0.35	27.70	27.70

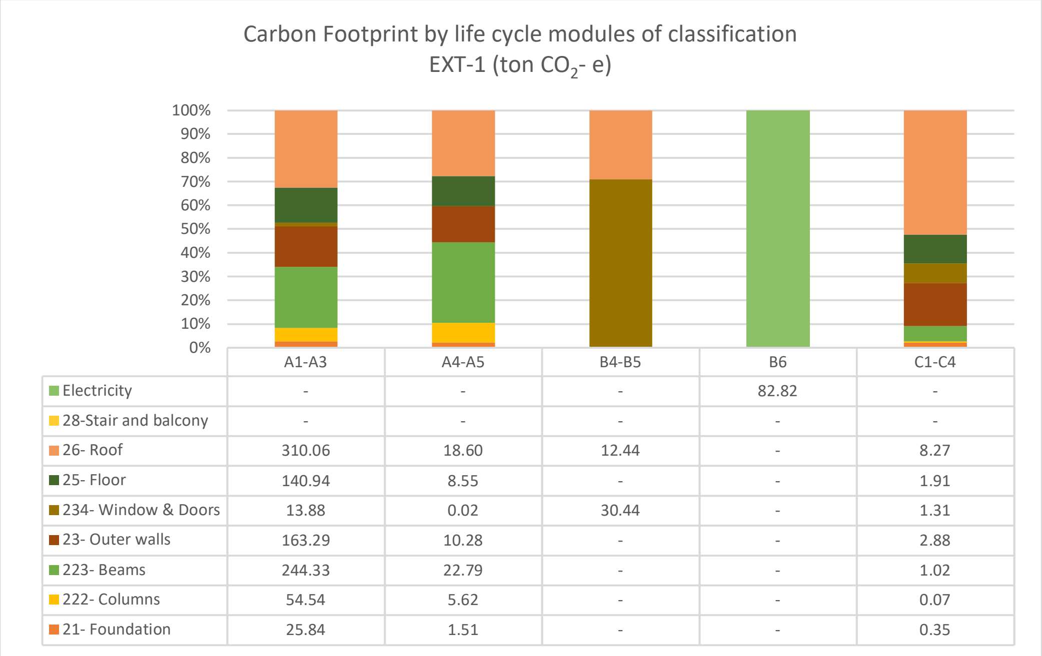
Figure 4-7:LCA results by components' classification

Based on the building components, the roof has the highest footprint in all cases. The material use of the roof was bitumen roofing, and it has a significant impact on carbon footprint. Then, the outer walls and floors have the second-highest impacts, apart from the beams. Beams in the PM5 building are over designed. Moreover, floor and outer walls were built with concrete or masonry. Therefore, the impacts of these building parts are significantly high in scenarios EXT-1, NEW-1, and NEW-2. However, these impacts have been reduced after the carbon is offset in scenarios EXT-2, ADP-1, ADP-2, DEM-1, and DEM-2. Module D was not considered in all classification because the LCA webtool does not classify the result of module D, and the users are not allowed to edit.

The columns and foundation are the most negligible impacts due to the under design in the 19th century. The foundation is shallow, and the cast-iron columns are to support the upper-level slab and ceiling slab. The superstructure is a combination of outer walls, columns, and beams. The columns and beams are supporting mainly the slabs. Beams are over-used with a 400mm span between beams across the building. However, the maximum carbon footprint among all the materials is 349.38 (ton CO_2e) of the roof in EXT-1, NEW-1, and NEW-2.

4.2.1. Before rehabilitation

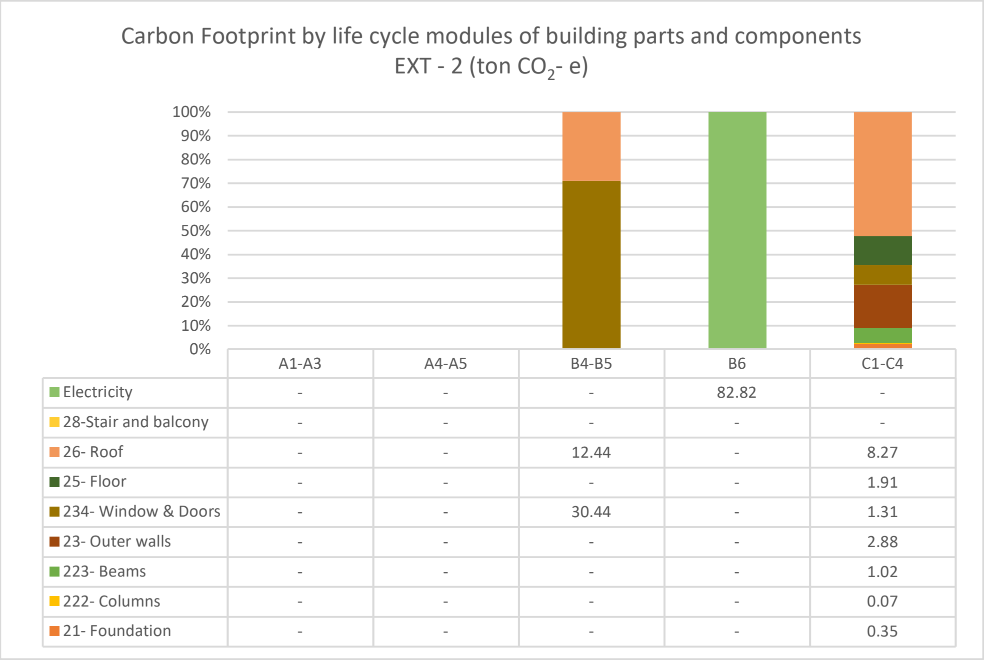
The results are presented in the Life Cycle Module of classification. For example, the carbon footprint of the foundation is displayed in modules A1-A3, A4- A5, and C1-C4, which are relevant to the building classification. However, the foundation is not applicable for module B4-B5 for replacement and module B6 for operational energy use.



	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	82.82	-
🟨 28-Stair and balcony	-	-	-	-	-
🟧 26- Roof	310.06	18.60	12.44	-	8.27
🟩 25- Floor	140.94	8.55	-	-	1.91
🟫 234- Window & Doors	13.88	0.02	30.44	-	1.31
🟫 23- Outer walls	163.29	10.28	-	-	2.88
🟩 223- Beams	244.33	22.79	-	-	1.02
🟨 222- Columns	54.54	5.62	-	-	0.07
🟧 21- Foundation	25.84	1.51	-	-	0.35

Figure 4-8:LCA results by components' classification (EXT-1)

Figure 4-8 shows the results of each building part and component of EXT-1. In this case, the foundation, columns, beams, and floors have not contributed to module B4-B5 because the structure components do not need to replace or refurbish. Outer walls are also built with concrete and masonry. Therefore, it is considered no repair or refurbishment is needed. The carbon footprint for B4-B5 is relevant only to the roof and windows & doors. Module C1-C4 included all the building parts and components.



	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	82.82	-
🟨 28-Stair and balcony	-	-	-	-	-
🟧 26- Roof	-	-	12.44	-	8.27
🟩 25- Floor	-	-	-	-	1.91
🟫 234- Window & Doors	-	-	30.44	-	1.31
🟫 23- Outer walls	-	-	-	-	2.88
🟩 223- Beams	-	-	-	-	1.02
🟨 222- Columns	-	-	-	-	0.07
🟧 21- Foundation	-	-	-	-	0.35

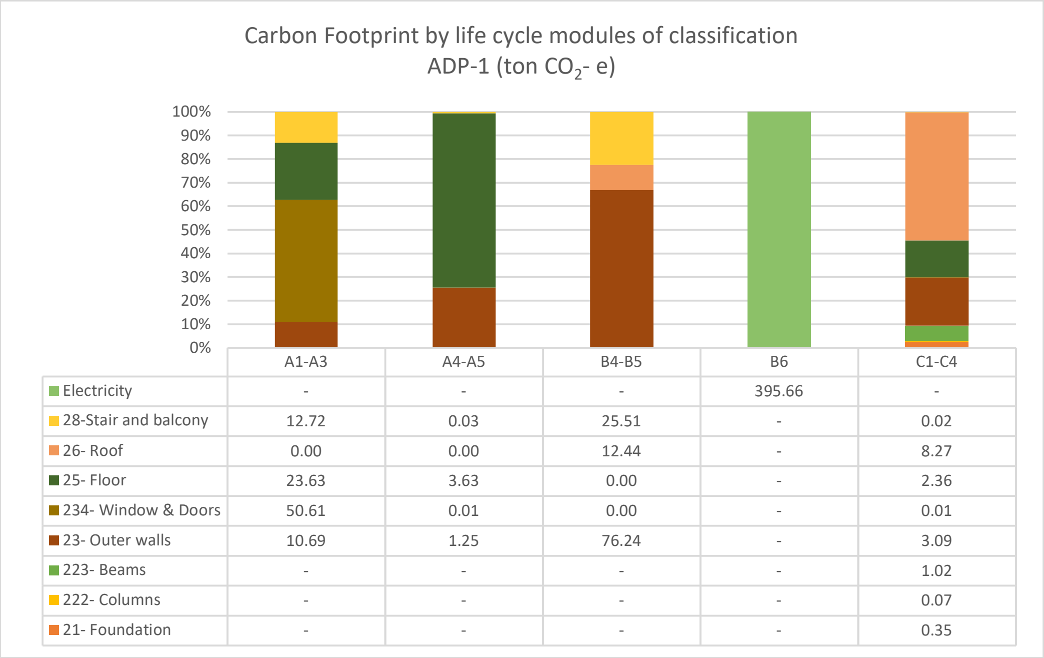
Figure 4-9:LCA results by components' classification (EXT-2)

Figure 4-9 represents the results of EXT-2's carbon footprint by classification. In this case, A1-A5 is zero-emission, and module B4-B5 includes only the roof, and windows & doors. However, module C1-C4 includes all the building parts and components. Thus, the overall result of this case is considerably low.

4.2.2. Adaptive reuse

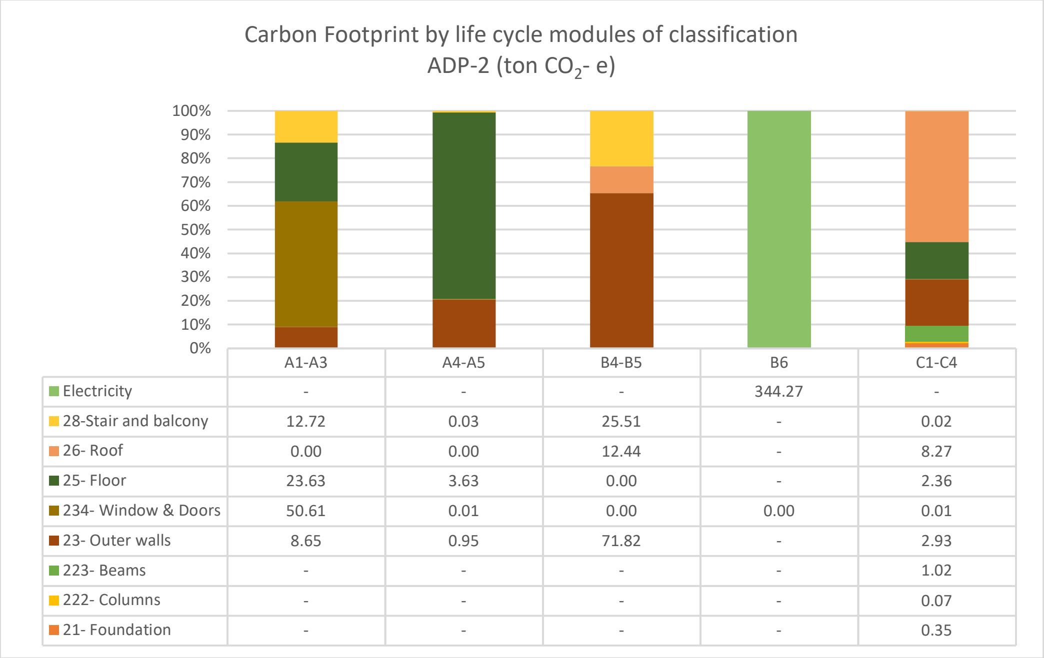
The LCA results by classification of adaptive reuse scenarios are presented in this section. Figure 4-10 and Figure 4-11 demonstrate the result of ADP-1 and ADP-2, respectively. Since these cases are the adaptive reuse scenario for the energy performance of the building, there are additional materials and components to achieve the requirement of NS-EN 3031. In both scenarios, additional materials for the outer wall and slabs are added. In addition, the windows and doors are replaced. The existing materials are zero-emission. Therefore, the assessments have applied only the additional materials and components in these scenarios.

Then, windows and doors have a significant impact because the wooden frames are replaced with aluminum frames. The windows and doors result in 50.61 (ton CO_2e) for module A1-A3 in both cases and this is the major impacts of the adaptive reuse scenarios. Moreover, the floor cover or screeding is added to all the slabs. Therefore, the slabs' result of ADP-1 is 23.63 (ton CO_2e) module A1-A3. Furthermore, the outer walls have been upgraded with indoor insulation and gypsum boards in ADP-1 and the carbon footprint of outer walls becomes 10.69 (ton CO_2e) for module A1-A3 in ADP-1. On the other hand, ADP-2 was not upgraded the outer wall but, the exterior finishes works have been done and the result of outer walls is 8.65 (ton CO_2e) in A1-A3. Module B4-B5 are combined the existing module B4-B5 of EXT-1 and B4-B5 of additional materials/ components. Thus, the results become significant, especially for outer walls, 76.24 (ton CO_2e) in ADP-1 and 71.82 (ton CO_2e) in ADP-2. In addition, an elevator was installed to access the upper floor, and the carbon footprints are 12.72 (ton CO_2e) in modules A1-A3 and 25.51 (ton CO_2e) in modules B4-B5.



	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	395.66	-
🟨 28-Stair and balcony	12.72	0.03	25.51	-	0.02
🟧 26- Roof	0.00	0.00	12.44	-	8.27
🟩 25- Floor	23.63	3.63	0.00	-	2.36
🟫 234- Window & Doors	50.61	0.01	0.00	-	0.01
🟫 23- Outer walls	10.69	1.25	76.24	-	3.09
🟩 223- Beams	-	-	-	-	1.02
🟨 222- Columns	-	-	-	-	0.07
🟧 21- Foundation	-	-	-	-	0.35

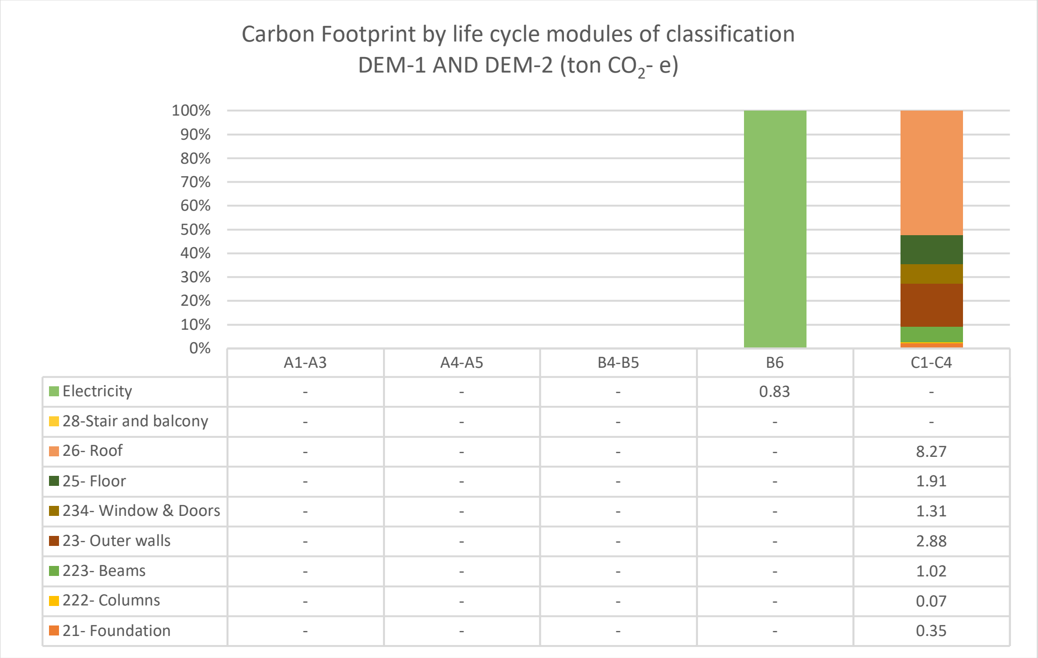
Figure 4-10:LCA results by components' classification (ADP-1)



	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	344.27	-
🟨 28-Stair and balcony	12.72	0.03	25.51	-	0.02
🟧 26- Roof	0.00	0.00	12.44	-	8.27
🟩 25- Floor	23.63	3.63	0.00	-	2.36
🟫 234- Window & Doors	50.61	0.01	0.00	0.00	0.01
🟫 23- Outer walls	8.65	0.95	71.82	-	2.93
🟩 223- Beams	-	-	-	-	1.02
🟨 222- Columns	-	-	-	-	0.07
🟧 21- Foundation	-	-	-	-	0.35

Figure 4-11:LCA results by components' classification (ADP-2)

4.2.3. Demolition



	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	0.83	-
🟨 28-Stair and balcony	-	-	-	-	-
🟧 26- Roof	-	-	-	-	8.27
🟩 25- Floor	-	-	-	-	1.91
🟫 234- Window & Doors	-	-	-	-	1.31
🟫 23- Outer walls	-	-	-	-	2.88
🟩 223- Beams	-	-	-	-	1.02
🟨 222- Columns	-	-	-	-	0.07
🟧 21- Foundation	-	-	-	-	0.35

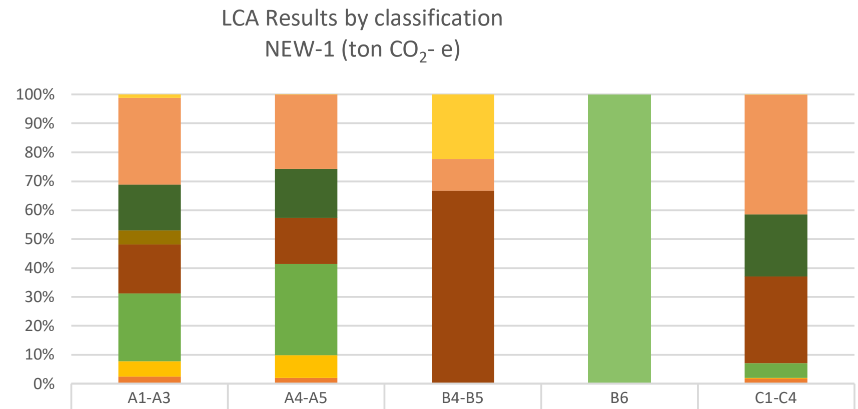
Figure 4-12:LCA results by components' classification (DEM- 1 & DEM-2)

LCA results of the demolition scenarios are represented here. Figure 4-12 shows the carbon footprint by classification for DEM-1 and DEM-2 and the results of both cases are the same. These scenarios consider that the existing materials become zero emissions. Therefore, apart from module C1-C4, all the other modules are zero. Module C1-C4 of the roof is 8.27 (ton CO_2e) for both cases and it is the highest impact in these scenarios. However, these scenarios did not consider the heritage values.

4.2.4. New Construction

The new construction scenarios are demonstrated in this section. Figure 4-13 shows the results of NEW-1, and Figure 4-14 shows NEW-2. These cases are the combination of the bill of materials (BOM) of the before rehabilitation scenario (EXT) and adaptive reuse scenario (ADP). Therefore, the results are included all the materials and modules.

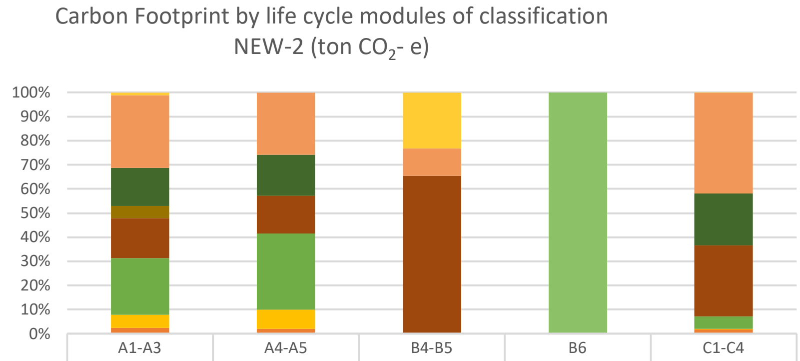
In the new construction scenario, the floors, roof, and outer walls are the main contributor of carbon emission due to the over-design of the building. For example, the outer walls are over-size unnecessarily. Moreover, the beams are also overused. Therefore, apart from the roof, floors, beams, and outer walls significantly impact the carbon footprint of the building materials, module A1-A3; 164.57 (ton CO_2e) for the floor, 173.98 (ton CO_2e) for the outer walls, and 244.33 (ton CO_2e) for the beams. Outer walls have the most impacts in module B4-B5 with 76.24 (ton CO_2e) and module C1-C4 with 5.97. However, the overall highest is for the roof. This could be due to the roof construction, which is the combination of bricklayer and insulation.


LCA Results by classification
NEW-1 (ton CO_2- e)

	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	395.66	-
🟨 28-Stair and balcony	12.72	0.03	25.51	-	0.02
🟧 26- Roof	310.06	18.60	12.44	-	8.27
🟩 25- Floor	164.57	12.18	0.00	-	4.27
🟫 234- Window & Doors	50.61	0.01	0.00	-	0.01
🟫 23- Outer walls	173.98	11.53	76.24	-	5.97
🟩 223- Beams	244.33	22.79	0.00	-	1.02
🟨 222- Columns	54.54	5.62	0.00	-	0.07
🟧 21- Foundation	25.84	1.51	0.00	-	0.35

Figure 4-13:LCA results by components' classification (NEW-1)

NEW-2 results are the same as the NEW-1 other than outer walls due to the insulation and gypsum board. The results for outer walls are 171.93 (ton CO_2e) in module A1-A3 which is slightly less than NEW-1 scenarios. However, Module B6 is identical to the ADP-2.


Carbon Footprint by life cycle modules of classification
NEW-2 (ton CO_2- e)

	A1-A3	A4-A5	B4-B5	B6	C1-C4
🟩 Electricity	-	-	-	344.27	-
🟨 28-Stair and balcony	12.72	0.03	25.51	-	0.02
🟧 26- Roof	310.06	18.60	12.44	-	8.27
🟩 25- Floor	164.57	12.18	0.00	-	4.27
🟫 234- Window & Doors	50.61	0.01	0.00	-	0.01
🟫 23- Outer walls	171.93	11.23	71.82	-	5.81
🟩 223- Beams	244.33	22.79	0.00	-	1.02
🟨 222- Columns	54.54	5.62	0.00	-	0.07
🟧 21- Foundation	25.84	1.51	0.00	-	0.35

Figure 4-14:Carbon footprint by life cycle modules of classification (NEW-2)

4.3. Life Cycle Assessment Results by Resource Types

The carbon footprint of resources is vital to study. Table 4-2 shows the results by resource types. Before rehabilitation scenarios and demolition scenarios are the same materials and quantities.

Table 4-2:LCA Results by resource types

Materials	EXT-1 /EXT-2	DEM-1 /DEM-2	ADP-1	ADP-2	NEW-1	NEW-2
Cement	707.10	707.10	707.10	707.10	707.10	707.10
Brick	29.28	29.28	29.28	29.28	29.28	29.28
Steel / metal	267.62	267.62	267.62	267.62	267.62	267.62
Particleboard	5.77	5.77	5.77	5.77	5.77	5.77
Bitumen	15.87	15.87	15.87	15.87	15.87	15.87
Insulation	1.45	1.45	2.30	1.45	2.30	1.45
Door/ window	45.66	45.66	50.63	50.63	50.63	50.63
Soil & gravel	6.19	6.19	6.19	6.19	6.19	6.19
Screed and plaster	-	-	41.41	41.41	41.41	41.41
Paint	-	-	80.60	80.60	80.60	80.60
elevator	-	-	38.27	38.27	38.27	38.27

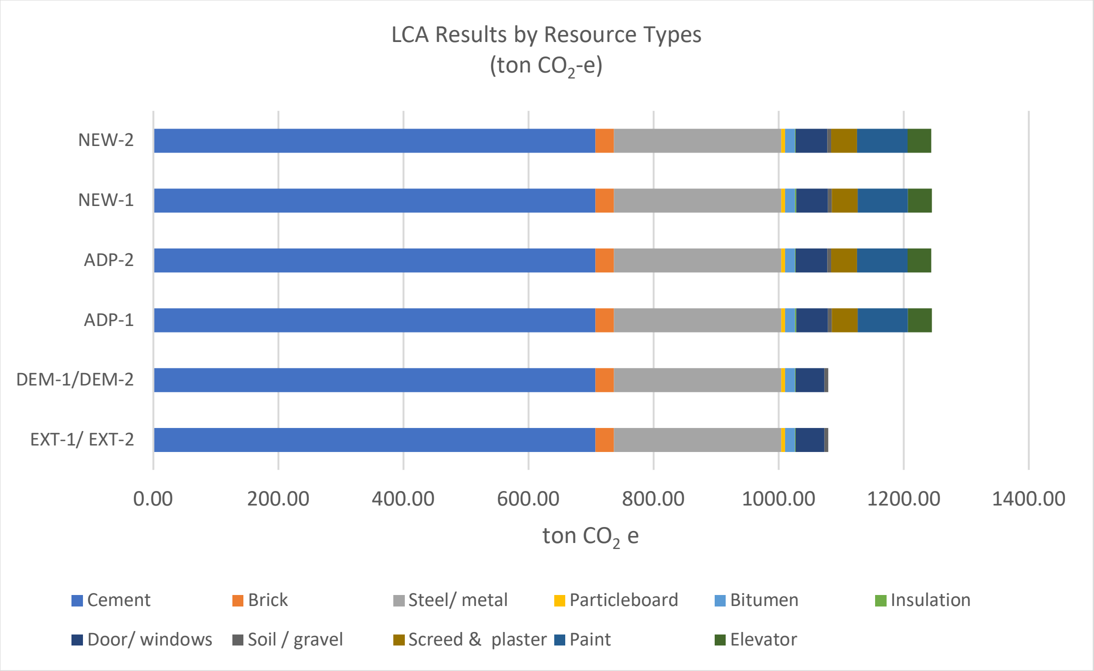
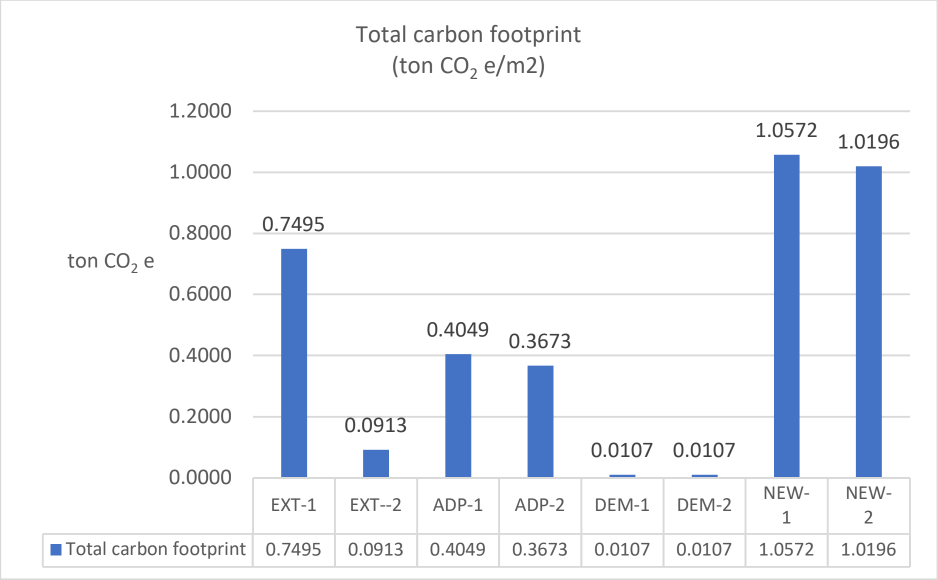


Figure 4-15:Life Cycle Assessment Results by resource types

Carbon footprint by resource types is shown in Figure 4-15. The dominant material type is cement ,707.10 (ton CO_2e). Then cast iron is the second-highest carbon emission with 267.62 (ton CO_2e). The carbon footprints of doors and windows are 45.66 (ton CO2e) before the rehabilitation scenario and demolition scenario and 50.63 (ton CO2e) in adaptive reuse and new construction scenarios. The emission of insulation is 1.45 (ton CO_2e) before rehabilitation scenarios, ADP-2, and NEW-2. However, due to the additional insulation for outer walls, the insulation has the impact, 2.30 (ton CO_2e) in the ADP-1 and NEW-1.

4.4. Total Life Cycle Assessment Results

4.4.1. Total Carbon Footprints



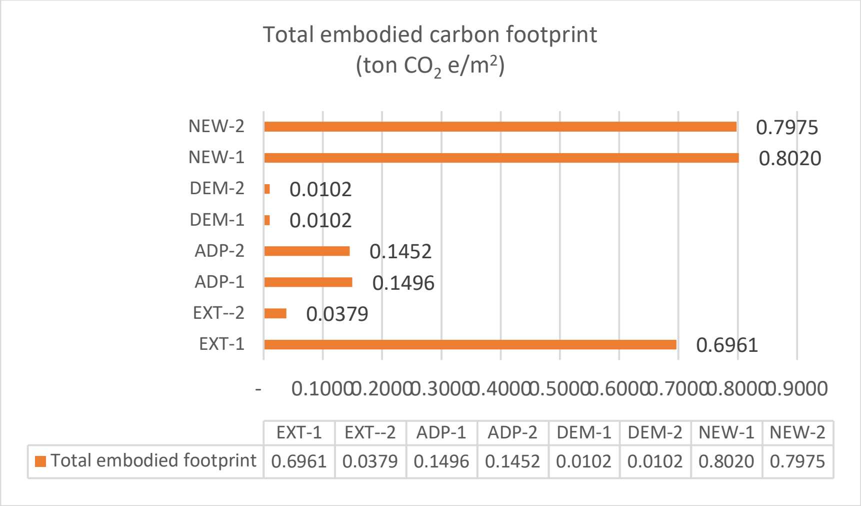
	EXT-1	EXT--2	ADP-1	ADP-2	DEM-1	DEM-2	NEW-1	NEW-2
■ Total carbon footprint	0.7495	0.0913	0.4049	0.3673	0.0107	0.0107	1.0572	1.0196

Figure 4-16:Total Carbon Footprint (ton CO2e/m2)

The total carbon footprint is compared in Figure 4-16. Adaptive reuse scenarios are significantly higher than EXT-2 with 0.4049 (ton CO_2e/m^2) in ADP-1 and 0.3673 (ton CO_2e/m^2) in ADP-2. The emission of EXT-2 is significantly low, 0.0913 (ton CO_2e/m^2) because it considered carbon was offset. EXT-1 has 0.7495 (ton CO_2e/m^2), and it did not consider carbon neutralization, and it is higher than the adaptive reuse scenarios. Due to considering the neutralization, the demolition scenarios' carbon footprints are considerably lower than others, with 0.0107 (ton CO_2e/m^2) in both DEM-1 and DEM-2. However, the DEM-1's impact is higher than DEM-2's because DEM is not reusing or recycling the deconstructive materials. The new construction scenarios have 1.0622 (ton CO_2e/m^2) in NEW-1 and 1.0246 (ton CO_2e/m^2) in NEW-2. These scenarios have the highest emissions. However, this comparison is within the system boundary. If module D is accounted into the calculation, the results wall be same as Section 4.1.5.

4.4.2. Total Embodied Carbon Footprint

Figure 4-17 shows the total embodied carbon footprint of the studied cases. The results are similar to the total carbon footprint. The before rehabilitation scenarios, EXT-1 and EXT-2 have the emission, 0.6961 (ton CO_2e/m^2) and 0.0379 (ton CO_2e/m^2), respectively. The adaptive reuse scenarios, 0.1496 (ton CO_2e/m^2) in ADP-1 and 0.1452 (ton CO_2e/m^2) in ADP-2. Both DEM-1 and DEM-2 have 0.0102 (ton CO_2e/m^2). The new construction embodied footprints are significantly high as 0.8069 (ton CO_2e/m^2) in NEW-1 and 0.8025 (ton CO_2e/m^2) in NEW-2.



	EXT-1	EXT--2	ADP-1	ADP-2	DEM-1	DEM-2	NEW-1	NEW-2
■ Total embodied footprint	0.6961	0.0379	0.1496	0.1452	0.0102	0.0102	0.8020	0.7975

Figure 4-17:Total Embodied Carbon Footprint

However, the difference between the scenarios which considered improving the energy efficiency of the building (ADP-1) and the scenarios that used the existing energy efficiency of the building (ADP-2) are different in total carbon emission. The embodied footprint of ADP-1 is higher than ADP-2 due to the extra materials. Moreover, the operational energy use of ADP-1 is higher than ADP-2.

4.4.3. Comparison of embodied emission and operational emission

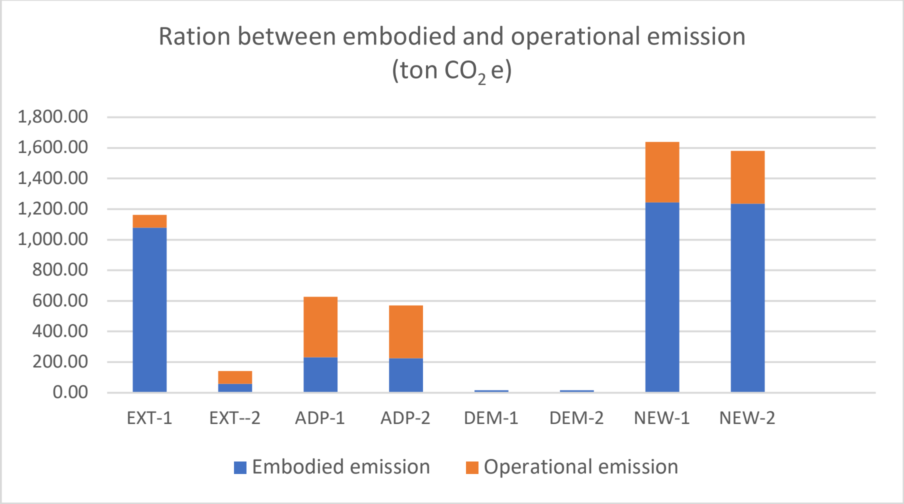


Figure 4-18:Ratio between embodied and operational emission

The embodied emission and operational emission are compared in Figure 4-18. The operation energy use B6 is higher in all adaptive reuse scenarios as the building was re-operated and more energy was used. However, embodied emission of adaptive reuse is about 40% of the total emission due to zero-carbon emission for the existing building. On the other hand, in new construction scenarios, the embodied emission is almost 80% of the total emission; therefore, although the same energy demand for both, the embodied emission of the adaptive reuse scenarios is more efficient than the new construction scenarios.

5. Discussion

Environmental impacts of the heritage building are indecisive matters for the building stock. For example, industrial buildings were built with concrete masonry in every part of the world during the Industrial Revolution. These industrial buildings are part of human history and revolution. Some of the buildings built in the early 19th century have been titled ***industrial heritage buildings*** by UNESCO (United Nations Educational, Scientific and Cultural Organization). Thus, these buildings are essential to reserve and reuse if possible. In this thesis, an industrial heritage building was investigated by comparing four different scenarios with eight sub-scenarios.

The **EXT-2's** emissions are considerably low due to emission zero of existing materials and low operational energy use. If the building is not rehabilitated, the materials and components will deteriorate slowly. However, this case is better than the demolition scenario as the socio-cultural value and heritage values are preserved.

Adaptive reuse scenario is comparatively high in emission due to the additional materials and operation energy use. The building is reused as a public area and enhances the social activities of the neighborhood. The cultural value and heritage value are also preserved. The two adaptive reuse scenarios, **ADP-1** and **ADP-2,** are slightly different due to the materials used. **ADP-2** has a lower environmental impact than ADP-1 and the most suitable scenario for rehabilitation. This scenario is reused as a public building by preserving the heritage and socio-cultural value. On the other hand, the rehabilitation of this building included heating and cooling demand as well as other electrical use. Moreover, it is practical to use the outer wall without upgrading as the PM5 building built with a large amount of concrete and brick, which can act as heat storage. It will warm the building in the night and cold during the day,

Although the energy efficiency of the building could not be achieved TEK 17 or Passive House criteria, the building has the appropriate energy efficiency, which can be waived from these criteria. Therefore, ADP-1 is considered to achieve the U-value criteria. This scenario reduces the heating demand but increases the cooling demand in the summertime. Therefore, the result of the energy demand is higher than the ADP-2, which is not improved the outer wall's thermal transmittance (U-value). It proved that the cooling and heating time and energy use need to be balanced in the heritage building. The less energy use in winter, the more energy use in summer. However, it depends on the climate and location of the building.

Demolition scenarios, **DEM-1 and DEM-2,** are unfavorable because the building was torn down without considering heritage and socio-cultural values. Although the building materials were neutralized and become zero-emission, the emission of demolition was significant. Then, the biogenic carbon storage will be emitted into the environment. Moreover, the building stock is affected due to the demolition. However, if the deconstructive materials are planned to reuse or recycle, the emissions of the **DEM-2** are low and set back from zero. Therefore the direct reuse of materials is critical for further research. The deconstructive materials should also avoid the process of recycling; this process impacts the environment. If the building must be demolished for a particular reason, the used materials must be reused as much as possible to minimize the carbon footprint of the material.

The new construction scenario, **NEW-1, and NEW-2** are also not favorable as the quantities of the material are not necessarily overused. The new building materials can be reduced by changing the building structure. For example, the beams and slabs can be built with reinforced concrete. Then, the outer walls' thickness will be reduced, and eventually, the materials' quantities are also reduced. Therefore, the builders will never rebuild the same building. If the new building must be rebuilt in the same place, the environmental impacts will be reduced for reuse materials. However, it will still be higher than the adaptive reuse scenario. In this study, the main finding is that heritage buildings must be rehabilitated with a new purpose, and the rehabilitation scenarios should be studied with different energy scenarios. The heritage building rehabilitation should neglect the energy criteria if the interior temperature is comfortable enough. The heritage building has been set back the carbon emission, and it is deserved to waive these criteria or standard.

5.1. Carbon Emission Profile of ADP-2

Selecting the most favorable scenario

Among all the cases, ADP-2 is the most incredible option for the rehabilitation of the PM5 building. This scenario gains both the social and environmental aspects. The environmental impacts of this option are lower than the other adaptive case ADP-2. Although the building is heated in ADP-2 scenarios and the new restaurant or other areas should be designed accordingly.

Carbon Emission Profile

Table 5-1:Total emission and embodied emission every ten years

Year	Service Life	Total Emission	Total Emission	Embodied emission	Embodied emission
		Ton CO_2 e/m^2	Ton CO_2 e/m^2-yr	Ton CO_2 e/m^2	Ton CO_2 e/m^2-yr
2020	0	0.0744	-	0.0744	-
2030	10	0.0966	0.0097	0.0744	0.0074
2040	20	0.1239	0.0062	0.0795	0.0040
2050	30	0.1513	0.0050	0.0847	0.0028
2060	40	0.1786	0.0045	0.0898	0.0022
2070	50	0.2142	0.0043	0.1032	0.0021
2080	60	0.2416	0.0040	0.1083	0.0018
2090	70	0.2690	0.0038	0.1135	0.0016
2100	80	0.2963	0.0037	0.1186	0.0015
2110	90	0.3319	0.0037	0.1320	0.0015
2120	100	0.3593	0.0036	0.1372	0.0014

🟩 Achieve the 60% of carbon deduction

Moreover, rather than installing the elevator to access the upper floor, using the standard staircase is more appropriate with heritage buildings and values and will reduce emissions. Furthermore, ADP-2 is the actual rehabilitation scenario. Therefore, to prove the ADP-2 is a favorable scenario, further study is carried out as below.

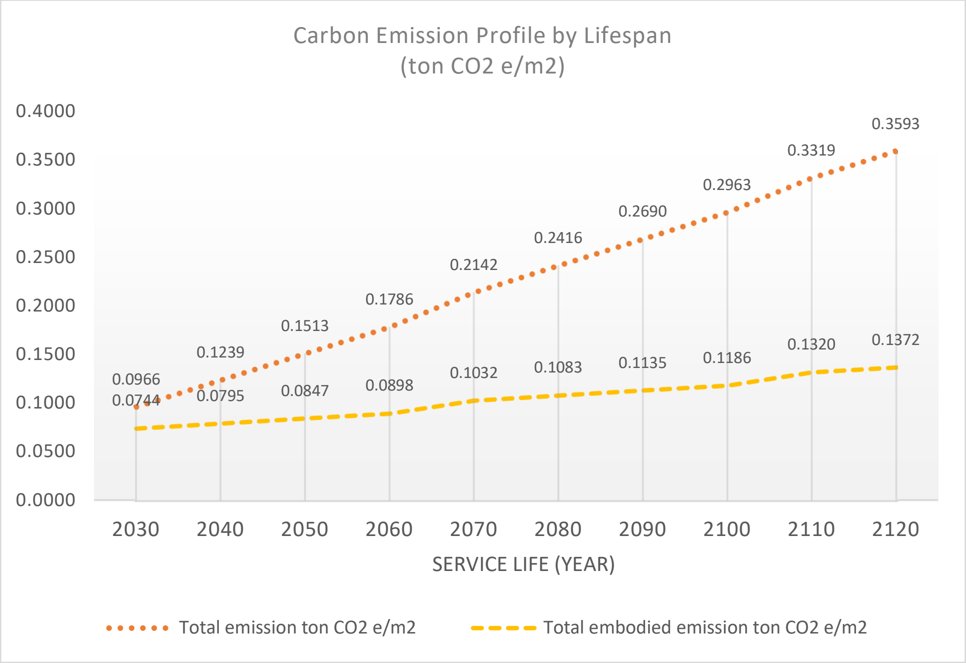


Figure 5-1:Carbon emission profile (ton-CO2e/m2)

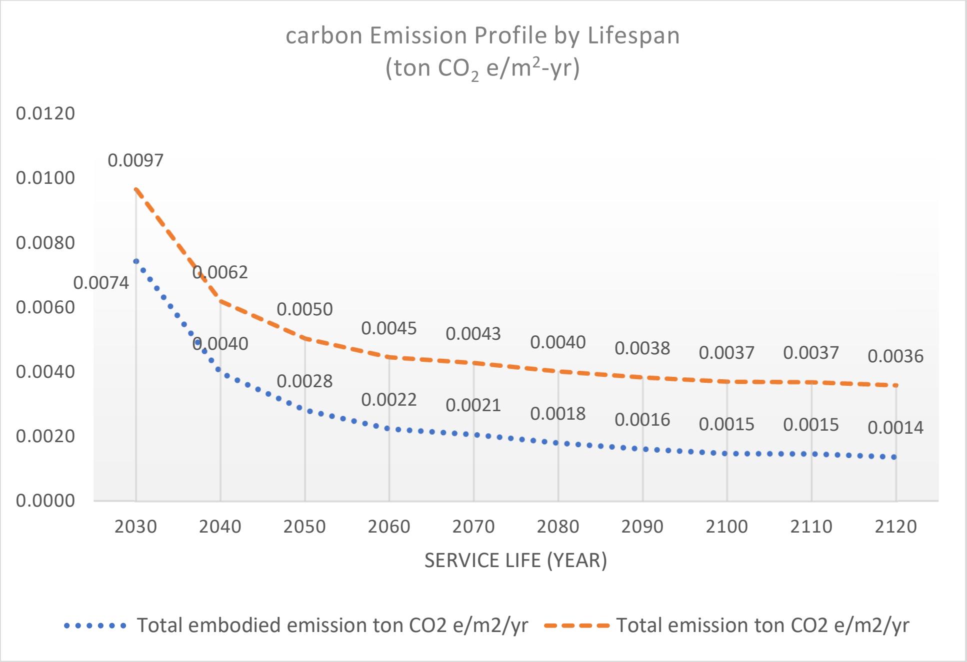


Figure 5-2:Carbon emission profile (ton-CO2e/m2 - yr)

The adaptation case ADP-2 was studied with different lifespans. Presume that the building was renovated in 2020. Then, an investigation for the carbon deduction during the lifespan with ten years interval of the building life span. Table 5-1 shows the LCA result of ADP-2 in two different units; ton CO_2 e/m^2 and tone CO_2e/m^2-year. The emission profile in ton-CO_2 e/m^2 is shown in Figure 5-1. The emission results in ton-CO_2 e/m^2 escalated, and the total emission has the higher impact as the operational energy use, module B6, is accumulating. However, the embodied emissions are gradually increasing due to replacing some building components. Therefore, both the total emission results will be higher in the longer lifespan. On the other hand, there is another carbon emission profile in ton-CO_2 e/m^2-yr, Figure 5-2. This profile includes the gross area of the building and the service life in the calculation. Then the profile reverses the other way. The emission was down quite deep between 2030 and 2050 and then slowly decreased along with the rest of the service life. The carbon will be neutralized when the profile hits zero.

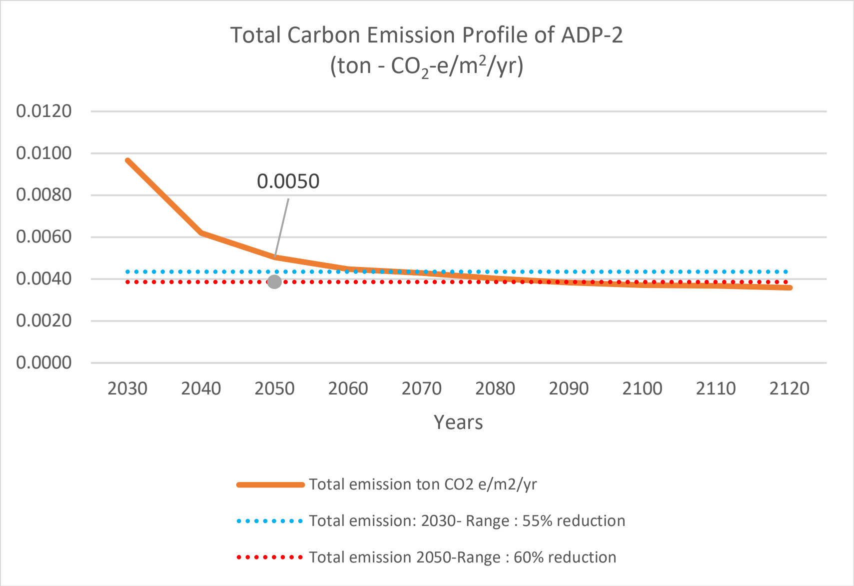


Figure 5-3:Total carbon emission profile of ADP-2 with reduction lines

Furthermore, according to the green deal agreement of the European Union, the European Commission aims to reduce carbon emission by 55% in 2030 and 60% in 2050. According to the carbon emission profile of ADP-2, it will not achieve the target for 2030 (55% reduction) in both emission profiles (total carbon emission and total embodied emission). However, the total embodied emission of 2050 is 0.0028 (ton-CO_2 e/m^2-yr), lower than the 60% reduction target, 0.0030 (ton-CO_2 e/m^2-yr). The embodied emission of the ADP-2 will achieve the green deal target in 2050, but the total emission can not be achieved. Therefore, the building energy use must be reduced further in order to gain better results in environmental aspects. The carbon reduction target points are presented in Figure 5-3 and Figure 5-4.

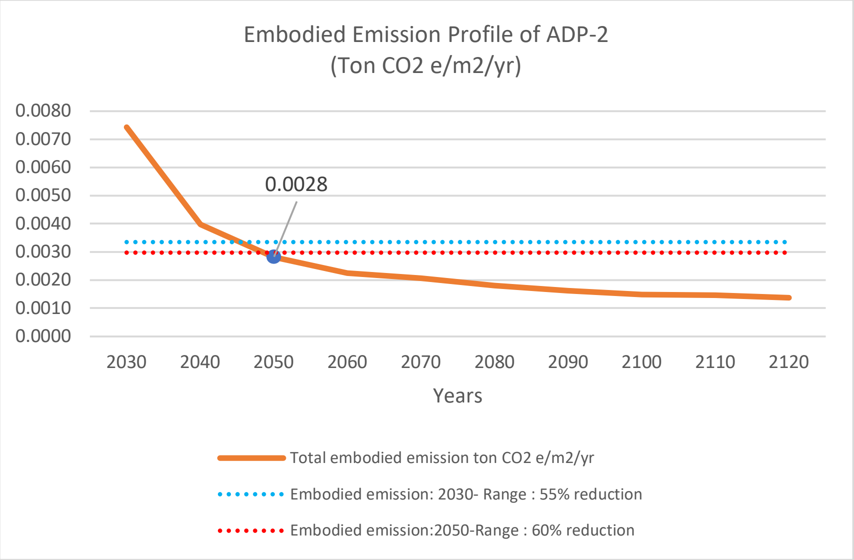
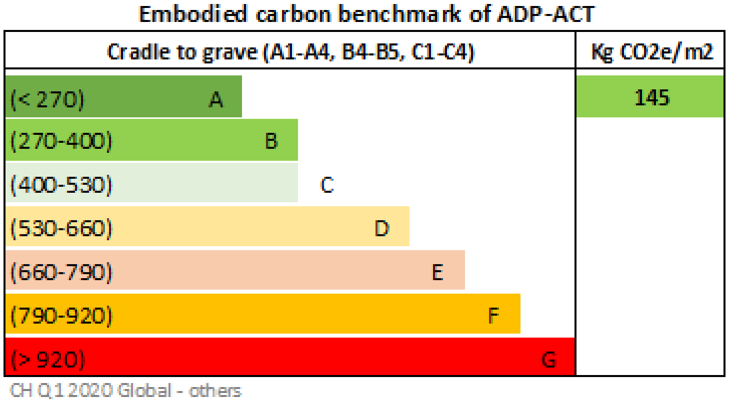


Figure 5-4:Embodied carbon emission profile of ADP-2 with reduction lines

Finally, this scenario preserves the cultural heritage value and brings back the socio-cultural value by creating a public infrastructure. Due to the building is not refurbished a lot and not considering the minimal building energy performance, the environmental impacts of the building were minimized. The embodied emission of the building (cradle to grave) is 145 kgCO2-e/m2, and it has achieved class A, according to CH Q1 2020 Global- other buildings (Figure 5-5). However, the figure is only based on the additional materials and components. The emission after the service life must be studied and explore the unfond environmental impacts of the building.


Embodied carbon benchmark of ADP-ACT

Cradle to grave (A1-A4, B4-B5, C1-C4)		Kg CO2e/m2
(< 270)	A	145
(270-400)	B	
(400-530)	C	
(530-660)	D	
(660-790)	E	
(790-920)	F	
(> 920)	G	

CH Q1 2020 Global - others

Figure 5-5:Embodied carbon benchmark of ADP-2

Nonetheless, the **indoor environment** must be considered wisely. The building can be heated only in the area needed to improve the indoor temperature and better environmental impacts than the complete heated scenario. The operational energy use B6 is the main contributor to the impacts after the carbon neutralization. Therefore, the energy performance of the building is critical. Other heritage buildings that do not need to preserve the inner wall's surface should consider the energy performance and indoor environment more precisely.

Moreover, the existing **columns' strengths** are not considered in this study. Therefore, recommend investigating the integrity of columns and beams. For example, although the outer walls are strong, the upper floor slab can be collapsed due to the age of the cast-iron columns. Therefore, **the structural assessment** of the building must be performed.

In addition, the **energy used for the demolition**, such as machinery, is not transparent in this study. According to OneClick LCA, Module D included installed materials benefit but did not include the used and exported energy. Demolition is not an option for a heritage building. If a regular old building must be demolished and construct a new one, the new building will be more energy-efficient and have fewer materials. However, the connection between the old building's demolition and new construction should be studied insight. Did the existing building neutralize or any spontaneous emission from demolition and destructive materials? The biogenic carbon storage will save some impacts by reusing the materials in another project. However, further research should be performed on the environmental impact of the demolition scenario.

Then, the **EPDs (Environmental Product Declaration)** of the old existing materials are according to the data available in OneClick LCA. These EPDs are not reflected precisely to the old and outdated materials. Therefore, the documentation, testing, and EPD verification of the existing materials must be researched further. The EPD verification of the old materials is critical due to the existing building stocks are increasing. Moreover, this verification is also needed for the building after carbon neutralizing. We need to examine how the old buildings help the environment and what is the side effect.

The heritage building is not only crucial to preserve the whole building. It is also **critical to preserve each material/ component.** For example, the windows (62 nos) of the PM5 building were replaced due to the wooden frames are not possible to reuse. Then, what is the result of module D for these windows? These windows have the same service life as the PM5 building. Therefore, cultural values must be considered for these windows. Even though these components cannot be reused, recycling is also not an option if the recycling progress changes the form or color of the components. Therefore, recommend using double windows, which is added new windows over the existing windows. In another way is calling an antique auction for the public. It will enhance the cultural value along with the heritage building's memory.

5.2. Limitation

There is some limitation creates the constraint of this study. First, the collective science data of the existing building was not sufficient to determine the building construction technique of PM5. Then, the lack of documentation for the building and materials to choose the suitable materials or components of the PM5. Moreover, the comprehensive method studies for the heritage infrastructure are limited. Moreover, the initial investigation or assessment was not carried before the rehabilitation. Therefore, the actual results of the before rehabilitation cannot be achieved. Finally, the adaptation of the building did not include the structural aspect. The actual adaptation purpose is only for the architectural aesthetic and energy performance of the building.

The static heating demand calculation was used to determine the building energy demand. In this study, no energy performance simulation was performed. In the initial research stage, the author believes that the adaptive reuse scenarios without considering hygrothermal performance will gain relevant results for both cultural and energy aspects. Therefore, the author decided to use the simple calculation method for this study. Moreover, this study is dedicated to the environmental impact assessment of the heritage building, and the energy performance is just for support aspect for consideration.

Regarding the EPD data of the products, the author used the average data from the One Click LCA as much as possible due to uncertain materials. The average value for clay bricks could not be extracted from One Click LCA, and a specific EPD was used for evaluation. The material choice for exterior paint is not accurate. The paint must be chosen wisely as the heritage building needs to consider chemical and additive use. Moreover, the roof of the building is not changed or repaired in this study. The materials data for the roof was unclear. Therefore, the roof is presumed a standard roof construction that was refurbished 50 years ago. Therefore, this research should be carried out with the explicit materials' EPD after performing several tests and simulations.

6. Conclusion

Nowadays, the sustainability environment is one of the most discussed issues in urban planning society. Adaptive reuse of existing building stock is an essential aspect of sustainable environments. The sustainable adaptation of the heritage building will contribute to a better environment. However, the rehabilitation of heritage buildings is a challenging process which must consider the different aspect.

In this study, an industrial heritage building (PM5) was explored. The initial use of the PM5 building was a paper machine, and it had have stopped working for a long time. Therefore, the building was not in use but allowed the public to access it without a specific reason. The building has passed over 130 years, and now the new owner is planning to reuse it as a public building with maker space and restaurant. The building is located on Smieøya island in Skien. The building holds the high social-cultural values of the paper industry in Norway. Therefore, the Skien municipal and Norwegian Directorate for Cultural Heritage (Riksantikvaren) decided to preserve the building. The property owner is also willing to use PM5 as a public activities area for their resident.

This study targets to understand how adaptive reusing the heritage building will benefit the sustainable society. Firstly, systematic research about the topic was carried out to understand the existing studies of heritage building rehabilitation and different rehabilitation scenarios. The literature research showed that the current study for rehabilitating heritage buildings has lacked in methodology and existing data study. Although the life cycle assessment is the most used method to assess the environmental impacts of the building, the database of the building materials is not relevant to the heritage building or existing old buildings. However, the author believed that the life cycle assessment is suitable for initiating the environmental assessment of heritage buildings. Moreover, the adaptive reuse method of the heritage building is slightly different from the ordinary existing buildings due to the soft value (socio-cultural values and heritage values) of the heritage building. Therefore, the rehabilitation of heritage buildings must consider the heritage values and social-cultural values.

Adaptive reuse of heritage buildings should not replace or repair a lot to reduce energy consumption. Each component of the heritage building has the equivalent heritage value to the whole building. Therefore, the adaptation should not affect the building components or materials' soft value. LCA method was used to evaluate the environmental impact of eight different scenarios. The scenarios mix the system boundary-based scenarios (before rehabilitation, adaptive reuse, demolition, and new construction) with the energy performance. Among all scenarios, the adaptive reuse scenario (ADP-2), has the most acceptable carbon emission compared to other adaptive reuse building. Therefore, this is the selected scenario to consider for the PM5 building's rehabilitation. Fortunately, the owner was planned the same as this scenario, and the outer walls were completed. The author recommends performing the life cycle analysis before the rehabilitation of any heritage building. A detailed analysis should be done to find the most appropriate function in adaptive reuse as a decision-making process.

As written above, the building materials or components also have the same social and cultural value as the main heritage building. Since the building was preserved, the materials and components also should be preserved. In this study, the wooden framed doors and windows were replaced with aluminum frames due to the building must be closed, and the existing windows were not possible to reuse. These windows have a significant impact on the building's carbon emissions. However, after replacing the windows, the old windows should not be disposed of or discarded due to the soft value of the heritage building materials. Instead, these windows should be selling for antique collections or display in a museum. Then the value of the windows increased, and the heritage value also will not vanish. Moreover, further study of the ADP-2 is performed with the time interval (10 years) to study the emission profile during the 100-year lifespan. Although 55% of carbon emission cannot be achieved in 2030, the profile is sufficient for the green deal target to reduce the 60% carbon emission in 2050 of total carbon emission.

The materials data based on OneClick LCA was not reliable to use for heritage building materials because the data-based materials are verified only for the new construction with advanced construction technology. The materials are extracted according to the drawings provided by the owner and quantify materials. Therefore, the databased of the heritage buildings' components must be retrieved and verify the environmental impacts of each component. This process should not be done for the stand-alone project. The environmental data documentation should be grouped by building period (example: 1880s or 1890s), the region (Eastern Europe or Nordic), construction technique (masonry or brick nogging). Then, the digitalization of heritage buildings should be carried out by scanning the project and convert a BIM model to quantify the materials. This model also can use in different simulations, for example, energy simulation and demolition simulation. Unfortunately, in this study, the project could not scan due to COVID-19 Pandemic. This study found that the rehabilitation method, which balances the heritage building's energy performance and soft value, is the best way to rehabilitate the building. Moreover, using it as a public building for social activities is also a unique purpose of the adaptive reuse of the building. It reduces energy use and enhances social value.

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8. Appendices

8.1 Appendix A, Data about the studied project

8.2 Appendix B, Materials and energy Input Data for LCA

8.3 Appendix C, EPD data of the materials

8.4 Appendix D, Energy demand calculation

8.5 Appendix E, Project Drawings and Photos

8.1. Appendix A: Data about the studied project

Table A-1: Bills of Materials (BOM)

Project specification:	
Construction year	1883
Number of floors	2
Building Length (m)	56
Building Breath (m)	13.6
Building gross floor Area (m2)	1550
Building height (m)	15.5 m (15.65 m)
Floor height (m)	5.15 (GF), 4.9 (UF)
Roof height (m)	5.55 (from ceiling slab to top of the roof ridge)
Windows	26 no of W1 (1.37 x 3.83)
	31 no of W2 (1.34 x 3.10)
	3 no of W3 (1.39 x 3.15)
	2 no of V4 (1.34 x 2.5)
Doors	1 no of D1 (2.56 x 4.66)
Wall thickness	***Conc/ Masonry wall***
	400mm @ front (GF+UF) and sides (GF)
	620mm @ back against the soil (GF + UF)
	250mm @ back (L2) and sides (UF)
	Brick wall
	130mm around the building
Slab thickness	300 mm (GF) and Ceiling slab
	350 mm (UF)
Columns	300 ∅ ,250 ∅ and 200 ∅ cast iron columns
Beams	Cast-iron beams and Masonry beams
Load-bearing component	Exterior walls, Column, Beams and, Slab
Foundation	Shallow foundation with stonewall

Table A-2 Bills of Materials and Assemblies

Materials / layers	L (m)	H (m)	T (m)	A(m²)	V (m³)	Remark
Dry stone wall - 2 stone wall						
Quarry stone	140	1	0.56	140	78.40	80% of total volume
Portland Cement	140	1	0.14	140	19.60	20% of total volume
Retaining walls (GF)						
Portland Cement	38.6	4.85	0.093	187.21	17.41	15% of total volume
Aggregates	38.6	4.85	0.372	187.21	69.64	60% of total volume
Outer walls (GF)						
Portland Cement	98.3	5.15	0.06	375.23	22.51	15% of total volume
Aggregates	98.3	5.15	0.24	375.23	90.06	60% of total volume
Bricks	98.3	5.15	0.14	375.23	54.03	80% of total volume
Portland Cement	98.3	5.15	0.04	375.23	13.51	20% of total volume
Masonry mortar (plastering)	98.3	5.15	0.01	375.23	3.75	
Outer walls (UF)						
Portland Cement	185.1	4.9	0.038	764.85	28.68	15% of total volume
Aggregates	185.1	4.9	0.15	764.85	114.73	65% of total volume
Bricks	185.1	4.9	0.14	764.85	110.14	80% of total volume
Portland Cement	185.1	4.9	0.04	764.85	27.53	20% of total volume
Masonry mortar (plastering)	185.1	4.9	0.01	764.85	7.65	
Outer walls (Domers)						
Bricks	35.00	3	0.20	105.00	21.00	80% of total volume
Portland Cement	35.00	3	0.05	105.00	5.25	20% of total volume
Masonry mortar (plastering)	35.00	3	0.01	105.00	1.05	
Cast iron column						
column (350mm ∅)-GF	30	1.25	0.05	0.76590	0.96	Hollow w/25 mm thk
column (250mm ∅)-GF	30	3.55	0.25	0.53010	1.88	Hollow w/25 mm thk
column (250mm ∅)-UP	30	1.25	0.25	0.53010	0.66	Hollow w/25 mm thk
column (200mm ∅)-UP	30	3.35	0.20	0.41220	1.38	Hollow w/25 mm thk
Floor Slabs						
Portland Cement (GF)	55.41	13.34	0.3	739.1694	33.26	15% of total volume
Aggregates (GF)	55.41	13.34	0.3	739.1694	133.05	60% of total volume
Portland Cement (UF)			0.35	1550	81.38	15% of total volume
Aggregates (UF)			0.35	1550	325.50	60% of total volume
Ceiling Slab						
Portland Cement (UF)			0.3	1550	69.75	15% of total volume
Aggregates (UF)			0.3	1550	279.00	60% of total volume
Cast-iron beams						
Grey cast iron (GF)	1917.6	0.2	0.05	0.01	19.18	
Grey cast iron (UF)	112	0.2	0.25	0.05	5.60	
Grey cast iron (CL)	112	0.2	0.25	0.05	5.60	
Masonry beams						
Portland cement (UF)	1917.6	0.2	0.25	0.05	14.38	15% of total volume
Aggregates (UF)	1917.6	0.2	0.25	0.05	57.53	60% of total volume
Portland cement (CL)	1917.6	0.2	0.25	0.05	14.38	15% of total volume
Aggregates (CL)	1917.6	0.2	0.25	0.05	57.53	60% of total volume
Roof						
bitumen roofing	55	17	0.025	935	23.38	
Bricks	55	17	0.210	935	157.08	80% of total volume
Portland Cement	55	17	1.210	935	226.27	20% of total volume
wooden board	55	17	0.020	935	18.70	
Insulation	55	17	0.250	935	233.75	Glass wool
wooden Board	55	17	0.020	935	18.70	
Doors				11.24		
Windows	62				273.15	
Additional materials						
Outer wall Paint				1327.29		
Floor screeding (GF)					73.92	
Floor screeding (UF)					36.96	
Elevator	1 Unit					

8.2. Appendix B: Materials and energy Input Data for LCA

Table B-1 Materials and Energy Input Data for LCA

Components and assemblies	Unit	EXT-1	EXT-2	ADP-1	ADP-2	DEM-1	DEM-2	NEW-1	NEW-2
Foundation									
Quarry stone	m^3	78.40	0	0	0	78.40	78.40	78.40	78.40
Portland Cement	m^3	19.60	0	0	0	19.60	19.60	19.60	19.60
Retaining walls									
Portland Cement	m^3	17.41	0	0	0	17.41	17.41	17.41	17.41
Aggregates	m^3	69.64	0	0	0	69.64	69.64	69.64	69.64
Painting – 0.04 mm	m^2	-	-	187.21	187.21	-	-	187.21	187.21
Outer wall (Ground floor)									
Gypsum board	m^3	-	-	4.5	-	-	-	4.5	4.5
Insulation (mineral wool)	m^3	-	-	37.52	-	-	-	75.05	37.52
Portland Cement	m^3	22.51	0	0	0	22.51	22.51	22.51	22.51
Aggregates	m^3	90.06	0	0	0	90.06	90.06	90.06	90.06
Bricks	m^3	54.03	0	0	0	54.03	54.03	54.03	54.03
Portland cement	m^3	13.51	0	0	0	13.51	13.51	13.51	13.51
Masonry mortar plastering	m^3	-	-	3.75	3.75	-	-	3.75	3.75
Painting – 0.04 mm	m^2	-	-	375.23	375.23	-	-	375.23	375.23
Outer wall (Upper floor)									
Gypsum board	m^3	-	-	11.47	-	-	-	11.47	11.47
Insulation (mineral wool)	m^3	-	-	99.43	-	-	-	152.97	99.43
Portland Cement	m^3	28.68	0	0	0	28.68	28.68	28.68	28.68
Aggregates	m^3	114.73	0	0	0	114.73	114.73	114.73	114.73
Bricks	m^3	110.14	0	0	0	110.14	110.14	110.14	110.14
Portland Cement	m^3	27.53	0	0	0	27.53	27.53	27.53	27.53
Masonry mortar plastering	m^3	-	-	7.65	7.65	-	-	7.65	7.65
Painting – 0.04 mm	m^2	-	-	764.85	764.85	-	-	764.85	764.85
Outer walls (dormer)									
Bricks	m^3	12.6	0	0	0	12.6	12.6	12.6	12.6
Portland Cement	m^3	3.15	0	0	0	3.15	3.15	3.15	3.15
Masonry mortar plastering	m^3	NA	0	0.63	0.63	-	-	0.63	0.63
Painting – 0.04 mm	m^2	-	-	63	63	-	-	63	63
Bricks	m^3	8.40	0	0	0	8.40	8.40	8.40	8.40
Portland Cement	m^3	2.10	0	0	0	2.10	2.10	2.10	2.10
Masonry mortar plastering	m^3	-	-	0.42	0.42	-	-	0.42	0.42
Painting – 0.04 mm	m^2	-	-	42	42	-	-	42	42
Column									
Iron - 350mm ∅-25 mm thk	m^3	0.96	0	0	0	0.96	0.96	0.96	0.96
Iron - 250mm ∅-25 mm thk	m^3	2.54	0	0	0	2.54	2.54	2.54	2.54
Iron - 200mm ∅-25 mm thk	m^3	1.38	0	0	0	1.38	1.38	1.38	1.38
Ground floor slab									
Portland Cement	m^3	33.26	0	0	0	33.26	33.26	33.26	33.26
Aggregates	m^3	133	0	0	0	133	133	133	133
Screeding 100 mm	m^3	-	-	73.92	73.92	-	-	73.92	73.92
Upper floor slab									
Portland Cement	m^3	39.98	0	0	0	39.98	39.98	39.98	39.98
Aggregates	m^3	159.94	0	0	0	388064	388064	388064	388064
Screeding 50 mm	m^3	-	-	36.96	36.96	-	-	36.96	36.96

Table B-1 Materials and Energy Input Data for LCA

Components and assemblies	Unit	EXT-1	EXT-2	ADP-1	ADP-2	DEM-1	DEM-2	NEW-1	NEW-2
Ceiling slab									
Portland Cement	m^3	34.27	0	0	0	34.27	34.27	34.27	34.27
Aggregates	m^3	137.09	0	0	0	137.09	137.09	137.09	137.09
Ground floor beam									
Grey cast iron	m^3	19.18	0	0	0	19.18	19.18	19.18	19.18
Upper floor beam									
Grey cast iron (primary)	m^3	5.6	0	0	0	5.6	5.6	5.6	5.6
Portland cement	m^3	14.38	0	0	0	14.38	14.38	14.38	14.38
Aggregates	m^3	57.53	0	0	0	57.53	57.53	57.53	57.53
Ceiling level beam									
Grey cast iron (primary)	m^3	5.6	0	0	0	5.6	5.6	5.6	5.6
Portland cement	m^3	14.38	0	0	0	14.38	14.38	14.38	14.38
Aggregates	m^3	57.53	0	0	0	57.53	57.53	57.53	57.53
Roof									
Bitumen roofing – 4mm	m^2	935	0	0	0	935	935	935	935
Bricks	m^3	157.08	0	0	0	157.08	157.08	157.08	157.08
Portland cement	m^3	226.27	0	0	0	226.27	226.27	226.27	226.27
wooden board - 20 mm	m^2	935	0	0	0	935	935	935	935
Insulation – 250 mm	m^2	935	0	0	0	935	935	935	935
wooden board – 20 mm	m^2	935	0	0	0	935	935	935	935
Door									
Doors	m^2	11.24	0	11.24	11.24	11.24	11.24	11.24	11.24
Windows	m^2	273.15	0	273.15	273.15	273.15	273.15	273.15	273.15
Stair/ elevator									
elevator	No	-	-	1	1	-	-	1	1
Energy demand									
Heating demand (kWh/yr)	-	-	-	47508	52509	-	-	47508	52272
Cooling demand (kWh/yr)	-	-	-	40789	19245			40789	19245
Lighting (kWh/yr)	-	26660	26660	26660	26660	26660	26660	26660	26660
Equipment (kWh/yr)	-	-	-	4670	4670	-	-	4670	4670
Hot water (kWh/yr)	-	-	-	7750	7750	-	-	7750	7750
Demolition (kWh/yr)	-	-	-	-	-	OCLCA[15]	OCLCA	-	-
Reuse/ recycling (kWh/yr)	-	-	-	-	-	-	OCLCA	-	-

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[15] OCLCA: OneClick LCA

8.3. Appendix C: Environmental product declaration (EPD) Data (OneClick L.C.A)

Table C-1 Materials and Energy Input Data for LCA

Materials	EXT-1 / EXT-2	ADP- 1	ADP-2	DEM-1/DEM-2	NEW-1 / NEW - 2
Quarry stone (1800 kg/m^3)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)
Portland cement	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)
Aggregate	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)
Brick (cannot fine average data)	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)
Masonry mortar	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)
Screeding (conc mix)	Average data (Denmark)	Average data (Denmark)	Average data (Denmark)	NA	Average data (Denmark)
Grey cast iron	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)
Painting	NA	Average data (OneCick LCA)	Average data (OneCick LCA)	NA	Average data (OneCick LCA)
Bitumen roofing	Average data (Norway)	Average data (Norway)	Average data (Norway)	Average data (Norway)	Average data (Norway)
Wooden board	Average data (France)	Average data (France)	Average data (France)	Average data (France)	Average data (France)
Insulation	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)	Average data (OneCick LCA)
Gypsum Board	Average data (Denmark)	Average data (OneCick LCA)	NA	NA	Average data (OneCick LCA)
frame Window	Average data (France)	Average data (France)	Average data (France)	Average data (France)	Average data (France)
elevator	NA	Oekobau.dat 2020-II	Oekobau.dat 2020-II	NA	Oekobau.dat 2020-II

8.4. Appendix D: Energy Demand Calculation

Table D-1: Outer Walls' U-Value: Ground Floor (ADP-1)

BRA (heated area)	761.6	m2	
Materials/ Assemblies	d (m)	Conductivity λ (W/mK)	R-Value (m²K/W)
R_{se}			0.13
Plastering (lime plaster)	0.01	0.15	0.07
Brick wall	0.18	0.15	1.20
concrete wall	0.40	0.15	2.67
Insulation (addition)	0.10	0.04	2.56
Gypsum board (addition)	0.012	0.21	0.06
R_{si}			0.04
R_{total}		(m²K/W)	6.72
U_{WGF}		(W/m²K)	**0.15**

Table D-2: Outer Walls' U-Value: Ground Floor (ADP-2)

BRA	761.6	m2	
Materials/ Assemblies	d (m)	Conductivity λ (W/mK)	R-Value (m²K/W)
R_{se}			0.13
Plastering (lime plaster)	0.01	0.15	0.07
Brick wall	0.18	0.15	1.20
concrete wall	0.40	0.15	2.67
R_{si}			0.04
R_{total}		(m²K/W)	4.10
U_{WGF}		(W/m²K)	**0.24**

Table D-3: Outer Walls' U-Value: Upper Floor (ADP-1)

Materials/ Assemblies	d (m)	Conductivity λ (W/mK)	R-Value (m²K/W)
R_{se}			0.13
Plastering	0.01	0.15	0.07
Brick wall	0.18	0.15	1.20
concrete wall (addition)	0.25	0.15	1.67
Insulation (addition)	0.13	0.04	3.33
Gypsum board (addition)	0.015	0.21	0.07
R_{si}			0.04
R_{total}		(m²K/W)	6.51
U_{WUF}		(W/m²K)	**0.15**

Table D-4: Outer Walls' U-Value: Upper Floor (ADP-2)

Materials/ Assemblies	d (m)	Conductivity λ (W/mK)	R-Value (m²K/W)
R_{se}			0.13
Plastering	0.01	0.15	0.07
Brick wall	0.18	0.15	1.20
concrete wall	0.25	0.15	1.67
R_{si}			0.04
R_{total}		(m²K/W)	3.10
U_{WUF}		(W/m²K)	**0.32**

Table D-5: Slab's U-Value: Ground Floor (ADP-1 & ADP-2)

Materials/ Assemblies	d (m)	Conductivity λ (W/mK)	R-Value (m²K/W)
R_{se}			0.13
concrete floor	0.30	0.15	2.00
Screeding	0.10	0.15	0.67
R_{si}			0.04
		R_{total}	2.8367
		λ	0.35
Floor area	761.6	m2	
Perimeter	139.2	m	
Characteristic dimension (B')	10.9425	m	
dt	1.7020	<	B'
U_0	**0.08**	(W/m²K)	

Table D-6: Roof's U-Value (ADP-1 & ADP-2)

Roof area	935	m2	
Height of the wall	5.15	m	
Materials/ Assemblies	d (m)	Conductivity λ (W/mK)	R-Value (m^2K/W)
R_{se}			0.04
Bitumen roofing	0.004	0.17	0.02
Brick wall	0.200	0.15	1.33
Gypsum board	0.024	0.21	0.11
Insulation (mineral wool)	0.246	0.04	6.15
air layer	0.050	0.025	2.00
Gypsum board	0.024	0.21	0.11
R_{si}	0.548		0.10
R_{total}		(m^2K/W)	9.88
U_{RF}		(W/m^2K)	**0.10**

Table D-7: Façade Orirentation of the building

Façade	F_h	angle (°)	table (°)	F_o	F_f	F_s
NE	1	20	30	0.91	1	0.91
SE	1	20	30	0.92	1	0.92
SW	1	20	30	0.925	1	0.925
NW	1	20	30	0.91	1	0.91

Façade	A_w	F_f	$A_w(1-F_f)$
NE	106.0432	0.3	74.23
SE	20.2217	0.3	14.16
SW	143.72	0.3	100.60
NW	7.8872	0.3	5.52

Table D-8: Total solar heat gain

$Q_{sol,i}$	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
NE	282	755	209	3380	5323	5847	5944	5018	2869	1263	385	171	33338
SE	183	402	856	1089	1431	1330	1346	1354	967	542	175	118	9799
SW	1311	2879	6122	7783	10226	9510	9618	9681	6913	3875	1252	848	70024
NW	21	56.20	155	251	395	434	442	373	213	93	28	12	2479
Total	1798	4093	9230	12504	17377	17124	17351	16428	10963	5775	1842	1151	115641

Table D-9: Heat gain factor from NS-EN 3031-2020

Heat gain	Wh/m2 (ops)	Wh/m2 (off)	
Equipment	0.98	0.1	NS EN-3031-2020
Person	3.18	0	NS EN-3031-2020
Lighting	5.43	0.7	NS EN-3031-2020

Table D-10: Heat Loss (ADP-1)

Heat Loss	area	U - Value	Flow rate	Cv	H(W/K)
Conduction					
Exterior wall - GF (H_D)	585.87	0.15			
Exterior wall - UF (H_D)	539.94	0.15			
Doors & Windows area (H_D)	284.39	0.8			227.51
Ground Slab (H_g)	761.60	0.08			59.62
Roof (H_D)	935.00	0.10			94.68
Thermal bridge (B3: NSPEK 3031-2020)	761.6	0.1			76.16
Convention					
Infiltration (H_{inf})	(Volume) 7654.08		321.47	0.33	106.09
Total heat loss coefficient (W/K)					564.05
Heat transfer W/m2K					0.74
0.74 > 0.5, thus the heat transfer is not achieved any criteria standard					

Table D-11: Heat Loss (ADP-2)

Heat Loss	area	U - Value	Flow rate	Cv	H(W/K)
Conduction					
Exterior wall - GF (H_D)	585.87	0.24			
Exterior wall - UF (H_D)	539.94	0.32			
Doors & Windows area (H_D)	284.39	0.8			227.51
Slab (H_g)	761.6	0.08			60.82
Roof (H_D)	935	0.13			118.72
Thermal bridge (B3: NSPEK 3031-2020)	761.6	0.1			76.16
Convention					
Infiltration (H_{inf})	7654.08		321.47	0.33	106.09
Total heat loss coefficient (W/K)					589.30
Heat transfer W/m2K					0.77
0.77 > 0.5, thus the heat transfer is not achieved any criteria standard					

Table D-12: Operational and Non-operation hour for cultural building

Heated area (m²)	760											
Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
External temp	-4.3	-4	-0.2	4.5	10.8	15.2	16.4	15.2	10.8	6.3	0.7	-3.1
Interior temp (ops)	21	21	21	21	21	21	21	21	21	21	21	21
Interior temp (off)	19	19	19	19	19	19	19	19	19	19	19	19
Temp different (ops)	25.3	25	21.2	16.5	10.2	5.8	4.6	5.8	10.2	14.7	20.3	24.1
Temp different (off)	23.3	23	19.2	14.5	8.2	3.8	2.6	3.8	8.2	12.7	18.3	22.1
hours (ops)	244	220	244	236	244	236	244	244	236	244	236	244
hours (off)	500	452	500	484	500	484	500	500	484	500	484	500

Table D-13: Heat Balance ADP-1

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heat transfer (ops)	-3476	-3102	-2913	-2194	-1401	-771	-632	-797	-1356	-2020	-2699	-3311
Solar gain	589	1340	3022	4094	5689	5606	5681	5378	3589	1891	603	377
equipment	182	164	182	176	182	176	182	182	176	182	176	182
personal	589	532	589	570	589	570	589	589	570	589	570	589
Lighting	1005	907	1005	972	1005	972	1005	1005	972	1005	972	1005
Heat gain (ops)	2364	2944	4797	5812	7464	7324	7456	7154	5308	3666	2321	2152
Heat balance(ops)	**-1112**	**-158**	**1885**	**3618**	**6063**	**6553**	**6824**	**6357**	**3951**	**1647**	**-378**	**-1159**
Heat loss (off)	-6577	-5864	-5420	-3961	-2315	-1038	-734	-1073	-2240	-3585	-4999	-6238
Solar gain	1210	2754	6208	8411	11688	11518	11671	11050	7375	3885	1240	774
equipment	38	34	38	37	38	37	38	38	37	38	37	38
personal	0	0	0	0	0	0	0	0	0	0	0	0
Lighting	266	240	266	258	266	258	266	266	258	266	258	266
Heat gain (off)	1514	3028	6513	8705	11993	11813	11975	11354	7669	4189	1534	1079
Heat balance (off)	**-5063**	**-2835**	**1093**	**4744**	**9678**	**10775**	**11241**	**10282**	**5429**	**604**	**-3465**	**-5160**
Heating/cooling (kWh/yr)	11640	8699	4327	-784	-7363	-9736	-10508	-9209	-3189	2981	8464	11398

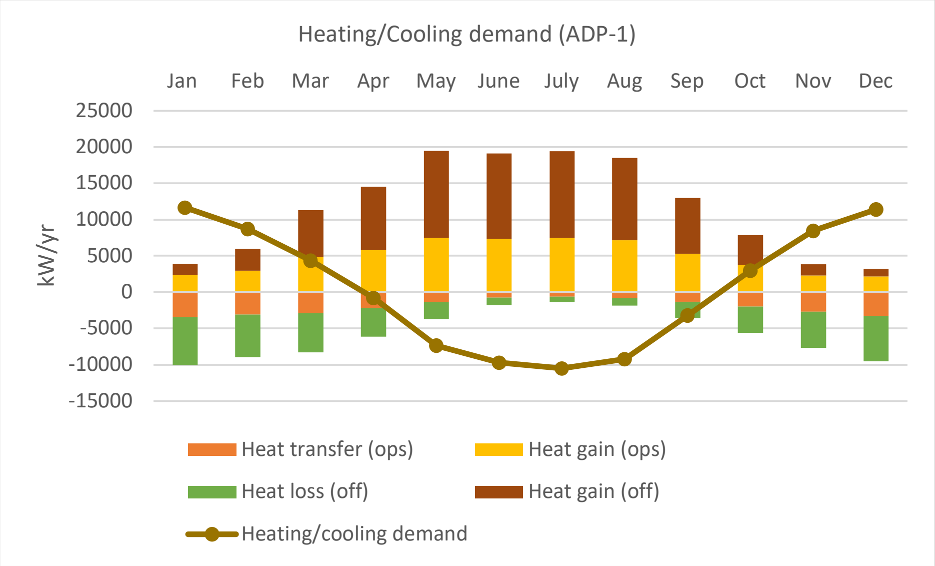


Table D14: Heat Balance ADP-2

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heat transfer (ops)	-3631	-3241	-3043	-2292	-1464	-806	-660	-833	-1417	-2110	-2820	-3459
Solar gain	589	1340	3022	4094	5689	5606	5681	5378	3589	1891	603	377
equipment	182	164	182	176	182	176	182	182	176	182	176	182
personal	589	532	589	570	589	570	589	589	570	589	570	589
Lighting	1005	907	1005	972	1005	972	1005	1005	972	1005	972	1005
Heat gain (ops)	2364	2944	4797	5812	7464	7324	7456	7154	5308	3666	2321	2152
Heat balance(ops)	**-1267**	**-297**	**1754**	**3520**	**6000**	**6519**	**6796**	**6321**	**3891**	**1556**	**-498**	**-1307**
Heat loss (off)	-6871	-6126	-5662	-4138	-2418	-1084	-767	-1121	-2340	-3745	-5223	-6517
Solar gain	589	1340	3022	4094	5689	5606	5681	5378	3589	1891	603	377
equipment	182	164	182	176	182	176	182	182	176	182	176	182
personal	589	532	589	570	589	570	589	589	570	589	570	589
Lighting	1005	907	1005	972	1005	972	1005	1005	972	1005	972	1005
Heat gain (off)	2364	2944	4797	5812	7464	7324	7456	7154	5308	3666	2321	2152
Heat balance (off)	**-4507**	**-3182**	**-865**	**1674**	**5046**	**6240**	**6689**	**6033**	**2967**	**-79**	**-2901**	**-4365**
Heating/cooling demand	11378	9309	6527	2464	-2628	-5155	-5923	-4912	-627	3824	8124	10882

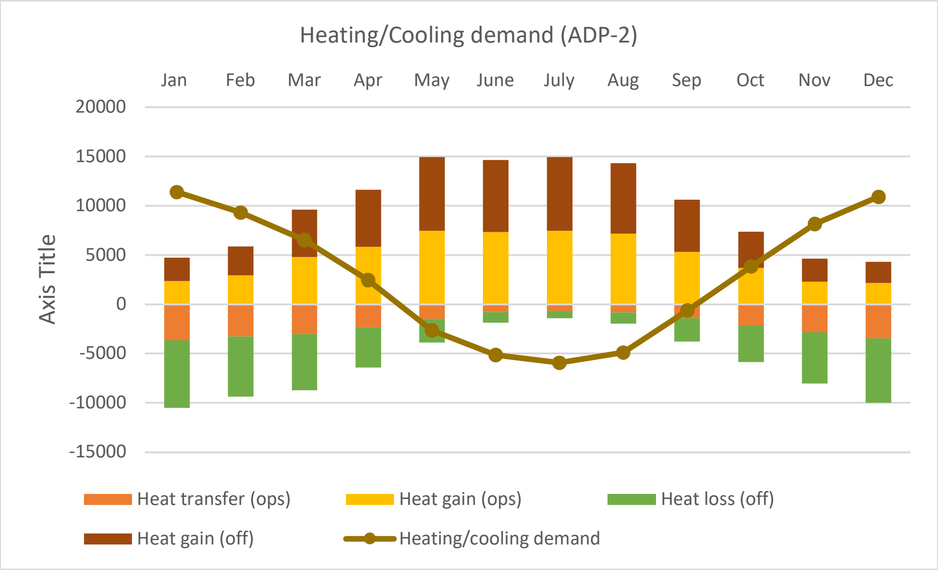


Table D15: Total Energy Consumption ADP-1 & ADP-2

	ADP-1			ADP-2		
	Energy req	Area	Eng demand	Energy req	Area	Eng demand
	kWh/m2-yr	m2	kWh/yr	kWh/m2-yr	m2	kWh/yr
Heating demand			47508			52509
Cooling demand			40789			19245
Lighting	17.2	1550	26660	17.2	1550	26660
Equipment	3	1550	4650	3	1550	4650
Hot water	5	1550	7750	5	1550	7750
Total Energy Demand			**127357**			**110814**

8.5. Appendix E: Project's drawings and Photos

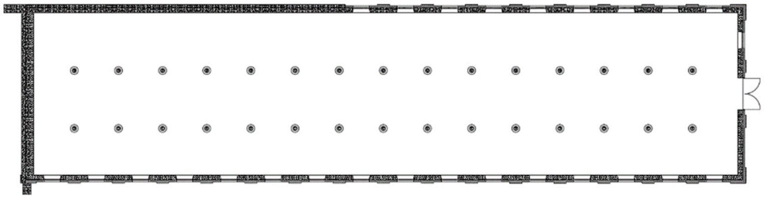


Figure E-1: Ground Floor Plan

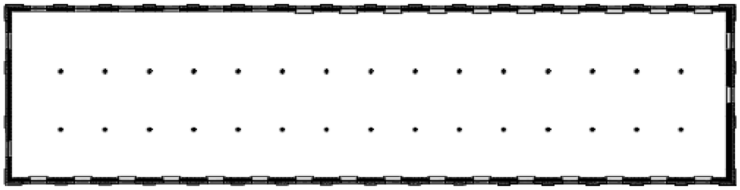


Figure E-2: Upper Floor Plan

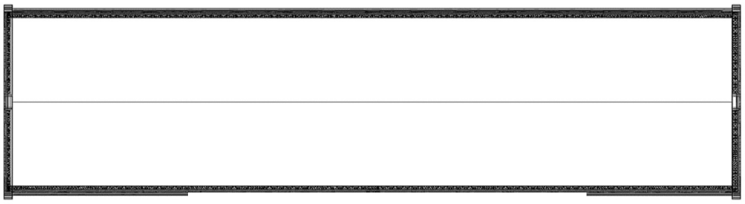


Figure E-3: Roof Plan

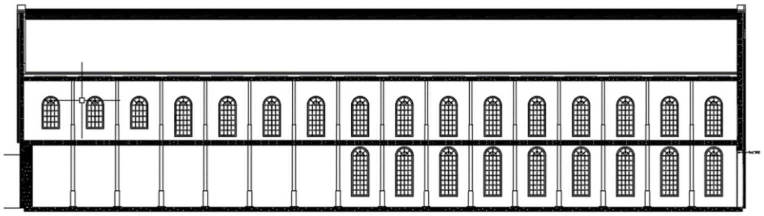


Figure E-4: Longitudinal Section

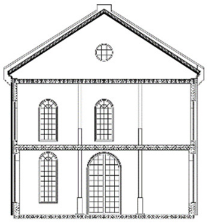


Figure E-5: cross Section

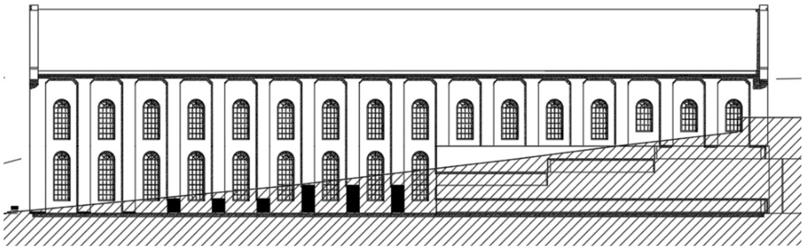


Figure E-6: Elevation-1
(view from Telemark Cannel)

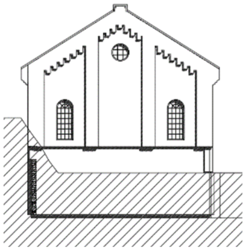


Figure E-7: Elevation -2

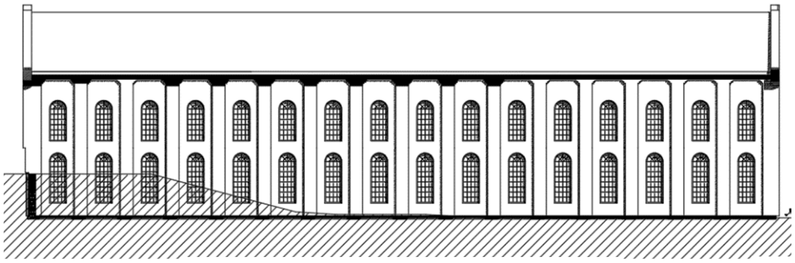


Figure E-8: Elevation -3
(view from inland)

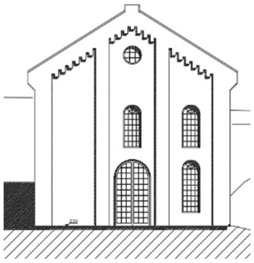
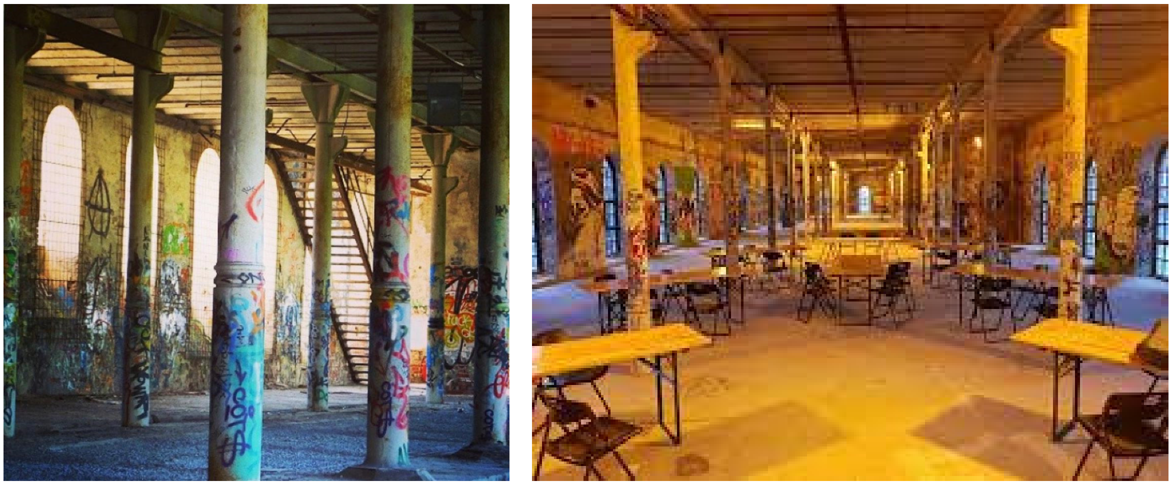


Figure E-9: Elevation -4
(Entrance)



Interior (Before and after)

Exterior Façade (Before)

Exterior façade (After)

KHIN SU SU KYAW
(Alias SUSAN)

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EDUCATION

Oslo Metropolitan University, Oslo Aug 2019 - June 2021

Master's Degree Programme in Structural Engineering and Building Technology

Subjects: Finite Element Method in Structural Analysis, Analysis and Design of Structures, Durability and Service Life of Structures, Building Physics and Climate Adaptation of Buildings, Sustainability Assessment and Life-Cycle Analysis.

Yangon Technology University, Myanmar Jan 2001- Jan 2005

Bachelor of Engineering (Civil Engineering)

Subjects: Building Materials, Structural Analysis (Timber, Steels, and Concrete), Hydraulic and Hydrology, Building Management, Construction Safety.

Government Technical Institute, Maubin, Myanmar Dec 1998- Nov 2000

Diploma in Engineering (Civil)

Subjects: Engineering mathematics, Fundamental in Structure Design, Cost Estimating, Surveying,

EXPERIENCE

SINTEF Community, Oslo June 2020-Aug 2020

Summer Intern

- Evaluation and testing of EE Settlement tool - Embodied emissions (LCA)

P&T Consultant Pte. Ltd, Singapore (formerly Palmer & Turner) Mar 2011- Oct 2014

Project Assistant (Architectural Aspects)

- Drafting and designing of multi-story buildings (Highrise/ Residential Projects)
- Assist the Project Architect/Manager on design and technical issues.
- Preparing Drawing and Documents for Authority Approval, Tender, and Construction.

Unison Construction (Chang Hua) Pte Ltd, Singapore Jun 2008-Dec 2010

Draftsperson

- Drafting coordination drawings for construction purpose
- Preparing progress reports and updating it according to progress
- Logging and monitoring of submission status. (Client and consultant approval)

Art Wave Decoration and Design Engineering Co., Ltd, Myanmar Jun 2006- Dec 2007

Interior Design Engineer

- Involved in interior decoration design for commercial buildings & residential buildings

Public Works, Ministry of Construction, Myanmar May 2004 -May 2006

Junior Assistant Engineer

- Drafting of structural drawings in Bridge Projects

PROJECTS

Bartley Residences (Executive Condominium), Singapore	Mar 2012- Nov 2014
Austville Residences (Executive Condominium), Singapore	Mar 2011- Mar 2014
Domus Condominium, Singapore	Dec 2009- Dec 2010
Cycle & Carriage Automobile Showroom, Singapore	June 2008-Dec 2009

ADDITIONAL INFORMATION

- Software Knowledge: Simapro, One-click LCA, Revit, AutoCAD, Navisworks, Recap, WUFI, Matlab, Abaqus
- Interest: Yoga, Hiking, Volunteering