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Arian Loli

Zero Emission Refurbishment of the Built Environment

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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU), Trondheim, Norway in partial fulfilment of the requirements for the degree of Philosophiae Doctor.

This doctoral work has been performed at the Department of Architecture and Technology, NTNU, Trondheim, between September 2016 and June 2020, with Associate professor Chiara Bertolin as the main supervisor and co-supervision of Prof. Eir Ragna Grytli and Prof. Tommy Kleiven.

This work is part of the project Zero Emission Refurbishment of the Built Environment supported by the Onsager Fellowship Programme (Project 80420120).

Abstract

Nowadays, measures that aim minimum environmental impact are conceived for recent buildings. Greenhouse gas (GHG) emissions are reduced and balanced from renewable energy sources in a lifecycle perspective, while energy saving is achieved with cost-effective actions that secure comfort benefits. However, maintenance and adaptation interventions in historic buildings do not have the same objectives as in modern buildings. Additional requirements have to be followed, such as the use of materials compatible with the original and the preservation of authenticity to ensure historic, social, cultural and artistic values over time.

The presented work aims to overcome the collaboration difficulties among different communities associated with heritage conservation through the definition of a framework that includes all the necessary steps from study to practice in a methodologic way. The Zero Emission Refurbishment (ZER) method considers conservative requirements and environmental impact for the selection of the most sustainable intervention measures. It recategorizes the protection status of the buildings with the decay level of the materials to find suitable low-carbon interventions that satisfy the requests of the involved stakeholders. The results, given at a district scale, enable the intervention works to be implemented through large-scale projects, thus ensuring their uniformity and reduction of time and cost of the actions.

The ZER method is flexible and comprehensive, and it can be applied to diverse built environments. It can be further improved through practice and research, maintaining the principle of independence of the involved communities where the output of each community serves as the input for the other. Future work has to be motivated towards unifying the categorisation systems regardless the location, increasing the accuracy of the decay assessment for the components and pointing areas of the buildings which can serve for the production and storage of the necessary energy to reach ZER balance.

The application of the method in a block of buildings in the city of Trondheim showed the reduction potential of emissions before undergoing large-scale interventions. The overall carbon footprint of the intervention measures, linked with the energy improvement of the buildings after the completion of the works, serves as an indicator for the estimation of renewable energy generated from the neighbourhood and therefore, for the shift towards Zero Emission Neighbourhoods in historic urban cities. Working with heritage buildings adds complexity to the standard interventions; however, 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.

Sammendrag

Det finnes i dag en rekke løsninger for å redusere miljøavtrykket når nye bygninger oppføres. Utslipp av klimagasser i et livsløpsperspektiv reduseres, og balanseres fra fornybare energikilder. Samtidig oppnås energisparing gjennom kostnadseffektive tiltak som også sikrer komfort. Når det gjelder vedlikehold og tilpassing av historiske bygninger, har man imidlertid ikke de de samme målsetningene som for nyere bygg. Det stilles flere krav til vedlikehold og oppgraderinger av eldre og historiske bygninger - blant annet skal materialvalget være kompatibelt med den opprinnelige bygningsstrukturen, for slik å bevare byggets autentisitet og sikre at de historiske, sosiale, kulturelle og kunstneriske verdiene blir bevart over tid.

Arbeidet som presenteres her har som mål å løse de samarbeidsutfordringene ulike fagmiljøer innen kulturarv opplever seg imellom, gjennom å definere et rammeverk som omfatter alle de nødvendige trinnene fra teoretisk planlegging til praktisk gjennomføring av tiltak, satt inn i et metodologisk system. Metoden Zero Emission Refurbishment (ZER), grovt oversatt til Nullutslipp Renoveringsmetoden, baserer valg av materialer og inngrepsmetoder på konservative krav hva gjelder påvirkning på miljøet, samt en målsetning om å velge bærekraftige tiltak. Den tar utgangspunkt i bygningenes vernestatus, og gjør en vurdering basert på denne målt opp mot materialenes forfallsgrad. Formålet er å finne passende tiltak med lavt karbonavtrykk, som samtidig tilfredsstiller kravene fra de involverte partene og interessentene. Når metoden anvendes på et større område, slik som en bydel, legger dette til rette for at tiltak kan implementeres gjennom større prosjekter, og på denne måten sikre et uniformt resultat, samtidig som totale kostnader og tidsbruk reduseres.

ZER-metoden er fleksibel og omfattende, og kan anvendes på ulike typer bygde miljø. Metoden kan ytterligere forbedres ettersom erfaringer tilegnes og ny forskning publiseres, noe som sikrer autonomien til de involverte partene og grupperingene. Slik kan et miljøs erfaringer bidra med ny kunnskap hos en annen gruppe. Fremtidig arbeid må være motivert av å samordne kategoriseringssystemene uavhengig av geografisk plassering, for slik å øke nøyaktighetsgraden ved tilstandsvurderinger av bygningselementer og for å lettere identifisere hvilken del av bygget som er best egnet for produksjon og lagring av tilstrekkelig energi til å nå ZER-balanse.

Metoden ble anvendt på et kvartal i Trondheim, som resulterte i et estimat av hvor mye utslipp kunne reduseres før eventuelt større tiltak ble iverksatt. Det totale karbonavtrykket for tiltakene ble knyttet opp mot bygningens beregnede reduserte energibehov etter gjennomførte tiltak, og indikerer behovet for å generere fornybar energi i nabolaget i skifte mot nullutslippsområder også i historiske bygningsmiljøer. Bygninger som er en del av vår kulturarv tilføyer økt grad

av kompleksitet til tiltaksvurderingene, da flere hensyn må tas. Det å finne løsninger for å redusere klimagassutslipp og samtidig sørge for gode bevaringsløsninger er likevel en utfordring som er verdt å ta på seg, av hensyn til både vår generasjon og generasjonene som kommer etter oss.

Acknowledgements

During this trip, I met many helpful and friendly people that contributed to complete this thesis. Today I want to thank each and everyone who was in any way involved in this.

First and foremost, I owe my sincere gratitude to my supervisor, Assoc. Prof. Chiara Bertolin, for giving me the opportunity to join the project and guiding me energetically through the path. Thanks for the devoted availability, motivation and patience even when the road got tough. Special appreciation also goes to my co-supervisors, Prof. Eir Ragna Grytli and Prof. Tommy Kleiven, for their scientific advice and many helpful discussions and suggestions.

I would like to acknowledge the coordinators of the Climate for Culture project from the Fraunhofer Institute for Building Physics, particularly Dr. Johanna Leissner and Dr. Ralf Kilian, and Dr. Lola Kotova from the Climate Service Center Germany that provided necessary data for the research.

I also want to thank my colleagues at the Faculty of Architecture and Design for the beautiful time I had with each of them. I am grateful to the academic and administrative staff of the Department of Architecture and Technology and the Department of Mechanical and Industrial Engineering for their professional support and friendly help, without whom it would have been challenging to complete this work.

I would like so much to thank my fellow PhD-ers who went through hard times with me, cheered me on, and celebrated each accomplishment: Juana, Elena, Lucy, Steinar, Kristian, Maria, Dave, Eirik, Ray, David, Filippo, Sassu, John, Ellika, Biljana, Shabnam, Albogasto, Sonja, Eszter, Zofie, Savis, Mrudhula, Aleksandar, Lillian, Ragne, Maja. I consider myself very lucky to have met all of you. With so many cool people that I shared great moments inside and outside the NTNU, I may have forgotten to mention someone, so I apologise for that.

Many thanks go to my good friend Ergys Puka. Having known him since the high school era and starting the PhDs at the NTNU at the same time, we have developed strong bonds for life. My Albanian friends in Trondheim, Abedin Gagani, Eduard Gagani and Enio Marku deserve a special thankfulness for making me feel like home.

Last, but not least, I am heavily indebted to my parents, Elmira and Alqi, and my brother Enea for their endless love, support and encouragement throughout the years. I cannot find any pertinent words, even in Albanian, to express my gratitude to them for always being available whenever needed and helping in whatever way possible despite the long distance between us.

Thank you all once again – without you, this work would not be possible!

Contents

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Nomenclature

3ENCULT	Efficient Energy for EU Cultural Heritage
CEN	European Committee for Standardization
COST	European Cooperation in Science and Technology
EFFESUS	Energy Efficiency for EU Historic Districts' Sustainability
ESL	Estimated Service Life
EU	European Union
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air Conditioning
ICOMOS	International Council on Monuments and Sites
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LM	Lifetime Multiplier
MBP	Moisture Buffer Potential
NZEB	Nearly Zero-Energy Buildings
PV	Photovoltaic
RCP	Representative Concentration Pathway
REMO	Regional Model
RH	Relative Humidity
RSL	Reference Service Life
TEK	*Byggteknisk Forskrift*
ToW	Time of Wetness
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
ZEB	Zero Emission Building
ZEN	Zero Emission Neighbourhood
ZER	Zero Emission Refurbishment

List of Appended Articles

1 Loli, Arian; Bertolin, Chiara. (2018) **Towards Zero-Emission Refurbishment of Historic Buildings: A Literature Review.** *Buildings.* vol. 8 (2).

2 Bertolin, Chiara; Loli, Arian. (2018) **Sustainable Interventions in Historic Buildings: A Developing Decision-Making Tool.** *Journal of Cultural Heritage.* vol. 34: 291-302.

3 Loli, Arian; Bertolin, Chiara. (2018) **Indoor Multi-Risk Scenarios of Climate Change Effects on Building Materials in Scandinavian Countries.** *Geosciences.* vol. 8 (9).

4 Loli, Arian; Bertolin, Chiara; Kotova, Lola. (2020) **Service Life Prediction of Building Components in Times of Climate Change.** *IOP Conference Series: Materials Science and Engineering.* Approved for publication.

5 Loli, Arian; Bertolin, Chiara; Kleiven, Tommy. (2019) **Refurbishment of Historic Buildings at a District Scale: Enhancement of Cultural Value and Emission Reduction Potential.** *IOP Conference Series: Earth and Environmental Science (EES).* vol. 352 (1).

6 Loli, Arian; Bertolin, Chiara. (2020) **Application of Zero Emission Refurbishment Method at a District Scale.** *Proceedings of the 2nd International Conference on Urban Risks (ICUR2020).* Approved for publication.

1. INTRODUCTION

1.1. Background

1.1.1. Sustainability in existing and historic buildings

In recent years, the green buildings have been the keyword of the construction industry, with several products and technologies developed to reach the demanding targets towards sustainability (Ahn et al. 2011). The recent policies in the building sector dictate to design and construct structures in a balanced approach between economic, environmental and social aspects, enhancing sustainability and competitiveness of the industry (Tsimplokoukou et al. 2014). In particular, many national and international policies dictate the construction of nearly zero-energy buildings covered by energy from renewable sources, including from renewable sources located on-site or nearby (European Parliament 2010, European Parliament 2018). On the other hand, the legislation regarding the emissions of existing buildings is still vague despite these buildings form the majority of the constructions and show the lowest sustainability scale (Mazzarella 2015). According to the report "Buildings for Our Future" (Global Buildings Performance Network 2013), the energy consumption in buildings can be reduced by 30% compared to today's levels, if the best practices are applied globally by 2050 (Shnapp 2014).

Furthermore, the renovation potential of existing buildings in the European Union (EU) is enormous, with up to 110 million buildings which require renovation (Artola et al. 2016) as around 35% of them are over 50 years old and there is a slow replacement rate (Buildings Performance Institute Europe 2011). In Norway, approximately 80% of the existing residential buildings are built before 2000 (Statistics Norway 2020). According to the statistics, the average annual energy consumption of a residential house in Norway is 172 kWh/m^2 meanwhile for a building built after 2000 the energy consumption reduces to 150 kWh/m^2.

From an environmental point of view, the numbers lead to the conclusion that greenhouse gas emissions from old dwellings are higher due to the more significant number of buildings and higher consumption of energy. In the economic aspect, the comparison demonstrates that residents in old buildings likely pay 15% more for electricity supply each year and the cost of maintenance is higher than the new buildings (Statistics Norway 2020). Besides, these buildings, due to their age and material quality, have a higher risk of decay and destruction. From a sociologic perspective, the old buildings give higher lack of comfort for their residents caused by an absence of design standards in the era they were built.

In the big group of existing buildings, historic buildings hold a significant part due to their age and their historic value in giving people a sense of identity and continuity (Feilden 1985). Therefore, national directives like the Cultural Heritage Act in Norway (Ministry of Climate and Environment 1978) tend to raise awareness of safeguarding and conserving the cultural heritage for future generations. In a cultural context, the historic buildings have been inherited to us by previous generations, and the main objective of various national and international legislation and policies is to protect them in all their variety and details. Consequently, the preservation of historic buildings has critical importance because, if done right, it gives benefits in the social aspect by strengthening the sense of belonging to the community, the economic aspects by increasing of incomes through leisure and tourism and environmental aspect by reducing the energy consumption.

1.1.2. Historic building's definition

There are many technic definitions and approaches for historic buildings in the literature. Among many versions, the European Committee for Standardization (CEN) in the standard EN 15898:2011 (European Committee for Standardization 2011) defines a historic building as a single manifestation of immovable, tangible cultural heritage that does not necessarily have to be a heritage-designated building. Another statement from the European Commission's Directorate in the COST Action C5 – "Urban Heritage - Building Maintenance" is more comprehensive and disposed to extend the group of historic buildings: "Apart from some very valuable historic buildings (the so-called monuments), we find a large number of buildings in European towns and cities which are far less important from a historic and architectural point of view. However, these buildings, taken as a whole, represent an important part of the heritage." (Hofmann and Aachener Institut für Bauschadensforschung und Angewandte Bauphysik 2002). The enlargement of the historic building's concept to a large band, possibly to a street, or district level, reflects the intervention needs for a category of buildings, usually private residential houses that were neglected in the previous interventions, as they were not holding specific memorable values.

Nowadays, the design projects typically call for the structures to perform their function in a specific design life which can be 50 years, 100 years, etc. (European Committee for Standardization 2002). The lifetime concept likely did not exist when the historic buildings were constructed; however, we would like it to be very long, tending to infinite (Clemente 2018). For this reason, this category of buildings requires high-quality interventions to ensure long term performance of the buildings, secure conveyance of their values and fulfil sustainability-driven criteria.

1.1.3. The involved stakeholders

The sustainable refurbishment of historic buildings has gained a lot of attention in the recent decades, including the first achievements of planning and executing preservation, protection, maintenance and restoration of immovable cultural heritage in a standardised way (European Committee for Standardisation 2009). Due to the wide range of required expertise, the overall intervention process from conception to practice is a complex issue that needs to be adequately resolved (Loli and Bertolin 2018). Generally, the affected groups of interest attempt to make decisions in their favour and sometimes the collaboration among different categories of stakeholders seems complicated.

For achieving the intervention goals, it is required strong cooperation from specialists of different fields such as urban planners, architects, engineers, researchers, conservators, buildings owners and others involved in heritage management. As the name "sustainable refurbishment of historic buildings" indicates, the concerned groups of interest can be grouped in three main categories: the sustainability community (with a particular focus on environmental impact), the material science community (material and refurbishment specialists) and built cultural heritage professionals (architects, historians, conservators, etc.). The historic value, as the only non-renewable asset (Sabbioni et al. 2010), should be the driving factor of the intervention works and should be preserved at any cost during the decision-making discussions. After the historic value is ensured, the material science community can suggest possible interventions and then, the environmental specialist can evaluate the environmental impact of them. This process, described here as a linear path, ideally should be an integrated and interdisciplinary process which is essential to meeting the historic buildings' needs appropriately.

Historic value, original materials, building design and envelope and other restraints can limit the choice of measures to be applied, and the interventions solutions may not justify their cost-effectiveness. Compared to existing buildings in general, the interventions in historic buildings are more demanding in terms of maintenance and adaptation and more challenging in energy-saving during the operational stage. Moreover, the preservation of historic buildings is posed at risk, not only due to natural weathering of their materials but also by the convenience of rebuilding instead of restoring or of developing renovation methods tailored to modern buildings (Loli and Bertolin 2018). Another threat to the buildings in the next decades is the climate change effect (Lisø 2006). For this reason, the intervention's aim is not only the reduction of the energy consumption and consequently the carbon emissions (climate change mitigation) but also the application of measures to withstand the climate of the future (climate change adaptation).

Dealing with historic buildings adds complexity to the standard process of interventions in existing buildings; however, due to the natural weathering and other sorts of threat, the time is not running in our side. For this reason, it is necessary to take advantage of the actual knowledge and tools for planning and applying effective measures that reduce greenhouse gas emissions while at the same time, ensuring the best conservation strategies.

1.2. Motivation and research questions

1.2.1. Motivation

A literature review was undertaken to provide justification and motivation for this thesis. The topic of "sustainable refurbishment of historic buildings" involves different research communities and asks for a review of large bodies of information from various fields. For this reason, the systematic literature review method was selected and applied at the junction between the environmental sustainability and the heritage sectors, as this method guarantees a proper mapping of different areas of knowledge and relevant research gaps and uncertainties and highlights research needs accurately (Petticrew and Roberts 2008).

Identification and counting of existing research publications in the field of the sustainable refurbishment of historic buildings was done using the online Elsevier database, Scopus. This platform was selected because it is the world's largest abstract and citation database of peer-reviewed literature (scientific journals, books and conference proceedings), with over 22,000 titles from more than 5000 international publishers (Elsevier 2020). The interests of the main research communities involved drove the choice of the two initial sets of keywords in the search. The first set was created to identify the publications related to sustainable frameworks applied to historic buildings by using the keywords "sustainab*" and "method*" and "histor* build*"; while the second research results related to interventions aiming at the preservation of historic buildings by using the keywords "preserv*" and "interven*" and "histor* build*". The two sets have in common only the category of analysed buildings, i.e., historic buildings, while they differ for the rest. The keywords were written keeping the root of the word and adding the asterisk symbol (*) after to include all the grammar forms of them. As the research topic is recent, the search was performed for scientific publications from the year 2000 until the present day (search performed in September 2017). The search results gave a total number of 274 publications, of which 118 resulted from the first set of keywords and 156 documents from the second set. After an early scan, the total number was reduced to 246, removing nine documents not written in English, nine duplicate documents, and ten lecturers' notes or conference proceedings' books. This final list was subject to a document analysis both in term of general characteristics, contents, gaps and needs.

The results of the analysis on the found articles show that 79% (n = 193) of the documents are published by researchers from the European continent, 10% of them (n = 25) are published in Asia, and each of the remaining continents has produced less than 5%. This result reflects the efforts and the financial availability that the European Commission is investing through the Framework Programme (FP) for Research and Technological Development to develop innovative and effective ways for preserving its built cultural heritage. In fact, over the last few decades, the most significant EU-funded research initiatives in the field, such as the projects (3ENCULT 2013, MOVE 2013, CLIMATE FOR CULTURE 2014, EFFESUS 2016, NOAH'S ARK 2017) have demonstrated valuable methodological approaches in the heritage protection field.

The search results reveal that the topic has received increasing attention among researchers in recent years. While the number of publications within this field was quite low (n = 2) in 2000, over the last few years that has increased significantly, reaching a maximum in 2015 with 38 publications followed by 2016 with 35, with oscillations that are linked with the large-funded projects running in the sector. (Figure 1.1)

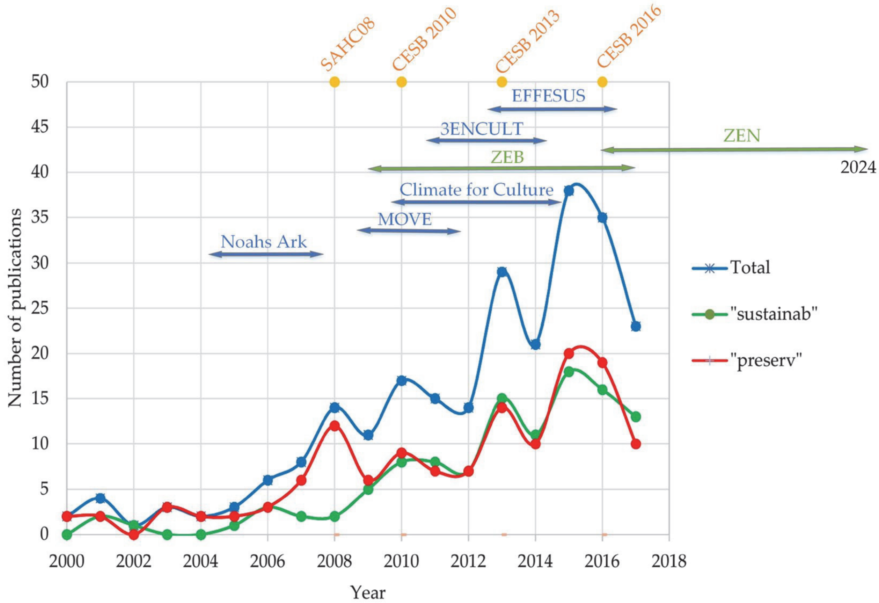


Figure 1.1. Distribution of documents by year of publication with an indication of some significant projects and conferences that have contributed to the research topic

An in-depth review was performed for articles that were proposing and discussing methodologic approaches in the intersection of sustainability and intervention actions on historic buildings (Figure 1.2). It consisted of full-text readings of a total of 48 articles to understand what has been done in the sector and to track future research needs.

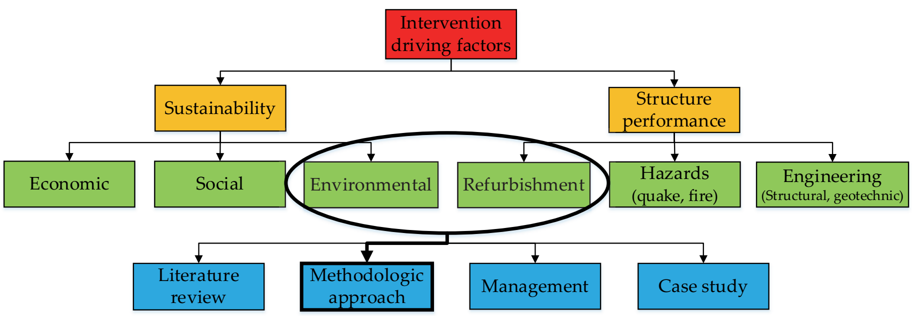


Figure 1.2. Flow diagram for the content review of the documents

The in-depth literature review showed that almost all the published methodological approaches evaluate the actual performance of the buildings and suggest the application of interventions to improve the energy performance and related environmental impact. Energy and environmental improvements are always assessed during the operational phase in two stages: before and after the conclusion of interventions. No methods are proposed to assess the environmental impact of the refurbishment process itself.

Most of the suggested methods were focused on the building scale. It leads to the conclusion that the research should be performed in a broader spatial context for historic buildings, i.e., extending the methodologic approach to the neighbourhood scale. This enlargement makes the path for sorting and grouping these buildings regarding their historic values and physical characteristics. Moreover, finding a sustainable solution for groups of buildings that hold the same significance and preservation status would likely result in time and money-saving than to treat each building separately.

Besides, all the published methods regarding intervention processes are fragmentary with a focus on different stages or procedures and based on the partial needs of various stakeholders. This result makes the important finding that there is a need for a multi-disciplinary, inclusive method which can confront and link different issues and all the processes from conceptual design to implementation and can help the stakeholders in:

- improving the protection of the historic, cultural, and socio-economic value of the building;
- identifying levels of intervention from monitoring results and the state of decay of the material;
- reducing the operating (heating in particular) and maintenance costs without trying to compromise the comfort of occupants and value of the building;
- planning present and future interventions to face slow cumulative or immediate hazardous events;
- using a lifecycle assessment (LCA) approach to find optimal combinations that maximize the reuse of materials, thus reducing the carbon footprint of interventions.

1.2.2. Research questions

The identified gaps stated above serve as drivers throughout the presented work in this thesis, intending to ensure interventions that will respect conservation principles, the adoption of minimal technical interventions (avoiding unnecessary replacement of historic fabric), compatibility, and reversibility. The main question that arises after the literature review was:

"How to include the main necessary steps and involved stakeholders to plan correct and effective sustainable interventions that (first) safeguard the significance of historic buildings?"

The answer to this question can be found through the definition of a methodology that links the main stakeholders into the decision-making process. The outcome of the method should give recommendations about the suitable interventions, which not only safeguard the historic value and durability of materials but also serve as a motor for the reduction of the emissions in the district scale.

As stated in the above paragraph, in this thesis, it will be given a particular focus on the intervention processes itself and their environmental impacts. For doing so, it is necessary to answer the sub-question:

"What types of interventions can be applied to historic buildings, and how can they be categorized?"

The results from the above question are significant because it is the intervention phase which has the leading role when dealing with the historic value. A wrong intervention action can compromise the significance of the building and sometimes can lead to irreversible loss of the value. Moreover, environmentally speaking, from the types of measures applied during the intervention phase also depend the energy performance (and consequently, the carbon emissions) of the "new" renovated building during the operational stage.

Historic buildings have been inherited to us from the previous generations, and they are intended to live for centuries. Therefore, it is our duty to preserve and transfer them to the future generations (Clemente 2018) by not only safeguarding them from present and constant threats but also to adapt them from the expected climatic changes in the future. This goal can be achieved by answering the following sub-question:

"How to consider the effects of climate change in the process of refurbishment, and how does this affect the service life?"

By answering these research questions, the methodologic framework, while ensuring at best the preservation, has the potential to become a powerful tool in planning the time and type of future interventions, thus, increasing the buildings' lifetime and reducing the economic and environmental cost. It can be applied effectively in the decision-making process because its primary goals are to include the work of different involved communities (sometimes opposing each other) and give strong emphasis to the reduction of emissions during and after intervention phase, thus contributing towards global decarbonization targets.

1.3. Structure of the thesis

Apart from the Introduction chapter, the thesis is divided into three main parts which aim to fulfil the research goals and motivation discussed in the above paragraph.

- The second chapter discusses the materials and methods that are needed for the creation of the framework. It is not a typical descriptive chapter of what has been done in the sector, but it includes important results and novel assessing solutions that are needed for the creation of a comprehensive framework. The chapter has been divided into three independent sections that represent the main groups of stakeholders discussed above: the built cultural heritage, material science and environmental specialists. The second section which deals with the service life prediction of components and assemblies is furthermore conceived by two subsections: one related to the inclusion of climate change in the risk assessment for indoor and outdoor environments and the second to the overall decay estimation of the components. At every section, there have been described the leading achievements of the corresponding communities which will serve as a basis to assess the building's components and actions in different perspectives. Each section and subsection of the chapter has been conceived in such a way that the state-of-the-art is explained in the first half and author’s contribution in the field in the second, together with the relevant discussions and comments on the topic.
- The third chapter shows the steps of application of the Zero Emission Refurbishment (ZER) method at a district scale. It links the results of the second paragraph in a single methodologic approach which is flexible and comprehensive. The first section of the chapter describes the framework in a theoretical way, and later an example of application to a case study has been performed for a better understanding of it. Discussions about the presented framework are given at the end of the chapter.
- Finally, the last chapter highlights the conclusions of the performed work and gives recommendations for further research in the field which are necessary to improve and enlarge the novel framework.

The scheme of the thesis is given in Figure 1.3.

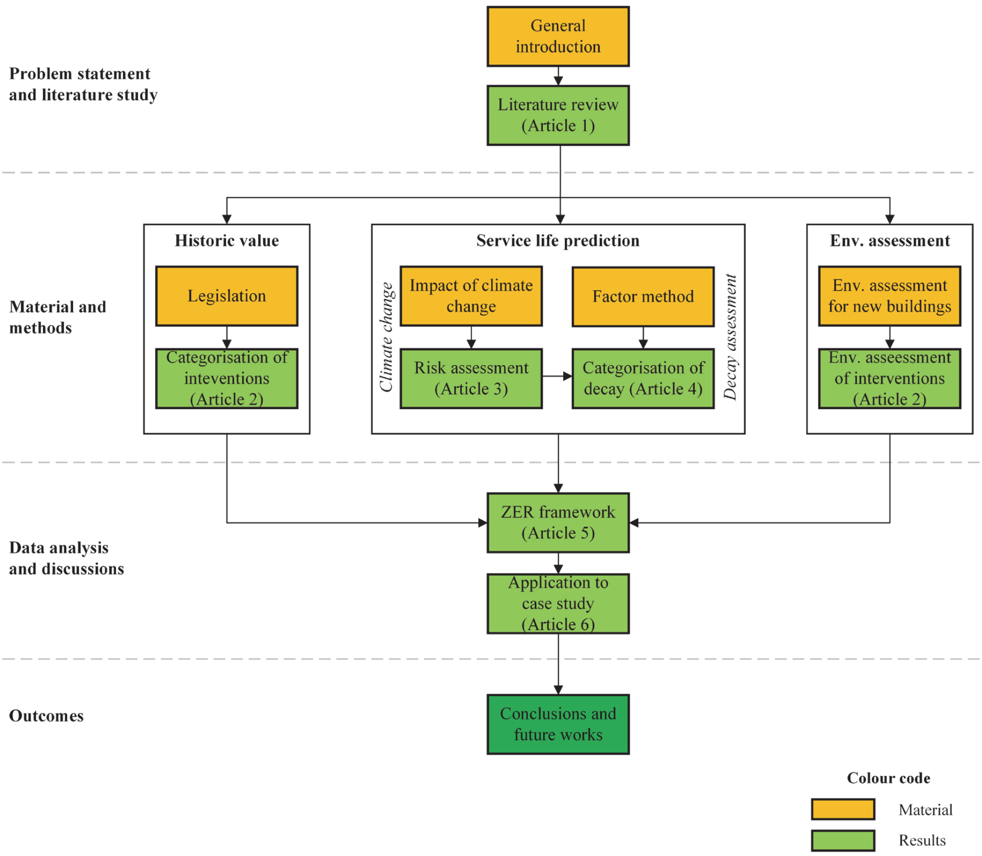


Figure 1.3. Scheme of the PhD thesis

Figure 1.3 shows the flow of the thesis and gives an overview of the multi-disciplinary work that has been conducted. The results, which have been spread throughout the thesis, are highlighted in green, together with the corresponding articles which have been published in the relevant fields. The original version of the articles can be found in the Appendix chapter at the end of the thesis.

As shown in Figure 1.3, the thesis is a collection of six academic articles that are interrelated between them and that are published, or their final version has been approved for publication as follow:

- **Article 1**

In Article 1, the recent literature regarding the topic is reviewed. The results revealed that there is a need for a methodological approach regarding the interventions in historic buildings that should be inclusive and applicable to large scale. Moreover, the review suggested that in the method, special attention should be given to the impact and selection of the intervention processes, especially when dealing with cultural heritage buildings.

- **Article 2**

Article 2 integrates a life cycle approach within building preservation principles. First, the set of all possible interventions that can be applied to existing buildings with a particular focus on historic buildings is explained and after, a categorization of interventions regarding their environmental impact and the basis of calculations of the carbon footprint of the intervention stages is given.

- **Article 3**

Article 3 presents a method to estimate the level of risk indoors and outdoors for a range of 16 buildings, with different sizes and construction materials, which considers the effects of climate change in the future. The results provide useful information to understand the types of structures that resist better to climate change impact and the locations that are more exposed to risk in the Scandinavian region.

- **Article 4**

Article 4 presents an overview of the factor method in the estimation of the serviceability of the building components, with a special focus on historic buildings. It gives a short explanation of the factors and suggested subfactors that constitute the method by including the technical compatibility, economic viability, use of the building, indoor/outdoor environments and effects of the climate change.

- **Article 5**

Article 5 links the achievements of the previous articles into a 3-D decision-making framework and presents the steps of application of it on a building component. The proposed Zero Emission Refurbishment method analyses, at once, the existing constraints and guidelines introduced from the main categories of stakeholders and selects suitable low-carbon interventions that satisfy the requests of them.

- **Article 6**

Article 6 shows the steps of application of the Zero Emission Refurbishment method in a block of buildings in the city of Trondheim. Calculation of the carbon footprint of the interventions in the block, linked with the energy improvement of the buildings after the completion of the works, serve as an indicator for the estimation of renewable energy generated from the district to reach Zero Emission Neighbourhood targets.

This thesis puts the above-published articles into a common context and summarizes the work done. Some parts of the thesis are taken from the sections of text in the articles. Other parts are new and provide some more in-depth insights. The headings of the thesis are given in Table 1.1.

Table 1.1. Structure of the PhD thesis with results shown in green

1. Introduction

- Background
- Motivation and research questions **(Article 1)**
- Structure of the thesis

2. Material and methods

- Historic value
  - Legislation in the preservation of historic buildings
  - The categorization of interventions in historic buildings **(Article 2)**
- Service life prediction of components and assemblies
  - Climate change effect
    - Impact of climate change on cultural heritage assets
    - Risk assessment for the indoor and outdoor environment **(Article 3)**
  - Decay assessment
    - Factor method
    - The categorization of the level of decay **(Article 4)**
- Environmental assessment
  - Environmental assessment of Zero Emission Buildings
  - Environmental assessment of intervention works **(Article 2)**

3. Zero Emission Refurbishment

- The framework of the Zero Emission Refurbishment method **(Article 5)**
- Application to a case study **(Article 6)**
- Discussions

4. Conclusions and future works

- Conclusions
- Recommendations for future works

5. Bibliography

6. Appendix

2. MATERIAL AND METHODS

2.1. Historic value

2.1.1. Legislation in the preservation of historic buildings

The first approach when dealing with actions in the existing built environment is to use the current regulations and laws as a basis for planning of interventions that preserve the cultural heritage value (Tweed and Sutherland 2007). Based on the value that they represent, historic buildings have different protection statuses which can be of an international, national or local level. The international institutions (UNESCO, ICOMOS, etc.) deal mainly with the conservation of the outstanding buildings (the so-called monuments) which have specific protection status and huge restriction for change.

At the national level, the institution that is responsible for the management of the cultural heritage of Norway is the Directorate for Cultural Heritage (*Riksantikvaren*). The legal basis for the management of the national patrimony is described in the Cultural Heritage Act (*Lov om kulturminner*), with the general aim to protect archaeological and architectural monuments and sites, and cultural environments in all their variety and detail (Directorate for Cultural Heritage 2020). Under the terms of the act, all the tangible cultural heritage (buildings, tools, objects, etc.) before the year 1537 are automatically protected by the law while those dating from 1537 onwards require a protection order, which is granted on a case-to-case basis (Ministry of Climate and Environment 1978).

Another act governs the monuments and sites of Norway at a municipal level, known as the Building and Planning Act, which ensures that the preservation of the cultural heritage is considered in all planning processes of the municipalities (Ministry of Local Government and Modernisation 2008). Under this act, the local government is responsible for ensuring that the historic, architectural or any other cultural value will be retained as much as possible when any rehabilitation or renovation work is done.

Besides, every municipality in Norway can take political decisions and list the cultural heritage or cultural environments inside the municipality. The list includes both the patrimony protected by the Cultural Heritage Act (*Fredet*) and the ones that are not in the national list (Directorate for Cultural Heritage 2020). Furthermore, every municipality can create its marking system of their cultural heritage buildings which is developed from the Cultural Heritage Management Office (*Byantikvaren*).

One of the most detailed lists in Norway is compiled from the Municipality of Oslo known as the Yellow List (*Gul Liste*) (Oslo Kommune 2020). It provides an overview of the cultural monuments and environments of the capital, and it is the tool used from the *Byantikvaren*'s office for the preservation of the city's history. The list is not intended to be final, but it is in constant change with different buildings that are inserted in it. The buildings are divided into three main protection categories: protected under the Cultural Heritage Act (*Fredet*), protected by regulation under the Building and Planning Act (*Vernet*) or listed from the municipality (*kommunalt listeført*). In the online map of the municipality of Oslo, the categories are coloured with three different colours as below:

- Red stands for protected buildings under the Cultural Heritage Act (*Fredet*). This category encompasses the buildings with national historic value, and it is the strictest form of protection for cultural monuments and environments. Typically, the preservation status includes both interior and exterior of the building; however, the list describes the objectives and limits for each voice, making a clear overview of what the protection covers. Interventions in such category of buildings (even of low-level such as new paint or change in colour) require and approval from the *Byantikvaren* office.
- Orange stands for buildings protected under the Building and Planning Act (*Vernet*). There are specific rules for this category of buildings related to their particular area. The municipality sets the limits of what can be allowed to change to existing buildings and the type of new buildings that can be built within the area.
- Yellow stands for municipal listed buildings (*kommunalt listeført*), which is the largest group of buildings on the list. The members do not have formal protection status, but they are listed as conservation worthy. This group is created from the *Byantikvaren*'s office, and it does not pose restrictions for the buildings because the decision for changes is ruled by the Planning and Building Act. Once a building is registered to the Yellow List, all documents regarding construction projects are forwarded to *Byantikvaren*'s office which may submit an advisory statement regarding the project.

Figure 2.1 shows an extraction from the online yellow list map of the Municipality of Oslo.

Figure 2.1. Example of the classification map of the Oslo municipality (extracted from (Oslo Kommune 2020))

The list of the cultural environments of Norway, especially the ones protected under Cultural Heritage Act (*Fredet*), is publicly available through the tool named *Askeladden* (Directorate for Cultural Heritage 2020), where the access needs to be granted, or through *Kulturminnesøk*, an open-access webpage with information compiled from multiple sources in addition to *Askeladden* and the Yellow List (Directorate for Cultural Heritage 2020).

A similar categorization system as in Oslo is applied to buildings in most of the municipalities of the country, with small differences related to the local circumstances. In the Municipality of Trondheim, apart from the listed buildings (marked with letter F), there is a large number of protected buildings (*Vernet*) which are categorized in three main groups (A, B and C) according to the value that they represent (Trondheim Kommune 2020). This classification mainly includes the buildings built before 1960, and it is set by external survey and inspection on the properties. Together with historic data, the Trondheim municipality provides useful information for the buildings about the laser data and basic vector data (the type of building, year of construction, usage status, material, area, number of floors, spatial coordinates, etc.) through the Maps and Surveying Office (Trondheim Kommune 2020).

In Figure 2.2, it is shown an example of the historic value categorization of the buildings according to the municipality list.

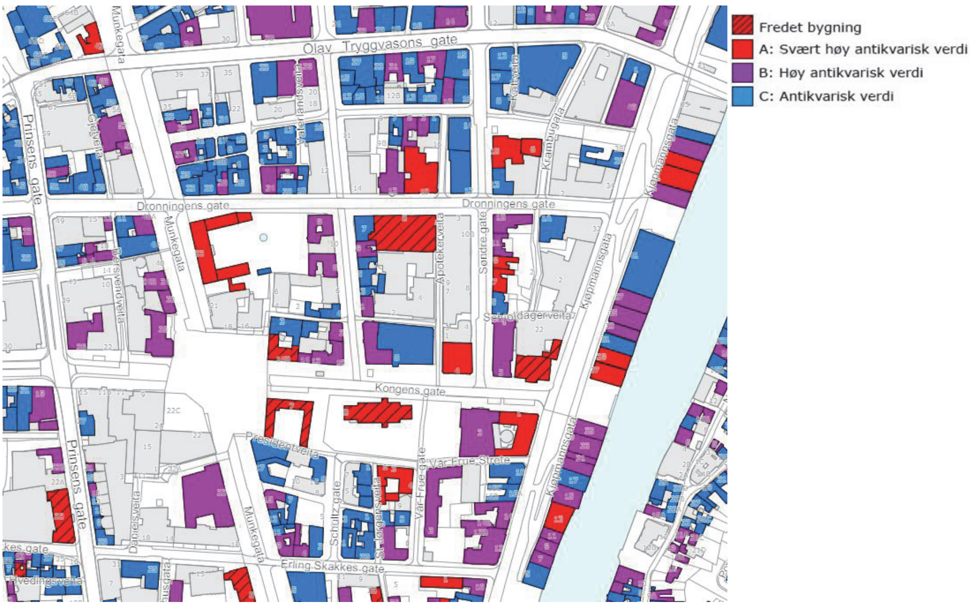


Figure 2.2. Example of the classification map of the Trondheim municipality (extracted from (Trondheim Kommune 2020))

In category A and B fall the buildings that are rare in one or many ways. For being so, the building:

- is and always has been entirely or almost unique,
- has been instrumental in introducing a new direction in the field of construction,
- belongs to building types that used to be common but now are almost disappeared,
- is rarely well-preserved,

- is considered eligible for particularly caring care because of their current or past use, or association with persons or events.

On the other hand, category C encompasses buildings and facilities that have historic value to some extent (similar to the ones coloured in yellow to the Yellow List of Oslo). It is the category with the more significant number of the buildings, and many of them are included because of their value as part of the existing built environment (Trondheim Kommune 2020).

Further interdisciplinary developments (e.g. DIVE method (Reinar et al. 2010)) has been applied from the municipality of Trondheim on some historic buildings to have an overview about the capacity for change in these buildings and type of the interventions allowed to them (Trondheim Kommune 2016).

The categorization of the built and cultural environment is flexible, and many countries and cities use different scaling systems to categorize their buildings. However, experts in regions with similar climatic conditions and architectural attributes encourage the participation in interdisciplinary, international projects and emphasize the importance of collaboration between built cultural heritage professionals and decision-makers for unifying the assessment of historic buildings' values (National Board of Antiquities 2006, Reinar and Riksantikvaren 2009).

2.1.2. The categorization of interventions in historic buildings

The overall classifications of the built environment from administrative institutions (as examples in the above paragraph) provide useful and necessary information to a broad audience, especially the buildings' owners, urban planners, architects, researchers and historians. Besides the categorization scale (represented by a letter or colour code), it is essential to know the level of change for the buildings in each group, i.e. the types of interventions that are allowed and the restrictions or attributes that should be preserved.

An intervention, by definition, is any type of action other than total demolition or deconstruction which can be applied to an existing building when the components or assemblies show signs of weakness, deterioration or hazardous conditions (e.g. fabric preservation) or have a decrease in performance (e.g. energy efficiency and comfort conditions) (Bertolin and Loli 2018). A comprehensive survey of definitions of the most used interventions in the existing buildings, with a particular focus to historic ones, is performed. The set represents the actions that cause a physical change to components or assemblies of the buildings and that are generally applied when the element is approaching or exceeding the end of the service life. The survey is conducted analysing the most relevant reports produced from the European Committee for Standardization that are focused on the preservation of the cultural environment (European Committee for Standardization 2011, European Committee for Standardization 2012, European Committee for Standardization 2017, European Committee for Standardization 2017, European Committee for Standardization 2017).

The set of all possible interventions that can be applied to existing buildings, with a special focus on historic buildings, is given in Table 2.1 and it serves as a milestone for the delicate process of identification and characterization of the allowed interventions in historic buildings. This outcome is given in the third column of the table and grouped in three different colours according to the possibility of application (Y = yes; N = no; Y/N = yes/no). The allowed interventions depend on the scale of protection of the building and must retain it in conditions to perform its function and maintain its heritage significance. The identification and characterisation were made through an extensive literature review on the conservation measures and actions aimed at safeguarding the built cultural heritage and its significance (Avrami et al. 2000, Clark 2001, De la Torre and Throsby 2002, Oxley 2003, Wood and Oreszczyn 2004, Rose 2005, Sedovic and Gotthelf 2005, Feilden 2007, Drury et al. 2008, Watt 2009).

Table 2.1. Definitions of interventions applied in the performance management of existing buildings.

Type of intervention	Definition of intervention	Application to historic buildings
Preservation	Act/process of applying measures necessary to sustain the existing materials, form, and integrity. It is part of the ordinary maintenance, and it includes indirect measures, e.g. monitoring as a process of measuring, surveying and assessing the material properties and factors of the environment which may change over time.	Y - It recognizes the historic building or an individual component as a physical record of its time, place and use, protecting its heritage value and keeping it in a proper state (Feilden 2007).
Conservation	Action/s applied directly on a building fabric to prolong its life without the loss of authenticity and significance (Feilden 2007). It includes preventive and remedial conservation, thus involving both maintenance and stabilization interventions.	Y – Interventions are aimed at safeguarding the character-defining elements so to retain its heritage value and extend its physical life. Interventions have to be physically and visually compatible and identifiable through inspection and documentation. Chemical or physical treatments, if appropriate, have to be as gentle as possible.
Maintenance	Routine, cyclical, non-destructive interventions (i.e. combination of technical, administrative, and managerial actions) applied during the lifecycle of a building to secure its uninterrupted use at the desired level of activity (Feilden 2007). It includes both preservation and preventive conservation actions.	Y – Maintenance aims at sustaining the historic building in an appropriate condition, to retain its significance, to slow the deterioration and slightly increase the performance level. It entails periodic inspection, routine, cyclical non-destructive cleaning, and refinishing operations.
Repair	Action applied to a building or part of it to recover its functionality and its appearance (original condition). Minor repairs of damaged or deteriorated materials can be part of maintenance.	Y/N – In historic buildings, the repair is generally viewed as a remedial conservation intervention to recover functionality and the appearance of deteriorated materials. It must be preferable before replacements and based on evidence, to respect heritage significance. In case of the use of new materials, they have to match the old in composition, design, colour and texture.

Refurbishment	Action that modifies an existing building to bring it to an improved, acceptable condition. It includes both alteration and intervention, i.e. facelift or refit to the envelope to enhance its appearance, function, or extensive actions to reach modern standards (e.g. energy retrofitting).	Y/N - Refurbishment in a historic building is allowed when respect the construction techniques, material or heritage significance. Any exterior alteration/ new addition needs to be distinguishable and compatible with historic materials, features, size, scale and proportion.
Rehabilitation	Act or process of making possible a (new) compatible use for a property. It can include elements of modernization as well as some extension works with even significant structural alterations.	Y/N –Rehabilitation of a historic building has to keep unchanged the function or propose a contemporary use compatible with its heritage value. It has to interpret the property value with a minimum change to its distinctive materials, features, and spaces.
Renovation	Action, driven by law/regulations requirements, to upgrade of components, elements and systems (including energy efficiency) to the today`s level. It can include stabilization and consolidation works as damp proofing measures and timber treatments.	Y/N – Renovation to upgrade a historic building up to the today`s comfort levels is generally not a conservation action as it cannot respect its significance. Modern materials and technical installation cannot be compatible with original fabric, finishing, character-defining features and original energy performance.
Restoration	Action to bring the existing building back to a former condition. It is usually restricted to derelict or ruinous buildings. It can include substantial reconstruction works of parts of the building.	Y/N – Restoration of a historic building involves the risk of loss of the historic and artistic value due to the modification of character-defining features. When protecting its heritage value, the restoration reveals and recovers the state of a = building or component as it appeared at a particular period in its history. Still, it can also result in the removal of features from previous historic periods.
Replacement	Construction action to replace an entire character-defining feature with new material because the level of deterioration or damage of the existing materials excludes repair. The operation can be in connection with a change of use or an upgrade of the building.	N – In a historic building, the replacement of a character-defining feature, of intact or repairable material is not allowed. Replacement becomes a conservation action when the material is reused after replacement.
Demolition	The action of removing existing materials and/or parts of the building. It cannot be defined as an intervention, i.e. a physical change or alteration of a building.	N – Demolition is an option that cannot be considered for a historic building because all the efforts to retain its historic, artistic, cultural and social values have to be guaranteed over time.

The interventions in Table 2.1 can also be divided into two main categories: maintenance and adaptation, which are referred respectively:

- Maintenance is considered any type of intervention that maintains performance as it is and is applied to historic buildings to retain the value embodied in the historic fabric,
- Adaptation is any kind of work to the building beside maintenance which changes its function, capacity or performance.

Demolition is not a permitted measure for historic buildings; however, it is included in the table because it may be applied in some exceptional circumstances, especially when the safety of the structure is compromised.

The whole set of interventions that can be applied to existing buildings during their performance management process and shown in Table 2.1 can also be visualized in a schematic form (Figure 2.3) (Douglas 2006). Regarding historic buildings, all maintenance interventions (blue colour) are allowed while concerning adaptation interventions, only those labelled in red can be applied if they respect the conservation requirements and guarantee the historic value.

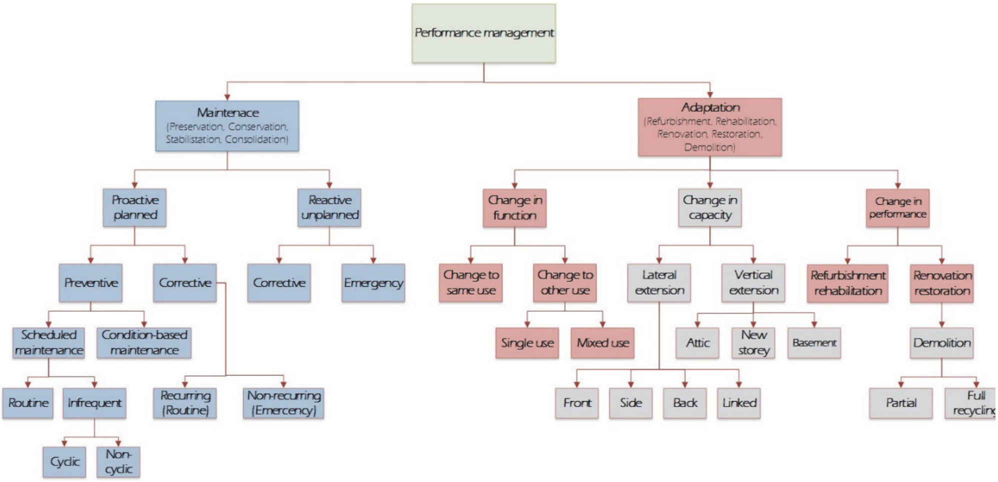


Figure 2.3. Set of interventions that can be applied to an existing building. All types of maintenance interventions can be applied to historic buildings (blue) while only ones in red can be applied during adaptation actions (Douglas 2006)

Usually, both maintenance and adaptation are applied when an existing building is below its minimum acceptable standard, either to increase its condition up to its original status or to achieve an optimal standard (e.g. increase the energy efficiency). This judgement is not always possible for historic building due to restrictions deriving from legislative protection and the need to preserve unchanged their character-defining features and significance.

Summary 2.1.

Heritage buildings are a non-renewable resource of our identity and continuity; therefore, the preservation of their significance should be the driving factor during the decision-making processes for interventions on them. To ensure such, international and national institutions establish regulations and laws which serve as a basis for planning the intervention works according to the value that needs to be safeguarded. The diverse classification systems of the built environment provide important information for the stakeholders regarding the allowed interventions, restrictions and attributes that should be preserved.

In this context, a comprehensive survey of definitions of the possible interventions in existing buildings, with a special focus to historic ones, is performed. While all types of interventions can be applied to an existing building, the allowed interventions in a historic building depend on the level of protection of the building and on the warranty of preserving its heritage significance. The set of interventions serves as a milestone for the delicate process of identification of the permitted maintenance and adaptation actions in historic buildings, which aim to preserve or improve the existing character-defining features.

2.2. Service life prediction of components and assemblies

2.2.1. Climate change effect

2.2.1.1. Impact of climate change on cultural heritage assets

Climate change is one of the biggest challenges that our society is facing in recent decades, with its impact not only limited to the temperature increase (Vautard et al. 2014). Long-term climate projections have demonstrated that the planet will face a significant change of annual precipitations, floods, sea level, winter snow cover, number and size of glaciers, etc. (Intergovernmental Panel on Climate Change 2007). Special attention is given to the impact of climate change on the buildings and cities where most of the daily human activities occur (Roaf et al. 2010). The topic gains extra importance when the research is concentrated on how climate change affects the built cultural heritage (Fatorić and Seekamp 2017). Therefore, it is crucial to know how the new climate will affect the indoor environment of such structures for assuring proper management of them (CLIMATE FOR CULTURE 2014).

To investigate the potential impact of climate change on historic buildings and their interiors, a large-scale integrated EU-Project named CLIMATE FOR CULTURE was launched by linking high-resolution regional climate models with building simulation tools in order to produce projections of future indoor climates in historic buildings (CLIMATE FOR CULTURE 2020). The goal of the project was to inform the stakeholders about the imminent climatic risks and to propose effective adaptation and mitigation strategies for preserving at best our precious cultural assets in the long-term future. The project provided 55,650 climate and risk maps that identify the most urgent outdoor risks for Europe and the Mediterranean region until 2100 as well as risks for indoor historic artefacts. The maps, through the colour codes, show the level of risk, both for outdoor and indoor environments, for 16 building types and 19 environmental variables.

The results of the project can be used to understand how the climatic changes affect the buildings in natural conditions (without the use of mechanical indoor heating, ventilation, and air conditioning (HVAC) systems) regarding their geographical location, building size, window size, and constituting material. In the CLIMATE FOR CULTURE project, the general assessment and map creation process has been carried out using the following specifications:

- **Emission scenario**

The impact of climate change on historic buildings was evaluated using the high-resolution regional climate model REMO which provides climate change projections for entire Europe at 12.5 km spatial resolution (Jacob et al. 2012). Two emission scenarios were applied in the project. The first is the mid-line A1B scenario, which considers a CO_2 emission increase until 2050 and a decrease afterwards (Intergovernmental Panel on Climate Change 2000). The second is the more recent Representative Concentration Pathway 4.5 Emission Scenario (RCP4.5) of the IPCC assessment report 5 (AR5) (Intergovernmental Panel on Climate Change 2013). This scenario is based on long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover, which stabilizes radiative forcing at 4.5 watts per metre squared (approximately 650 ppm CO_2 equivalent) in the year 2100 without ever exceeding that value.

➢ **Locations**

Climate data assessment and simulations were calculated for a regular grid that covers entire Europe, including the Mediterranean region, as shown in Figure 2.4.

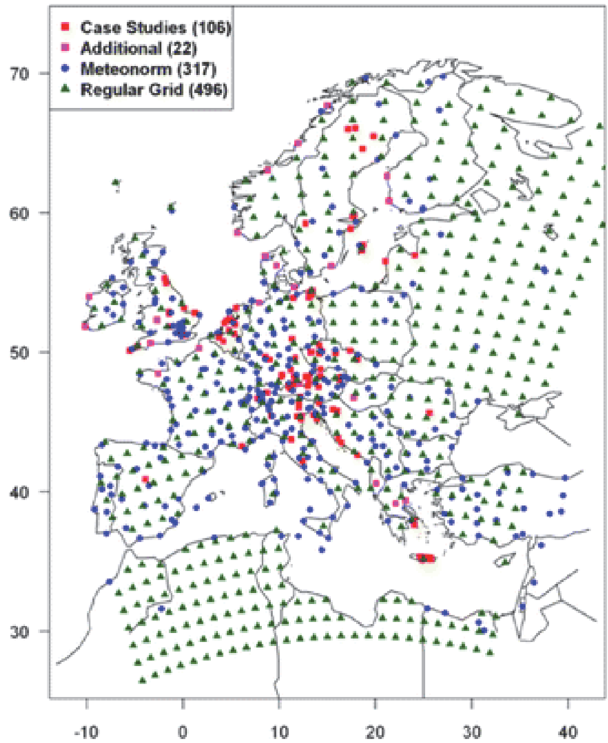


Figure 2.4. Grid of sites for which outdoor climate data are simulated (Leissner et al. 2015)

➢ **Time windows**

The climate data were produced for all the climate-induced variables from hourly data elaboration over two 30-year time windows: 2021–2050 (Near Future) and 2071–2100 (Far Future), maintaining the period 1961–1990 (Recent Past) as a reference period (Table 2.2).

Table 2.2. Time windows used for simulations in the CLIMATE FOR CULTURE project

Recent Past (RP)	Near Future (NF)	Far Future (FF)
1961–1990	2021–2050	2071–2100

- **Buildings**

Indoor climates of historic buildings were modelled and simulated following two different approaches. The first consisted of the development of a full-scale multizone dynamic hygro-thermal whole building simulation while the second used a simplified hygro-thermal building model. The first model gives more detailed results about the temperature and relative humidity inside the building, but it has a high development cost and takes long simulation time. The simplified model provides reliable results within a short simulation time. For this reason, the latest was applied in the CLIMATE FOR CULTURE project to predict the indoor temperature and relative humidity. It has the restriction to be adequate to buildings without active mechanical HVAC systems and to request all the necessary measured values for the parametrisation of the model (Leissner et al. 2015). Through this model, it was possible to perform simulations on 16 generic sacred buildings, virtually located in all grid cells, for producing indoor climate data and risk maps. The general layout of buildings is composed of a rectangular floor plan, a gable roof, and long walls in the North-South direction with windows only on the long walls. Each of the buildings is unconditioned, and their matrix is a combination of their volume (small/large), window area (small/large), structure (heavyweight/lightweight), and moisture buffering capacity (MBP) (low/high).

- **Indoor Deterioration Variables**

The variables, according to the CLIMATE FOR CULTURE results, for each mechanism of indoor deterioration (mechanical, chemical, and biological) and assigned to different building materials (wood, masonry, and concrete), are reported in Table 2.3 and Table 2.4 (Bertolin and Camuffo 2014).

Table 2.3. The main variables to estimate indoor deterioration in wooden buildings

Mechanical Damages	Chemical Degradation	Biological Deterioration
Panel (base material) Panel (pictorial layer) Jointed element Cylindrical element	Lifetime multiplier	Mould Insects

Table 2.4. The main variables to estimate indoor deterioration in masonry and concrete buildings

Mechanical Damages	Chemical Degradation	Biological Deterioration
Salt crystallization cycles Thenardite-Mirabilite cycles [1] Freeze-thaw cycles Frost days index	Lifetime multiplier Time of wetness	Mould

[1] Only for concrete structures.

A short explanation for the indoor decay-linked mechanisms, according to the CLIMATE FOR CULTURE deliverable (Ashley-Smith 2013), is given as follows:

- *The mechanical risk for wooden elements: panels, jointed, cylindrical elements*

The relative humidity (RH) of the air affects the moisture content in a wooden element. As the moisture content changes, so do the dimensions of the element, which set up internal stresses that lead to deformations. At low stresses, the wood behaves elastically, with reversible deformations while above a certain threshold of strain (the yield point), the deformation becomes plastic, the change is not reversible anymore, and the material fails. The damage functions used in CLIMATE FOR CULTURE for this type of elements are based on Martens' interpretation (Martens 2012) of studies by (Mecklenburg et al. 1998, Jakieła et al. 2008, Bratasz 2010). Different response times are used in the algorithm to smooth out the RH fluctuations in order to represent better the moisture changes experienced in the substrate of various building elements in wood. The strains induced by the expected changes are calculated, and a final assessment is made to evaluate if the resultant strain falls in the area of elastic (green code), plastic (orange code), or failure (red code) response.

- *The mechanical risk for masonry and concrete*

Salt-crystallization cycles. Damage from salt crystallization occurs at the interface between air and the object, or beneath the surface of the object. The surface gets covered by a mass of small crystals that destroy the visual integrity or disfigure the natural appearance of masonry or concrete. When this occurs below the surface, the visible result is surface disruption and loss of material. The damage function for stone weathering is studied from (Grossi et al. 2011), and predictions in the context of climate change are discussed in the atlas of NOAH'S ARK EU-project (NOAH'S ARK 2017) and reported by (Lankester and Brimblecombe 2012). The damage function used in CLIMATE FOR CULTURE project for calculating the number of cycles counts the transition that occurs in a range around 75% RH (independently from the temperature) as this is the threshold of deliquescence of the sodium chloride.

Thenardite-Mirabilite cycles. Similarly, the porous stone might be destroyed due to the pressure exerted during the transition from the thenardite (Na_2SO_4) to the mirabilite ($Na_2SO_4 \times 10H_2O$) that occurs with the inclusion of 10 molecules of water in the hydrated crystal. Mirabilite exerts a very high crystallization pressure on the porous wall causing the damage of stone. A pressure of 10 MPa occurs when the RH increases across value described by a critical $RH = 0.88 \times T + 59.1$. Repeated cycles may accumulate stress, and in the long-term, they may cause severe decay. The damage function used in CLIMATE FOR CULTURE counts the transition that occurs in the thenardite-mirabilite system and estimates a green code for up to 60 cycles, orange code for 60÷120 cycles, and red code over 120 cycles.

Freeze-thaw cycles. When water goes from liquid to solid phase within a porous masonry element or in a structural crack, it increases in volume, which can cause damaging stress. If this stress is repeated cyclically, the brick or stone becomes weaker, and eventually delaminates and spalls. The theoretical background of freeze-thaw cycles is discussed by (Camuffo 2013) and in the atlas of NOAH'S ARK project (Sabbioni et al. 2010). The damage function counts the number of cycles between $T < -3°C$ (freeze) and $T > +1°C$ (thaw) that occur in one year. The results of CLIMATE FOR CULTURE maps indicate a green code for up to 30 freeze-thaw cycles, orange code for cycles between 30 and 60, and red code for more than 60 cycles during the year.

Frosting time is considered the total amount of time (in hours) during the year when the air temperature (outdoor or indoor) is below zero degrees Celsius. The effect of frosting time over cultural heritage materials has been studied by (Camuffo 2013). Separately, this variable is not helpful to predict material damage, but it may serve as an indicator for further investigations. Frosting time can be a useful parameter in sub-zero temperature zones (many zones in the Scandinavian countries) where it determines the penetration risk of the ice front through the building wall. The level of risk according to CLIMATE FOR CULTURE maps is estimated green for up to 2400 h/year, orange for frosting time between 2400 and 4800 h/year, and red for more than this value.

- *Chemical risk*

Lifetime Multiplier (LM) is the ratio between the predicted lifetime of the material subjected to the environmental conditions and the predicted lifetime at standard conditions of 20°C and 50%RH. When LM > 1, the material will last longer than the standard conditions (green code) while for LM < 1, the rate of deterioration is greater and the lifetime shorter. The level of LM < 0.5 (half of the lifetime), is defined as the threshold of high risk and is illustrated in red.

The calculation of the LM for different types of materials is done using the equation (1) derived by (Michalski 2002):

$$LM = \left(\frac{50\%}{RH}\right)^{1.3} \times e^{\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{293}\right)} \qquad (1)$$

where RH is the relative humidity [%], T is the absolute temperature [K], Ea is the activation energy [J/mol], and R is the constant of gas (8.314 J/(mol K)).

In the calculations, the value of activation energy (the least possible amount of energy which is required to start a reaction) is considered 59.24 kJ/mol for wood and 42.5 kJ/mol for masonry and concrete. The values are taken as average because the activation energy can vary for a different range of materials. The equation does not consider the effects of very low or very high RH, but it can be a good indicator of the decay rate if the LM will increase or decrease in the future.

Time of Wetness (ToW). The biological, chemical and mechanical hazards have a high probability of manifesting themselves if the surface of the buildings remains wet for a long time. In the CLIMATE FOR CULTURE project, the time of wetness is defined as the number of hours per year in which the RH > 85% and the temperature of the surface is lower than the dew point temperature ($T_{SURF} < T_{DP}$). When the RH = 85%, the T_{DP} is around 2÷3 degrees lower than the air temperature. In general, the rough correlation is $T_{DP} \approx T - (100\text{-}RH)/5$.

ToW is a good indicator for risk evaluation as the presence of moist can generate mould growth, freeze-thaw damage and salt damage in the stone and masonry buildings. The predictions for outdoor environment estimate a decrease of around 300 hr/year from the average of about 5000 hr/year across Europe, with an exception in few western coastal areas and parts of western Russia.

- *Biological risk*

Mould growth is an extensive problem that implicates human health and the integrity of the material. The effects on heritage items can vary from light powdery dust to severe stains, which weaken and disintegrate the substrate material. It is assumed that at temperatures above 0°C and relative humidity above 70%, the mould spores can germinate. The rate of growth depends on the climatic conditions, type of material, but also the accumulation of dirt and dust in case of inorganic materials. The maps of CLIMATE FOR CULTURE have been developed using the Sedlbauer isopleths system (Sedlbauer 2001). They consider a growth rate of less than 50 mm/year as safe (green), a growth rate between 50 and 200 mm/year as possible damage (orange), and an annual growth rate greater than 200 mm as damage (red).

Insects can be another cause of damage to heritage items. The damage can be caused by certain moths and beetles such as longhorn beetle, deathwatch beetle and some forms of insects such as carpenter ant, termite, silverfish, booklice. The risk of damage from insects depends on relative humidity for some species and temperature for most insect types. The critical factors in assessing risk are climatic conditions, type of insect, and the vulnerability of the organic material such as wood. The insects' activity is present in temperatures of 5÷30°C, but below 15°C, their damage is limited (Child 2013). The results for the CLIMATE FOR CULTURE project have been achieved by calculating the annual degree-days over 15°C ((days × (T−15)) with RH > 75% and T < 30 °C for humidity dependent insects and T < 30°C for temperature-dependent ones.

- **Outdoor Deterioration Variables**

In Table 2.5 and Table 2.6 are given the variables of each outdoor deterioration mechanism for different building materials (wood, masonry, and concrete) (Bertolin and Camuffo 2014).

Table 2.5. The main variables to estimate outdoor deterioration in wooden buildings

Mechanical Damages	Chemical Degradation	Biological Deterioration	Energy Demand	Extreme Events
Frosting time Dry days index Wet days index		Mould Insects	Tropical days	Heavy precipitation

Table 2.6. The main variables to estimate outdoor deterioration in masonry and concrete buildings

Mechanical Damages	Chemical Degradation	Biological Deterioration	Energy Demand	Extreme Events
Salt crystallization cycles Thenardite-Mirabilite c. [1] Freeze-thaw cycles Frosting time Dry days index Wet days index	Time of wetness	Mould	Tropical days	Heavy precipitation

[1] Only for concrete structures.

Some of the variables are the same as for the indoor risk and are explained in the above paragraph. For the decay-linked mechanisms that are linked with the outdoor environment, a short explanation according to the CLIMATE FOR CULTURE deliverable D4.2 (Ashley-Smith 2013) is given as follows:

- *Mechanical risk*

Dry days index shows the maximum number of consecutive days in a month with the amount of rainfall lower than 1mm. In general, dry weather is a good opportunity to visit heritage properties, although, in long term perspective, an unusual number of dry days can put the buildings in risk. This risk is mainly due to the dry out and shrinkage of the soil in the foundations that can cause inclination, subsidence or cracks in the structure. Moreover, a long period of dryness can be favourable for catastrophic events such as wildfires and dust storm. The risk from dry days is not the same in all the locations. It is considered that 15 consecutive dry days can be risky in areas with usual high precipitations but normal for the buildings located in the Mediterranean region.

Wet days index is the opposite of the dry days' index. It shows the highest number of consecutive days in a month where the amount of rainfall is higher than 1mm. A high number of wet days leaves the material wet for a long time, and this puts in action other chemical and biological decay mechanisms. Significant consecutive rainfall days pose in risk directly the building's material and indirectly through the soil around them. A wet soil distends, the water cannot be absorbed from the soil, and the risk of floods is more eminent. In practice, wet days can be useful for inspection visits to detect leakages and damages caused by rainfall. The wet days' index should be linked with the amount of the total precipitation for a better evaluation of the risk and damage in the areas.

- *Energy demand risk*

Tropical days index measures the number of days per month or year with the minimum temperature higher than 20°C. This index is not substantial in some parts of northern Europe but the presence of high temperatures for a long time in the southern part of the continent can have side effects. The index does not measure the number of consecutive days but merely the number of days with the $T > 20°C$; therefore, it cannot be related to the heatwave effect. However, a significant number of days with temperatures higher than the usual increases the demand for cooling and therefore for energy supply, especially in heavyweight buildings which do not tend to cool down fast due to the thick wall sections. A high number of tropical days increases the chances for wildfire and tropical thunderstorms with the consequence of heavy precipitations. The index does not have a universal threshold value, but the increase or decrease over time can serve as a useful indicator for planning sustainable measures.

- *Extreme events risk*

Heavy precipitation index measures the number of days per month or year with daily precipitations higher than 10 mm. Heavy rainfall days increase the probability of infiltration of water into buildings, either directly into the materials or indirectly through overloaded sewage systems. The number of heavy rain days is not necessarily linked with the amount of rainfall. Therefore, it cannot be used alone to predict the material damage, even if the number of days with heavy precipitation increases. However, high and continuous precipitations increase the risk of flash and flooding. The same as for the tropical days, the heavy precipitation index has no universal risk threshold, so the most helpful outcome is the trend over time.

2.2.1.2. Risk assessment for the indoor and outdoor environment

➢ **Future indoor and outdoor climates**

The results of the CLIMATE FOR CULTURE project are a useful tool for the cultural heritage managers to plan efficient and effective adaptation and mitigation strategies for sustainable preservation of these invaluable cultural assets in the times of climate change. The outdoor climate influences the cultural heritage structures, both in terms of outdoor and the indoor environment (Leissner et al. 2015). The main scope of the project was the estimate the impact of climate change in the indoor environment, which is driven by the change in the outdoor climate (Ashley-Smith 2013). These predictions, linked with building simulations allow the estimation of indoor and outdoor climate variables (temperature T, relative humidity RH) and indoor and outdoor damage variables for mechanical, chemical and biological decay using automated methods (Huijbregts et al. 2015). The values of climate and damage variables serve as a basis for the assessment of risk in the indoor and outdoor environment.

The risk induced indoor and outdoor by climate change is assessed by the combination of indoor and outdoor climate data with the damage functions of the variables. The assessment tool presented here is a general tool which evaluates the decay level for the building materials indoors and outdoors. To do such, the values of the damaged variables explained in Section 2.2.1.1 obtained from the CLIMATE FOR CULTURE projections, will be used as input to assess the deterioration level of different building materials. The level of decay for each variable is divided into six category levels: very low, low, medium, medium-high, high, and very high. The threshold values for each decay level are established from the description of the variables in the CLIMATE FOR CULTURE deliverable (Ashley-Smith 2013) and the colour code of the risk maps from the project output which considers the likelihood and the impact of the decay (Loli and Bertolin 2018). The boundary values for each level of indoor and outdoor variables are given in Table 2.7.

Table 2.7. The table of risk assessment for the main deterioration variables

Variable name	Unit	Very Low	Low	Med.	Med.-High	High	Very High
Panel—base material	[-]	0.333	0.667	1	1.333	1.667	2
Panel—pictorial layer	[-]	0.333	0.667	1	1.333	1.667	2
Jointed element	[-]	0.333	0.667	1	1.333	1.667	2
Cylindrical element	[-]	0.333	0.667	1	1.333	1.667	2
Salt crystallization cycles	[no/year]	30	60	90	120	150	180
Thenardite-Mirabilite cycles	[no/year]	30	60	90	120	150	180
Freeze-thaw cycles	[no/year]	15	30	45	60	75	90
Frosting time	[h/year]	1200	2400	3600	4800	6000	7200
Time of wetness	[h/year]	1200	2400	3600	4800	6000	7200
Dry days index	[days/month]	3	6	9	12	15	18
Wet days index	[days/month]	3	6	9	12	15	18

Tropical days index	[days/year]	15	30	45	60	75	90
Heavy precipitation index	[days/year]	15	30	45	60	75	90
Lifetime multiplier—Wood	[-]	1.5	1.25	1	0.75	0.5	0.25
Lifetime multiplier—Masonry	[-]	1.5	1.25	1	0.75	0.5	0.25
Lifetime multiplier—Concrete	[-]	1.5	1.25	1	0.75	0.5	0.25
Mould growth	[mm/year]	25	50	125	200	400	600
Insects—humidity dependent	[DD/year]	500	1000	1500	2000	2500	3000
Insects—temp. dependent	[DD/year]	500	1000	1500	2000	2500	3000

The risk assessment in the table above is given for the outdoor and indoor damage variables. For climate variables (temperature and relative humidity), the risk assessment is done using the threshold values provided from the standard EN 16893:2018 (European Committee for Standardization 2018) as follows:

- **Indoor environment**

Temperature: The reference temperatures are taken from the standard regarding the relative risk of damage and deterioration due to temperature. In heated buildings, the human comfort range varies between 18°C and 25°C, while the lower limit for human occupation in the workplace is 16°C (13°C if much of the work is physical). Regarding the unheated buildings, there is an increasing risk of frost damage to the building structure, frozen pipes, etc. below 0°C, so a 5°C limit is a precautionary lower limit based on expectations of spatial and temporal variation.

Relative Humidity: The range values of relative humidity are also taken from the standard EN 16893:2018 regarding the relative risk of damage and deterioration due to relative humidity. According to it, below 30% RH, the risk of damage to organic materials by mishandling is increased despite the reduced rate of chemical degradation. On the other hand, for RH values above 70%, mechanical stability decreases for some materials.

- **Outdoor environment**

Temperature: Temperature is not a dominant factor in outdoor degradation reactions. The degradation functions of stone and masonry buildings do not depend on temperature, but its effects are relevant for wooden buildings because the temperature increase causes the presence of fungi. According to the CLIMATE FOR CULTURE, the most significant feature of the predicted outdoor temperature increase is its effect on indoor temperatures.

Relative humidity: According to the CLIMATE FOR CULTURE, the RH, in general, will be increased in the future. However, due to the simultaneous rise of the temperature in the atmosphere, this change is not significant. More specifically, the increase of the RH slightly influences the damage functions and mechanisms that depend on RH, such as time of wetness and salt crystallization cycles.

2.2.2. Decay assessment

2.2.2.1. Factor method

Buildings are prone to changing requirements over long periods, and it is imperative to work with the time rather than against it. For this reason, the estimation of service life (ESL) is an essential process before interventions that should be applied to structures of any type. Given the complexity of structures and materials, it is of primary importance to set up generally applicable methods using basic data and adapting these to different applications, exposure and user conditions (Brand 1995). There are many ways for calculating the ESL. According to the report "Performance-based methods for service life prediction" (Hovde and Moser 2004), the methods have been divided into two major groups: factor methods and engineering design methods. The application of the methods estimates the service life for a component or assembly (in years) together with its uncertainty by considering specific technical conditions (International Organization for Standardization 2011).

The framework of the factor method for service life estimations is given in the ISO 15686-8:2008 standard (International Organization for Standardization 2008). According to the factor method, the service life (in years) is calculated by multiplication of a reference service life (*RSL*) with different modifying factors, which consider the deviation from reference conditions based on the following equation:

$$ESL = RSL \cdot f_A \cdot f_B \cdot f_C \cdot f_D \cdot f_E \cdot f_F \cdot f_G \qquad (2)$$

where *ESL* = estimated service life; *RSL* = reference service life; f_A = factor A: quality of components; f_B = factor B: design level; f_C = factor C: work execution level; f_D = factor D: indoor environment; f_E = factor E: outdoor environment; f_F = factor F: in-use conditions; and f_G = factor G: maintenance level.

Factor method is a useful tool for evaluation and comparison of the lifetime of the components and assemblies, and it is in continuous improvement through new definitions of the necessary input data for RSL and factor values. In the process of service life prediction, main attention it is given to the valuation of the RSL as well as the estimation of the value of each of the factors. According to the ISO standard, the specific values of each of the factors are independent of each other, and it should be aware that the components are not mixed or taken into consideration multiple times. Below is given a short overview of the method as specified in the standard:

➢ **Description of the factors**

- *Factor A – inherent performance level*

The factor expresses the grade of the component as supplied. It represents the quality of the material itself or treatment which has been applied on the material for protection against atmospheric agents.

- *Factor B – design level*

The factor expresses the installation level of the component in the building. It is focused on the techniques of the design selected from the developers of the building as well as techniques of protection from weather agents, e.g. shelters, coatings, etc.

- *Factor C – work execution level*

The factor expresses the level of skill and control over the construction site. It considers the qualification scale of the workers at the site and the compliance of construction works according to the recommendations from manufacturers, technical safety regulations, material storage, ease of installation, etc.

- *Factor D – indoor environment*

The factor takes into account the exposure of the material/component to indoor agents of degradation and their severity. It considers all the different agents that affect the lifetime of the internal material/component. For many components, only indoor or outdoor environment influences the degradation; however, for specific components, especially the ones in the building envelope, both internal and external agents should be considered.

- *Factor E – outdoor environment*

The factor expresses the exposure to outdoor agents and their severity. It depends on the environmental conditions of the building's location. The value is set by considering all the degradation agents acting on the surface of the material. Depending on the type of material (wood, stone, masonry, etc.), different factor values can be assigned even for the same location.

- *Factor F – usage conditions*

The factor reflects the effect of the use of the building. The type of building and the flux of people defines the scale of wear and tear on the indoor material and components. Regarding outdoors, the type of the activities outside (adjacent) to the building (e.g. road with traffic density, delivery areas, etc.) can induce mechanical impact to the structure.

- *Factor G – maintenance level*

This factor expresses the level of maintenance assumed. The factor considers the accessibility to the areas which require special equipment for access (ladders, framework) as it can make the maintenance less frequent. Also, the type of ownership of the building determines the frequency and quality of the interventions.

The factor method can be applied both to single components or assemblies of them. When it is applied to assemblies, every component of the assembly together with the joints between them, should be considered.

- **Confidence interval**

In theory, each factor can take values that vary from 0 to infinite depending on the ratio between the service life of the specific component and the reference condition of it. However, in practice, it is recommended that the value of the factors is around 1 to ensure that the service life of the component in normal conditions is approximately the same as the one provided by its producer. The values of factors are set from the user of the method based on the experience, known actions, recommendations from literature, data from producers, results of testing, etc. When more than one value is found for the same factor, weighting or interpolation of data can be applied to decide the final value.

The reliability of the ESL results depends on the appropriateness of the assumptions made and quality of the input data. One of the biggest limitations of the method is the multiplication of a set of variables which increases the substantial uncertainty and therefore, it is not possible to calculate the service life of a component or the entire building precisely. However, the estimated service life together with the estimation of its uncertainty are necessary steps to be computed for achieving guide design decisions. For each ESL value calculated as a single number in years, it should be estimated a confidence interval as well (± in years) (International Organization for Standardization 2008). For the multiplication level, the confidence interval *ΔESL* is determined using the confidence intervals of all the variables of (2) as shown in (3):

$$\Delta ESL = ESL \cdot \sqrt{\left(\frac{\Delta RSL}{RSL}\right)^2 + \left(\frac{\Delta f_A}{f_A}\right)^2 + \left(\frac{\Delta f_B}{f_B}\right)^2 + \left(\frac{\Delta f_C}{f_C}\right)^2 + \left(\frac{\Delta f_D}{f_D}\right)^2 + \left(\frac{\Delta f_E}{f_E}\right)^2 + \left(\frac{\Delta f_F}{f_F}\right)^2 + \left(\frac{\Delta f_G}{f_G}\right)^2} \quad (3)$$

In practice, the confidence interval for each of the factors is considered ±50% of the deviation from the reference value of the factor. For example, a factor with value 0.9 has a confidence interval of ±0.05, while factor 1.0 has a null interval.

- **Some relevant distributions**

Any factor of the equation (2) can be expressed as a single value or a mathematical function which reflects the variance of the service life of the component within a respective factor category. In the latter case, the value of the factor is defined by means of a probability distribution or probability function. The types of distributions are established from the experts and the users of the method. For each factor, it is specified a median value, a minimum value and a maximum value. By knowing the median, minimum and maximum values and the type of the distribution, the unique shape of the function can be defined, and the value of the factor can be calculated for different percentiles using mathematical formulas or software applications. In practice, three percentiles are usually calculated (5%, 50% and 95%), following the suggestions of the ISO 15686-8:2008 standard. The most used fraction (50% of the value) expresses the mean value, while 5% and 95% fall respectively above the minimum value and under the maximum value.

- *Deterministic distribution*

In mathematics, a deterministic distribution is the probability distribution (continuous or discrete) of a single random variable as shown in Figure 2.5.

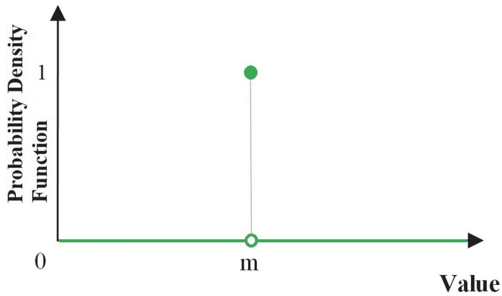


Figure 2.5. Example of a deterministic distribution

For deterministic distribution, the factor has a single possible value with a probability of 1. In this case, the percentile values are considered the same $f_{x5} = f_{x50} = f_{x95}$.

- *Normal distribution*

When the values of median, minimum and maximum are different from each other, there are needed different types of probabilistic distributions to calculate the value of the factor. The normal distribution can be applied when the median value is equidistant from the minimum and the maximum value, and it is one of the most common distributions in statistics. According to the European standard EN 1990:2002, it is assumed that the material properties follow a normal distribution unless specified otherwise (European Committee for Standardization 2002). The distribution is characterized by the values of mean μ and standard deviation σ, as shown in Figure 2.6.

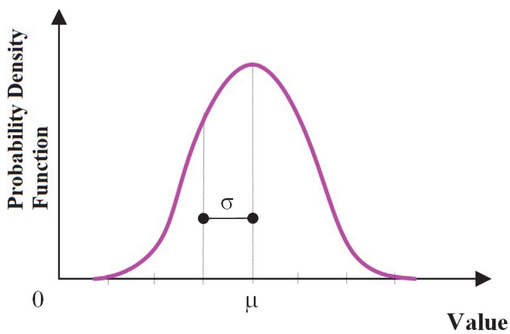


Figure 2.6. Example of a normal distribution

In this case, the mean value (50% percentile) is also the median one. The standard deviation σ is calculated as the square root of the variance of each data point x_i of the entire population n, as given in equation (4):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}} \tag{4}$$

Approximately 95% of the area under a normal distribution lies within two standard deviations from the mean value. The z-score expresses precisely how many standard deviations above or below the mean a data point is by the following equation:

$$z = \frac{x - \mu}{\sigma} \tag{5}$$

By utilizing z-score tables or software packages, different values of percentiles can be estimated. For the 5% percentile, the table gives z-score value equal to -1.65 and therefore:

$$f_{x5} = -1.65\sigma + \mu \tag{6}$$

Given the 95% probability of occurrence, the z-value score is 1.65, and the f_{x95} is:

$$f_{x95} = +1.65\sigma + \mu \tag{7}$$

- *Triangular distribution*

When the type of distribution is not defined by experts, the triangular distribution is the most straightforward shape to be applied to calculate the percentiles of the factors (Figure 2.7).

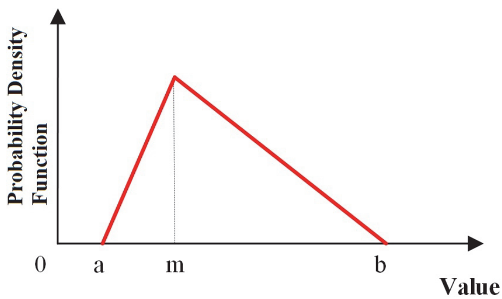


Figure 2.7. Example of a triangular distribution

The mean value is calculated as the average of the three values: most-likely, minimum and maximum as given by the equation:

$$\mu = \frac{a + m + b}{3} \tag{8}$$

Standard deviation σ is calculated utilizing the following equation:

$$\sigma = \sqrt{\frac{a^2 + m^2 + b^2 - ab - am - bm}{18}} \tag{9}$$

When employing this type of distribution, it is easy to calculate different values of percentiles using triangular ratios; however, the distribution is not widely used because the factor variations do not tend to have a linear dependence.

- *PERT distribution*

When the median value is closer to the suggested minimum or maximum value, then the curve of the distribution is asymmetric. In such cases, the experts recommend the usage of log-normal distribution which is a continuous probability distribution of a variable whose logarithm is normally distributed. This distribution is complex, and it requires a big mathematical background or usage of simulation software. To simplify the problem, the experts usually apply PERT distribution which is an alternative of a triangular distribution but with smoother shapes (Figure 2.8).

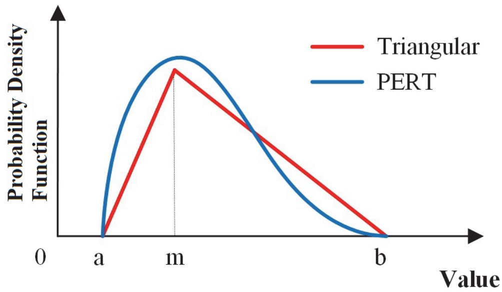


Figure 2.8. Example of a PERT distribution

The mean value μ and the standard deviation σ are calculated respectively, according to the equations (10) and (11). Different values of percentiles can be calculated using these parameters through software analysing tools.

$$\mu = \frac{a + 4m + b}{6} \tag{10}$$

$$\sigma = \frac{b - a}{6} \tag{11}$$

2.2.2.2. The categorization of the level of decay

The factor method is in continuous improvement through new definitions of necessary input data for the RSL and factor values. According to the standard, the specific values of the factors are independent of each other, and it should be aware that the components are not mixed or taken into consideration multiple times. Special attention is given where two or more agents interact or counteract, so their action does not produce a higher or smaller factor than the original case. The climate conditions, the atmospheric agents (heavy rainfall, hail, wind, etc.), the type of the landscape (e.g. risk-prone areas, vegetation, etc.) as well as the nature and frequency of activities conducted in the adjacent area (e.g. pollution, road with traffic density, delivery areas, etc.) can affect the status of building materials through similar mechanisms (e.g. mechanical decay caused by freezing-thawing cycles or crystallization-deliquescence cycles in the presence of water and salts; chemical decay caused by pollutants; biological decay caused by vegetation, mould and pest infestation; etc.).

The standard recommends that any factor which does not jeopardize the accuracy of the calculations due to small differences between the real and reference conditions should be omitted (International Organization for Standardization 2008). However, when dealing with historic buildings which carry invaluable cultural value and are sensitive to every type of change, each factor is considered important and should be considered in detail. To better underline the importance of mechanisms which influence the service life of the building envelope in historic buildings, each factor of equation (2) is further constituted by *j* number of subfactors as reported in equation (12):

$$f_i = f_{i_1} \cdot f_{i_2} \cdot \ldots \cdot f_{i_n} = \prod_{j=1}^{n} f_{i_j} \tag{12}$$

where *i* is the index of the factor (from A to G), and *j* is the index of subfactor (from 1 to n).

In Table 2.8, it is given a list of the main subfactors that are considered when evaluating the service life of assemblies in a historic building. The list has been compiled by taking into account the results of previous applications in the field (Moser and Edvardsen 2002, Silva et al. 2013, Brischke and Thelandersson 2014, Xiao et al. 2019) and risk agents that influence the indoor and outdoor environments as explained to the paragraph 2.2.1.2. The table is not exhaustive, and it can be subjected to further improvement and adaptation, according to the specific case studies.

Table 2.8. List of subfactors to be considered during the service life prediction of outer components in historic buildings

Aspect of interest	Factor	Subfactor
Inherent quality characteristics	**A – Inherent performance level**	A1 – Quality of the original material A2 – Quality of the later material A3 – Quality of the treatment *A4 – Manufacturing* [a] *A5 – Transportation* *A6 – Storage*
	B – Design level	B1 – Technique of design B2 – Sheltering B3 – Decoration B4 – Energy requirements
	C – Execution level	C1 – Level of workmanship *C2 – Implementation of the project* *C3 – Conditions of the site*
Environment	**D – Indoor environment**	D1 – Temperature (M, W) [b] D2 – Relative humidity (M, W) D3 – Freezing-Thawing cycles (M) D4 – Salt crystallization cycles (M) D5 – Thenardite-Mirabilite cycles (M) D6 – Time of wetness (M) D7 – Mould (M, W) D8 – Insects (W)
	E – Outdoor environment	E1 – Freezing-Thawing cycles (M) E2 – Salt crystallization cycles (M) E3 – Time of wetness (M) E4 – Dry days index (M, W) E5 – Frost days index (M, W) E6 – Wet days index (M, W) E7 – Heavy precipitation index (M, W) E8 – Tropical night index (M, W)
Operation conditions	**F – Usage conditions**	F1 – Type of use F2 – Flux of use F3 – Surrounding activities
	G – Maintenance level	G1 – Easy of maintenance G2 – Type of ownership G3 – Budget limitations

[a] Subfactors in italics apply to new buildings.
[b] Subfactors with index (M) apply to masonry buildings and with (W) to wooden buildings.

While inherent quality characteristics and operating conditions do not depend on the type of the material, the environmental factors (D and E) can affect the level of decay with regard on the type of material with whom they interact. The indoors and outdoors climate-induced risks manifest themselves on historical materials and components as mechanical, chemical and biological agents of deterioration, and they are represented by a set of sub-factors taken from the CLIMATE FOR CULTURE project. The values for these subfactors can be determined using the threshold values and the risk maps of the project regarding the location and type of building. In Table 2.8, the index (M) represents climate-induced decay components affecting masonry and stone buildings, while the symbol (W) for subfactors affecting wooden buildings. For building components that are estimated to live for decades, the value of ESL can be corrected by introducing a correction factor that considers the effects of climate change in construction materials. The correction can be achieved by using the results of the Near Future (2021-2050) or Far Future (2071-2100) scenarios for determining the subfactors for the indoor or outdoor environment.

Type of use and flux of persons entering the building influence directly the indoor microclimate. A high concentration of people in one room leads to change in temperature and relative humidity and therefore, influences microclimate conditions in the proximity of building materials which in turn, act on triggering indoor decay mechanisms. This activity is an important factor to be considered in historic buildings subjected to mass tourism which can be affected by direct wear of materials and by indirect decay caused by microclimate modifications. On the other hand, a no-use of the building may preserve the components from wear or tear, but it will influence their service life because of the lack of preventive conservation and scheduled maintenance. In historic buildings, the maintenance process has, therefore, significant importance because it keeps monitored the rate of decay, retains the original material in optimal status and prevents the loss of cultural heritage value extending the service life of the materials and structure in general. In most of the cases, a good practice of maintenance in historic buildings increases the cost of the action (compared with the cost of maintenance in an existing building with no significance) because of the attentive selection of materials which need to be compatible with the original ones, or the careful choice of interventions which must be reversible and implemented by craftsmen with unique expertise. This approach can be an economic barrier for most of the owners and heritage managers. Decision-makers, to minimize the risk of stacking in a “no-action” situation, should plan a range of adaption actions under different budget scenarios so that they can choose in a balanced approach between maintenance and budget (Xiao et al. 2019). Depending on the preservation target and the budget, the heritage managers should select among actions that aim to keep the estimated service life of building components the same as the reference one (preventive maintenance), to improve the service life of the component (rehabilitation) or to increase their service life significantly (renovation, restoration).

The prediction of the decay status on building components becomes, therefore, a necessary step to determine the time of the intervention action before the component or structure reaches the end of technical/functional service life. For this, the experts need to quantify the values of median, minimum and maximum for each subfactor as well as the type of distribution of them. After, different percentile values can be estimated for each subfactor, as explained in paragraph 2.2.2.1. The multiplication of all subfactors with the RSL value of the component or assembly gives the estimated service life in years. By setting a technical threshold, the calculated value is necessary to determine the time of intervention in the component before it reaches a high level of decay which would not only degrade the material but also will influence the cultural value of it. The value of the decay level becomes one of the main indicators in suggesting the time of the interventions and the frequency of their application. According to the value of the ESL in years, the status of component or assembly can be categorized to different scales of decay, e.g. low, medium or high. Logically, an estimated service life which is smaller than the reference value corresponds to a high level of decay, while a value of ESL bigger than the RSL shows a low decay level.

The framework gains more importance when it is applied to a group of buildings, e.g. in a street, block or district level. Like this, components of different buildings which have a similar value of service life can be grouped according to their decay level, and the same intervention can be applied to the same group of components.

The presented procedure gives a strong emphasis on the aspects of indoor and outdoor environments. The subfactors of these categories can be estimated by using the maps of Far Future scenario (2071-2100) by considering the climate change impact on building materials as projected by the CLIMATE FOR CULTURE project. As a result, the expected interventions will be planned by considering future climate predictions, thus increasing the accuracy in the plan of future interventions. (Figure 2.9).

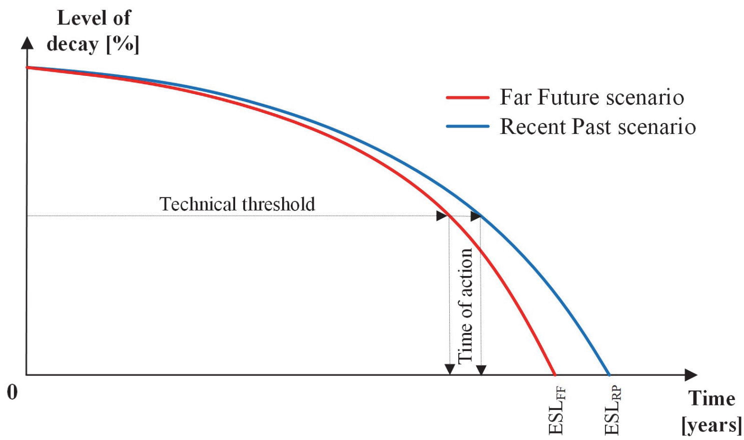


Figure 2.9. Climate change effect in the service life estimation

The factor method is a practical method to calculate the service life of new or in-use building components; however, the experts have expressed their reserves towards the method and suggest the improvement of it (Straub 2015). One of the biggest issues of the method is the difficulty to determine the factors and therefore, the uncertainty of the results. Another critique of the method is that it considers the factors independent from each other, which may not always be appropriate. However, when applying the same method (with the same marge of uncertainty) to a large built environment, e.g. a street or district level, from the results, it can be recognized the components that are in a higher risk of degradation, even though the estimation of the lifetime may not be accurate in an absolute sense. In a district scale, where the same level of inaccuracy is applied, the prediction allows the grouping of the components with similar values of service life, thus enabling the application of similar interventions to components with similar decay status.

Summary 2.2.

Buildings components and assemblies have different rates of decay over time due to the inherent characteristics of the materials, environmental conditions and operational use of them. Therefore, the estimation of service life (ESL) is an essential process to apply because it provides information about the location, time and the frequency of the intervention works one should execute before the component or assembly approaches the end of functional service life. Among different methods for service life estimation, the factor method is a suitable tool to evaluate and compare the lifetime of various components because it uses basic data and can be applied to several scenarios under different exposure and user conditions. For historic buildings, the assessment becomes an important heritage management tool since it should help to ensure both the integrity and the historic value of the materials.

In this paragraph, each mechanism which influences the serviceability of the building envelope components is highlighted by introducing a list of subfactors that constitute the elements of the factor method. The list is not exhaustive, and it can be subjected to further improvement and adaptation according to the specific case studies. With the introduction of the subfactors, the main aspects like the use of the building, type of ownership, budget limitations, design solution, adjacent area, climatic conditions, original material, level of craftsmanship, etc. are taken into consideration. The proposed factor method gains more importance when it is applied to a group of buildings because the components of different buildings with a similar service life value can be grouped together and the same intervention can be applied to the components with the same level of decay. A special focus is given to the effect of climate change on historic buildings components by presenting a new framework for the assessment of the environmental-related factors. To this purpose, the subfactors of indoor and outdoor environments can be estimated in relation to the constitutive material for three different time windows by utilizing the climatic projections provided by the European project CLIMATE FOR CULTURE; thus, integrating the effect of climate change in the tool.

2.3. Environmental assessment

2.3.1. Environmental assessment of Zero Emission Buildings

In recent years, green buildings have been the keyword of the construction industry, with several products and technologies developed to reach the demanding targets towards sustainability (Ahn et al. 2011). In particular, the international policies such as the review of the Directive 2010/31/EU of the European Commission on Energy Performance of Buildings dictate that all new buildings should be nearly zero energy buildings by the end of 2020 (European Parliament 2010). Moreover, this nearly zero amount of energy required during the operation of the building should be covered by energy from renewable sources, including the energy produced on-site or nearby in order to reach net-zero energy building. In Norway, the net-zero energy building definition is further expanded by applying a life cycle perspective. Thus, it includes not only the primary energy used in the building during annual operation but also the embodied energy (from materials, transport and construction) and end-of-life energy (from dismantling, transport and waste treatment) (Dokka et al. 2013). To achieve this, (the Research Centre on Zero Emission Buildings 2020) in Norway has developed a definition for zero emission buildings (ZEB) related to their production, operation and demolition (Andresen 2017). According to the definition of the centre, in a ZEB building, the balance is measured in terms of associated GHG emissions during the lifetime of a building instead of on direct energy demand and production (Dokka et al. 2013).

The assessment of the environmental performance of the building is performed through the European Standard EN 15978:2011 (European Committee for Standardization 2011). The calculations, based on Life Cycle Assessment analysis (International Organization for Standardization 2006, International Organization for Standardization 2006), include the building life cycle stages, as shown in Figure 2.10.

A1-3			A4-5		B1-7							C1-4				Beyond the life cycle
PRODUCT STAGE			CONSTRUCTION STAGE		USE STAGE							END OF LIFE				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manifacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling potential

Figure 2.10. Modular information of the different stages for the environmental assessment of buildings (European Committee for Standardization 2011)

According to the standard, the following stages are considered during the lifecycle of a building:

- Product Stage (Modules A1 to A3) includes the "cradle to gate" processes for the materials and services used in the construction, respectively, raw material extraction and processing (A1), transport of raw materials to the manufacturer (A2), and manufacturing of products and packaging (A3).
- Construction Process Stage (Modules A4 and A5) covers the transport processes of different construction products from the factory gate to the construction site (A4) and the practical processes for the completion of the construction works (A5).
- Use Stage (Modules B1 to B7) covers the timespan from the completion of the construction work to the time when the building is demolished. The modules include the use of construction products and services for protecting, conserving or controlling the building components (B1 to B5) and the impacts of the building-integrated technical systems and building-related furniture, fixture and fittings (B6 - B7).
- End of Life Stage (Modules C1 to C4) starts when the building is decommissioned and not intended to have any further use. The demolition process is considered as a multi-output process, and the modules include the on-site operations during the deconstruction of the building (C1), transport to disposal of the waste (C2), waste processing for reuse, recovery, recycling (C3) and/or for disposal (C4).
- Benefits and loads beyond the system boundary (Module D) are considered when components and materials that are subject of reuse, recycling and/or energy recovery, will serve as potential resources in the future (D).

The ZEB definition is characterised through a range of various ambition levels (Kristjansdottir et al. 2014, Fufa et al. 2016). The difference between them consists in the modules (and therefore, in the amount of emissions) that should be considered for compensation through renewable energy generation, as shown in Figure 2.11.

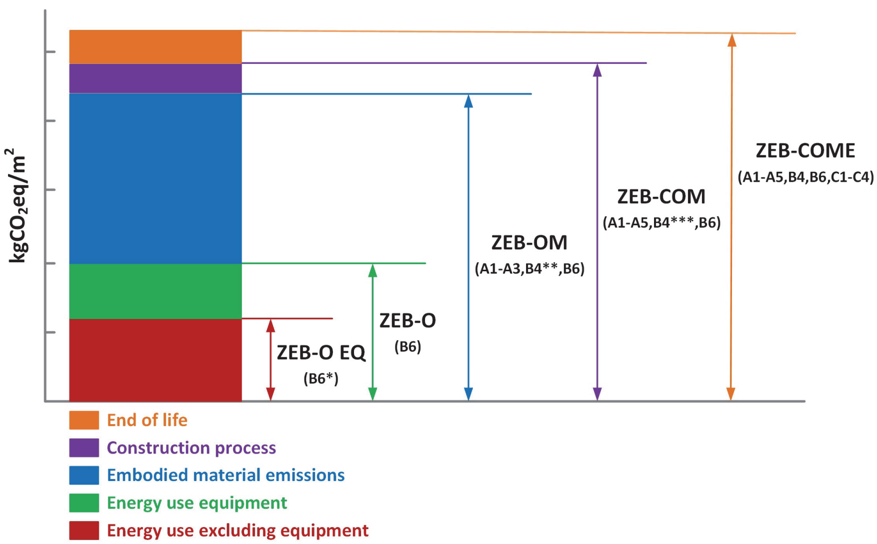


Figure 2.11. ZEB ambition levels (Fufa et al. 2016)

For new buildings, embodied and operational emissions should be compensated with on-site energy generated from renewables in order the reach the different Norwegian ZEB ambition levels as expressed by the equation (13):

$$\Delta CO_2 = CO_{2p} + CO_{2mo} + CO_{2e}(Q_d - Q_e) \qquad (13)$$

where:

CO_{2p} are the annualized **p**roduct stage emissions [kg CO_2 eq./m^2 per year],

CO_{2mo} are the annualized **m**aterial emissions during **o**peration (product stage replacement only) [kg CO_2 eq./ m^2 per year],

CO_{2e} is the averaged CO_2 eq. emission factor for **e**lectricity [kg CO_2 eq./kWh],

Q_d is the annual electricity **d**elivered to the building [kWh/m^2 per year],

Q_e is the annual electricity **e**xported to the grid from the building [kWh/m^2 per year].

The equation shows a simplified annually ZEB-OM balance focused on the Norwegian market. In other cases, the ZEB balance should be adjusted depending on the modules considered for compensation and the energy supply conditions. Figure 2.12 shows an illustration of ZEB-COME balance for a new building.

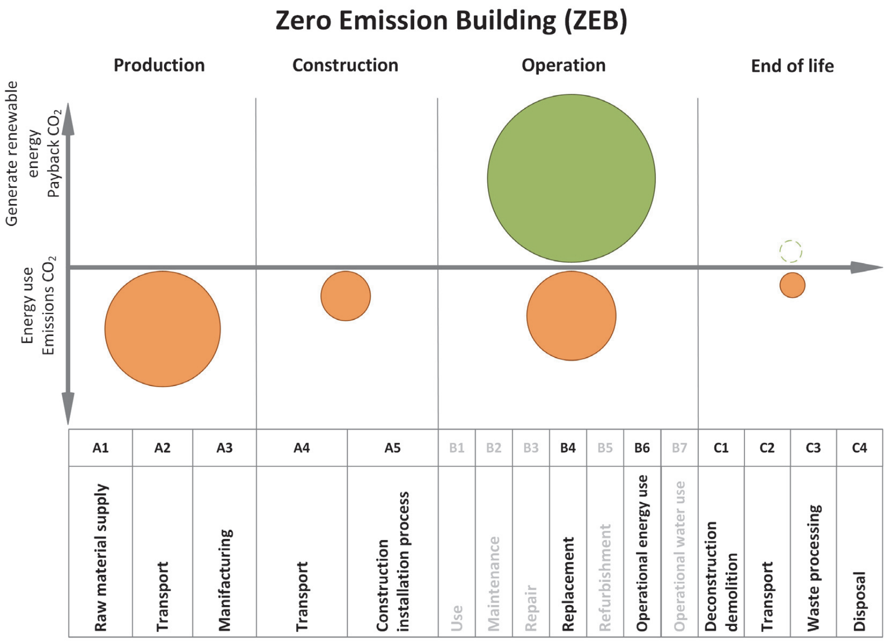


Figure 2.12. Illustration of the ZEB balance for a new building

2.3.2. Environmental assessment of intervention works

The latest report from the UN Intergovernmental Panel on Climate Change (IPCC) says that global warming poses a growing threat on natural and human systems and that its effects are being felt everywhere (Intergovernmental Panel on Climate Change 2018). To avoid such, the countries of the United Nations Framework Convention on Climate Change (UNFCCC) signed the Paris Agreement on 2015 with the main goal to keep the increase in global average temperature below 2°C above pre-industrial levels (and to pursue efforts to limit the increase to 1.5°C), recognizing that this would substantially reduce the risks and impacts of climate change (Rogelj et al. 2016). This long-term temperature goal can be reached by starting to undertake rapid reductions of greenhouse gas emissions as soon as possible.

To this aim, the construction sector, as responsible for 36% of global final energy use and 39% of energy-related carbon dioxide (UN Environment and International Energy Agency 2017), should be at the forefront of the decarbonisation process and start it sooner rather than later. In the European building sector, where about 35% of the buildings are over 50 years old, and almost 75% of the stock is energy inefficient (Buildings Performance Institute Europe 2011), the most effective cutting of emissions can be achieved by focusing at the renovation of existing buildings' stock with the long-term objective of facilitating the transformation of existing buildings into nearly zero-energy buildings (NZEBs) (European Parliament 2018). On the other hand, the legislation regarding the emissions of existing buildings is still vague although these buildings form the majority of the constructions and show the lowest sustainability scale (Mazzarella 2015).

For an existing building, the system boundary related to Life Cycle Assessment (LCA) includes all stages that represent the remaining service life and the end of life stage of the building. For a historic building, which is defined as an existing building which, additionally, manifests cultural, historical, aesthetic, social and economic values, the system boundary includes only the remaining service life of the building. The end-of-life stage is not considered as an option for this category, and it is expected to be applied when the structural stability of the building is not guaranteed. For these buildings, the end of life is considered only for particular components that need to be replaced during the intervention processes.

For reaching the sustainability goals, the historic buildings should undergo intervention measures that would enhance the historic value of the building, increase the service life of the components and, if possible, reduce the carbon footprint of them. The interventions need to follow the sustainability principles and to adopt the minimal technical interventions through principles of compatibility, reversibility and retreat-ability. The environmental impact of the intervention works is assessed by applying the LCA method to the materials and processes needed during the maintenance or adaptation works. According to the EN 15978:2011 standard, the modules that comprehend the intervention works are the modules B2 until B5, respectively Maintenance (B2), Repair (B3), Replacement (B4), and Refurbishment (B5) as shown in Figure 2.13:

A1-3			A4-5		B1-7							C1-4				Beyond the life cycle
PRODUCT STAGE			CONSTRUCTION STAGE		USE STAGE							END OF LIFE				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manifacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling potential

Figure 2.13. Stages considered for the environmental assessment of interventions in historic buildings

Module B1 encompasses the emissions during the regular use of building components, and it is not relevant during building intervention processes. For the same reason, the impacts of energy and water consumption during the normal operation of the building before the intervention (respectively B6 and B7), although high emission contributors are not taken into account. However, their values are dependent on intervention measures and decrease when adaptation interventions that improve energy efficiency are applied.

The intervention modules itself (B2 to B5) include emissions from production and transportation of new materials, the energy needed during installation processes, emissions from the end of life of components that need to be replaced, etc. With the same logic of the ZEB balance for new buildings in the equation (13), the balance of emissions during intervention actions on both existing and historic buildings is expressed by the following equation:

$$CO_{2,i} = CO_{2p} + CO_{2t} + CO_{2i} + CO_{2e} \cdot Q_{d,i} + CO_{2eol} \qquad (14)$$

where:

CO_{2p} are the emissions from the **p**roduction of new building components needed during the intervention [kg CO_2 eq./m^2],

CO_{2t} are the emissions from the **t**ransport of building components needed during the intervention [kg CO_2 eq./m^2],

CO_{2i} are the emissions during the **i**ntervention and **i**nstallation processes (cleaning, repair, replacement, construction of small components) occurred to the building [kg CO_2 eq./m^2],

CO_{2e} is the averaged CO_2 equivalent emission factor for **e**lectricity (e) [kg CO_2 eq./kWh],

$Q_{d,i}$ is the supplementary electricity **d**elivered to the building during the intervention process [kWh/m^2],

CO_{2eol} are the emissions from the **e**nd **o**f **l**ife of the removed components and ancillary products to repair or substitute [kg CO_2 eq./m^2].

The timespan of the proposed LCA equation is the time-period of the interventions process itself. The estimation of each component of equation (14) is performed using the boundaries of modules B2÷B5 as specified in the EN 15978:2011 standard. For this, the concept of the submodule is developed, and it represents a constituent part of the modules related to intervention works, as shown in Figure 2.14.

A1*-A3*			A4*-A5*		B1*	C1*-C4*			
PRODUCT STAGE			CONSTRUCTION STAGE		MAINTENANCE	END OF LIFE			
A1*	A2*	A3*	A4*	A5*	B1*	C1*	C2*	C3*	C4*
Raw material supply	Transport	Manifacturing	Transport	Construction installation process	Maintenance	Deconstruction demolition	Transport	Waste processing	Disposal

Figure 2.14. The submodules that constitute the intervention modules B2÷B5 of EN 15978:2011

The asterisk (*) symbol is used for each submodule that constitutes the modules B2-B5 as following:

- A1*÷A3* are the emissions from the production of new materials used for interventions (CO_{2p} in equation (14)),
- A4* are the emissions from the transport process of new materials during the intervention (CO_{2t} in equation (14)),
- A5* are the emissions during the cleaning, repair, replacement, and installation of new and repaired materials (CO_{2i} in equation (14)),
- B1* are the emissions from the electricity consumed from the building for constant control of chronic conditions of deterioration in order to maintain the performance of building fabric and building-integrated technical systems ($Q_{d,i} \times CO_{2e}$ in equation (14)),
- C1*÷C4* are the emissions from deconstruction, transport, waste processing and disposal during the end of life of a component that needs to be replaced, repaired, or refurbished (CO_{2eol} in equation (14)).

Three levels of intervention (low, medium, and high) can be defined in relation to the scale of action: low change interventions are called the interventions that encompass the emissions from Module B2, middle change interventions that express the emissions derived from Modules B3 and B4, and high change interventions whose emissions are calculated from Module B5.

Low change interventions (Figure 2.15) consist of maintenance works (Module B2). Depending on the scale of maintenance, the emissions can be calculated for both preventive conservation and remedial conservation actions. Preventive conservation includes the emissions during the periodical cleaning process of a building (A5*) and processes for maintaining the functional and technical performance of the building fabric and technical systems (B1*) which are shown in solid orange circles in Figure 2.15. In case of more profound interventions that require the installation of new components, the emissions of production and transportation of new materials should also be considered (A1*÷A4*) (shown with striped circles in the figure).

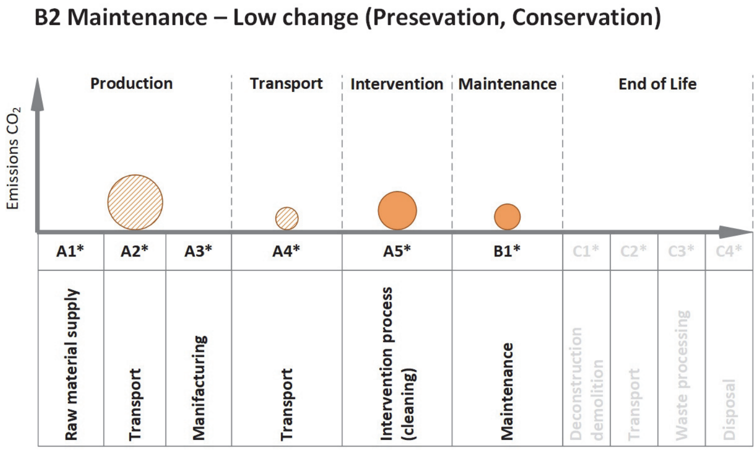


Figure 2.15. Emissions emitted during maintenance interventions such as preventive conservation (solid orange) and remedial conservation (striped circles)

Medium change interventions (Figure 2.16) refers to adaptation works, which are encompassed in the modules of repair (B3) and replacement (B4). The stages of this level include emissions during the production, transportation and installation of new materials used in the repair/replacement process (all submodules A*). During the adaptation work, some original building components may need to be substituted, so the emissions of these waste management and the end-of-life stage should also be considered (C1*÷C4*).

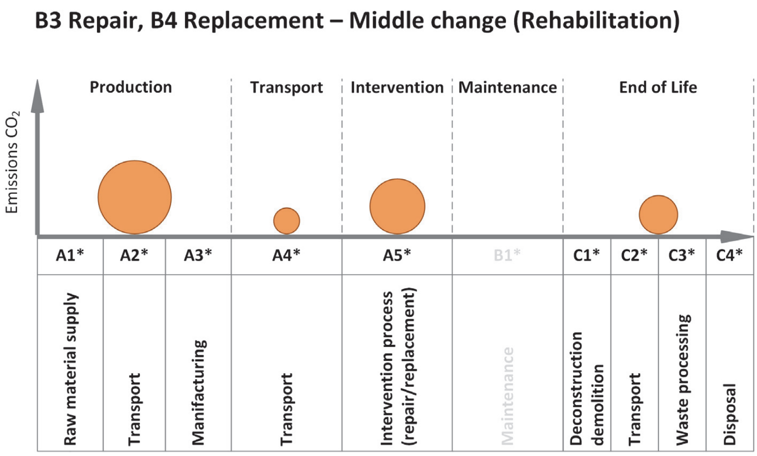


Figure 2.16. Emissions emitted during medium change interventions

The highest level of interventions (Figure 2.17) covers more in-depth actions than the possible repair and replacement of damaged materials. This category of works refers to the refurbishment (B5) module, and it includes the construction of new components which respect the fabrication technique and are compatible with original materials. By referring to the standard boundaries, refurbishment works include emissions from the manufacture and transport of new materials (A1*-A4*), and emissions during the installation and construction of items in the building as part of the refurbishment process (A5*). The emissions from the treatment of the removed components (C1*-C4*) should also be considered.

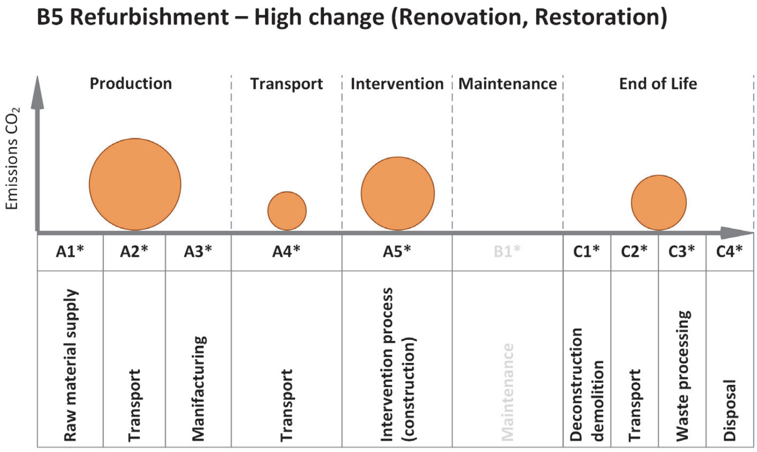


Figure 2.17. Emissions emitted during high change interventions

➢ **Relationship between the level of decay and level of interventions**

The levels of decay, which are expressed as the condition degree of an existing or historic building component, can be linked with all the type of recommended interventions to the structure (Table 2.1), as shown in Figure 2.18. Based on the decay assessment for components and assemblies described in the paragraph 2.2.2.2, the correlation between the three levels of decay (low, medium and high decay) and the categorization of the possible interventions to existing/historic buildings (low, medium and high change) should follow as close as possible the diagonal balance line (e.g., low decay – low intervention). Special attention is given to the case when the level of decay is low, but the energy efficiency of the buildings is not adequate, and therefore, high changes can be applied. On the other side, when the level of decay is high, but the building has restrictions of interventions due to its protection status, measures of a lower level are recommended.

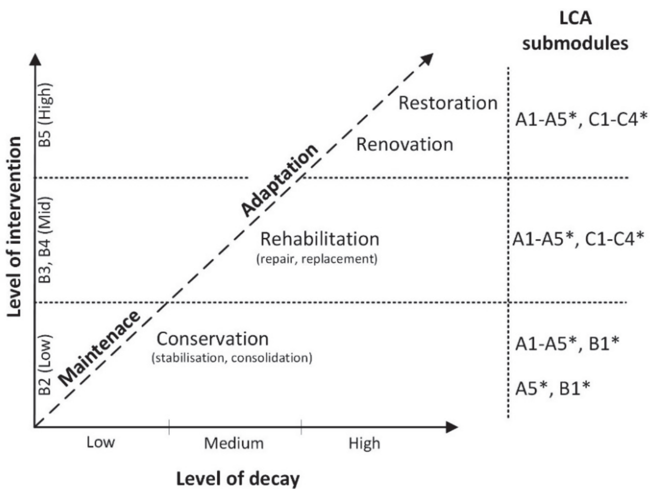


Figure 2.18. Relationship between the level of decay and levels of interventions that can be applied to existing or historic buildings

Summary 2.3.

In Norway, the international directives to reach net-zero energy buildings are extended in a life cycle perspective. Therefore, the balance is assessed by estimating the greenhouse gas emissions during the lifetime of a building instead of direct energy production and demand. In this regard, (the Research Centre on Zero Emission Buildings 2020) has developed a definition for zero emission buildings (ZEB) which is characterised through a range of various ambition levels related to the production, operation and demolition of the buildings. The difference between levels consists in the life-cycle modules that should be included for compensation through renewable energy systems.

Following the definition of the ZEB balance for new buildings, the balance of emissions during intervention actions on both existing and historic buildings is presented in this chapter. The environmental assessment of maintenance or adaptation actions is performed for the modules that comprehend the intervention works according to the European Standard EN 15978 (European Committee for Standardization 2011), respectively maintenance (B2), repair (B3), replacement (B4) and refurbishment (B5), and the concept of submodules is introduced for each of them. Depending on the quantity of works and the system boundaries, three levels of interventions are defined: low, middle and high change interventions. This categorization of interventions regarding the scale of action is important for the correlation between the level of decay of the components and the type and level of interventions on them.

3. ZERO EMISSION REFURBISHMENT

3.1. The framework of the Zero Emission Refurbishment method

3.1.1. Recategorization of the building's components and assemblies

The historic assessment of buildings views the built cultural environment as a qualitative and functional resource. Its results are mainly focused on giving the level of change allowed for specific building components rather than providing exact instructions on how the maintenance or adaptation interventions should be done (Reinar et al. 2010). On the other hand, the prediction of the materials' durability for different building components tells when and where the intervention should be done, but not the type of intervention that is needed. For this reason, the results of these two independent assessments should be merged before deciding the type, time and location of the intervention. Both the results of the historic and decay assessments for a specific component, obtained from different and independent classifications systems (as described in the paragraphs 2.1 and 0), can be placed in a two-dimensional (2-D) chart (Loli et al. 2019) as shown in Figure 3.1.

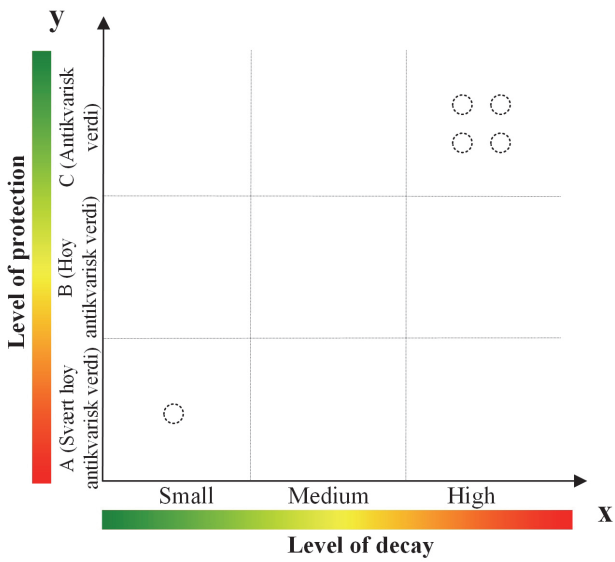


Figure 3.1. Regrouping of building components according to their decay status and protection level.

The service life is predicted for building components or assemblies while the historic value categorization is performed at a building scale together with different suggestions for interventions that are allowed to specific elements.

The circles in the figure show the number of intervention scenarios for a specific component or assembly schematically. It is expected few intervention scenarios for a component with a small level of decay and high class of protection, and an increase in the number of intervention scenarios for a component with high deterioration status and high capacity of change. A component or assembly should be preferably situated as close as possible to the origin of coordinates in the 2-D chart which corresponds to components with low decay level (require a low level of interventions) and high level of protection (allow a low level of intervention).

Each cell in Figure 3.1 contains information about the durability and performance of the constituting component or assembly (x-axis) and the scale of allowed intervention in accordance to their protection status (y-axis). In the figure, the grading system of the y-axis has been done following the categorization of the protected buildings (Vernet) in the city of Trondheim but depending on the categorization system of a specific municipality, different scales of protection level can be used.

For a specific component, in accordance to its position in the 2-D chart, one or more refurbishment intervention techniques that fulfil both the requests of reducing the decay and keeping unchanged or enhancing the value are provided. In most of the cases, especially in components with high capacity to change or high level of decay, more than one intervention scenarios can achieve the dual goal as shown schematically with a group of circles in Figure 3.1. When several intervention scenarios are suggested for a component in the chart, the most appropriate intervention scenario is selected following its environmental impact. Given the fact that the proposed refurbishment scenarios approach or even meet the actual technical standards (e.g. thermal insulation), then the environmental impact of how it is achieved should be considered. Moreover, applying the environmental impact of works for the selection process of the interventions would lead to the principles of maintenance, repair and reuse as much as possible from the original fabric over the replacing procedures. This low-carbon selection driver is in the same line with the standard approach used by building conservators. The new variable transforms the diagram of Figure 3.1 from a two-dimensional chart into a three-dimensional (3-D) chart (Figure 3.2) with emissions of the intervention works (modules B2÷B5 of EN 15978:2011) as the third constituent of it (z-axis).

Ideally, it is preferred that a component is situated near the origin of the diagram because for a component with a low level of decay and possibility to change, it is expected a low environmental impact from the intervention measure. For the components that are situated far from the origin of coordinates, the suitable intervention could be proposed in a way that it would shift the component towards the centre. This move towards the origin of coordinates means that the other rounds of intervention actions would result in a lower environmental cost.

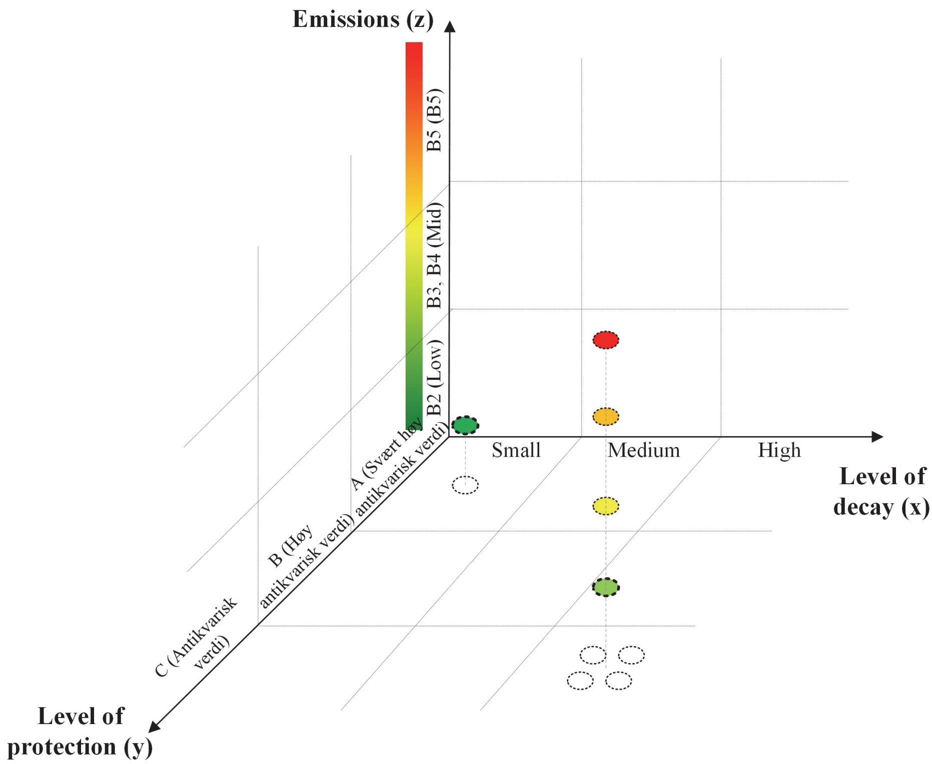


Figure 3.2. Inclusion of the environmental cost (emissions) of the intervention works in the decision-making process

3.1.2. The shift towards district level

The framework can be applied for components and assemblies of a single building, but it has the potential of application to a group of buildings in the same street, district or city because of their similar typology and construction technique. The latest is achieved by placing all the different building components and assemblies of the street, block, district, etc. in the cells of the matrix in Figure 3.1 regarding their level of protection and level of decay. When the district is heterogeneous regarding types of buildings, it is expected that different component sections can have the same level of decay and protection. In such cases, these components are placed at the same cell of the chart, splitting the cells of Figure 3.1 into partitions that correspond to the number of different components with the same level of decay and protection. The method can also be applied when all the buildings are different from each other, and in such case, it would follow the practice of calculations on a building by building basis.

The application of the framework in a district scale aims to estimate the environmental cost (emissions) of the intervention works of the buildings in a street, neighbourhood or city scale. Therefore, for all the different components with a specific level of protection and level of decay in the diagram, it is proposed one or more intervention scenarios that fulfil the requests of reducing the decay, keeping unchanged or enhancing their value and improving the energy efficiency of the building, and the environmental cost is calculated for every scenario. For each of the components, it should also be quantified their presence in the district expressed in surface unit or piece. As the main goal is the sustainable refurbishment of historic buildings, the main focus is given to the components connected directly to the energy efficiency and GHG emissions, i.e. the external components such as outer walls, windows and roof. The entire emissions from the intervention measures performed at district level E_i are then calculated by the following formula:

$$E_i = E_{i,w} + E_{i,o} + E_{i,r} \qquad (15)$$

where:

$E_{i,w}$ are the emissions from interventions in the entire **w**alls,

$E_{i,o}$ are the emissions from interventions in the entire **o**penings (windows and doors),

$E_{i,r}$ are the emissions from interventions in the entire **r**oofs of the district.

The environmental cost of intervention works in the walls of the district $E_{i,w}$ is calculated with the following equation:

$$E_{i,w} = \sum_{j=1}^{n} \left(A_j \times CO_{2,j} \right) \qquad (16)$$

where:

j is the index number of the wall component (a unit of $1m^2$ wall with a specific level of protection and level of decay) placed in the 2-D diagram,

A_j is the total area of the wall component j in the entire district [m^2],

$CO_{2,j}$ is the environmental cost of the chosen intervention scenario calculated by the means of equation (14) for $1m^2$ of wall component j [$kgCO_2$ eq./m^2].

The same calculations as for walls should be performed to estimate the environmental cost of the intervention measures in the openings and the roofs of the buildings by means of an equation similar to (16). Depending on the case, especially for openings like windows and doors, the calculations are performed similarly, but for one piece instead of one-meter square. In such case:

$$E_{i,o} = \sum_{k=1}^{n} \left(n_k \times CO_{2,k} \right) \qquad (17)$$

where:

k is the index number of the window component (one piece of a window with a specific level of protection and level of decay) placed in the 2-D diagram,

n_k is the total number of the window component k in the entire district [piece],

$CO_{2,k}$ is the environmental cost of the chosen intervention scenario calculated utilizing equation (14) for one piece of window component k [$kgCO_2$ eq./piece].

3.1.3. Payback approach

After the environmental impact of the intervention processes is estimated (modules B2÷B5 regarding EN 15978:2011) by means of equation (15), the emissions during the operational phase (Modules B1, B6 and B7) should be calculated to evaluate the payback energy to be generated by renewables. Simply, the total emissions from the interventions E_i need to be added to the amount of emissions from the operation energy consumed from the district after the completion of the works (E_{op}) to calculate the total emissions E_{ZER} to be balanced from the renewable energy generated from the block for reaching the Zero Emission Refurbishment (ZER) neighbourhood. This is expressed through the equation (18) applicable to historic buildings after the intervention process:

$$E_{ZER} = \frac{E_i}{t} + E_{op} \tag{18}$$

where:

t is the duration of the intervention actions [years].

The emissions of the intervention processes E_i are calculated for the interval of time which is necessary to complete the works [kg CO_2 eq.] while the emissions from the operational phase E_{op} are usually measured annually [kg CO_2 eq./per year]. In the operational component, the calculations are performed for the surface which is related to the heated floor area of the buildings and should not be confused with the area in m^2 of the building envelope elements (walls, windows or roofs). Like this, the equation (18) is transformed into the unit equation (19):

$$CO_{2e} \cdot Q_e = \frac{E_i}{A_f \cdot t} + CO_{2e} \cdot Q_d \tag{19}$$

where:

CO_{2e} is the averaged CO_2 eq. emission factor for **e**lectricity [kg CO_2 eq./kWh],

Q_d is the annualized electricity **d**elivered to all the buildings [kWh/m^2 per year],

Q_e is the annualized electricity **e**xported to the grid from the buildings [kWh/m^2per year],

A_f is the heated **f**loor area of the buildings [m^2],

E_i is the emissions during **i**ntervention stages (maintenance, repair, replacement or refurbishment) in all the components of buildings calculated by means of equation (15) [kg CO_2 eq.].

The energy to be generated from renewables depends on the scale of the interventions applied to the historic buildings. The emissions of the intervention processes (E_i) may not be significant in value compared with emissions from operational use (E_{op}), but the selection of the right processes has enormous importance in the carbon footprint of the "new" buildings as well as in retaining the historic value of them.

The energy performance after the intervention is expressed through a coefficient of intervention k_i, which is the ratio of the energy demand of the buildings after the intervention processes with the demand before, as given in the equation (20):

$$k_i = \frac{Q_d}{Q_d'} \tag{20}$$

where:

Q_d is the annual electricity delivered to the building after the intervention,

Q_d' is the annual electricity delivered to the building before the intervention.

According to the level of the intervention, the coefficient k_i can have two values:

$k_i = 1$ for low change (maintenance) interventions that do not reduce the energy demand of the buildings,

$k_i < 1$ for medium or high change interventions that improve the energy performance of the buildings.

Schematic relation of emissions to be generated from renewables before and after each type of intervention is given in Figure 3.3.

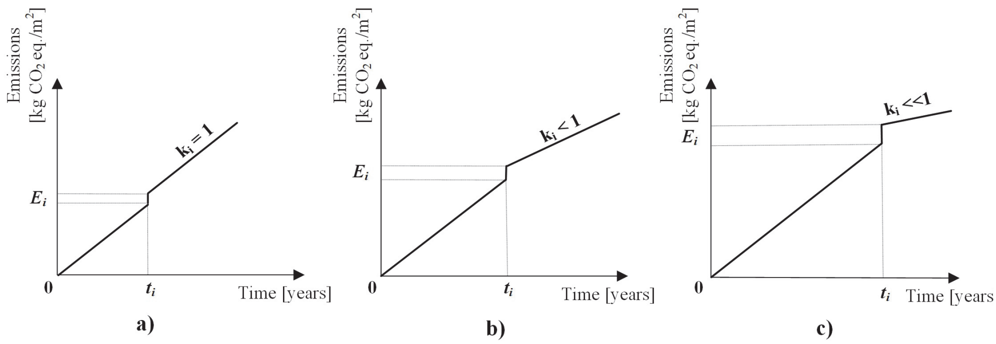


Figure 3.3. Cumulative emissions to be paid back from renewable energy sources after a) maintenance (B2), b) repair, replacement (B3, B4) and c) refurbishment (B5) interventions

Figure 3.3a shows the emissions after a low change (maintenance) intervention that does not reduce energy demand. Figure 3.3b and c express the reduction of energy demand schematically, respectively, after a medium (repair, replacement) and a high change intervention (refurbishment).

The Zero Emission Refurbishment (ZER) balance can be expressed schematically through Figure 3.4, which is a resemblance of the ZEB building's balance. The difference stands that historic buildings are studied only for the operational stage. The payback energy should be generated while the historic buildings are in use. In the case of existing buildings that hold no significance, emissions of the end-of-life stage should also be included for the payback balance, and a comparison of energy use and emissions between intervention scenario with demolition and new construction should be performed in a lifecycle perspective.

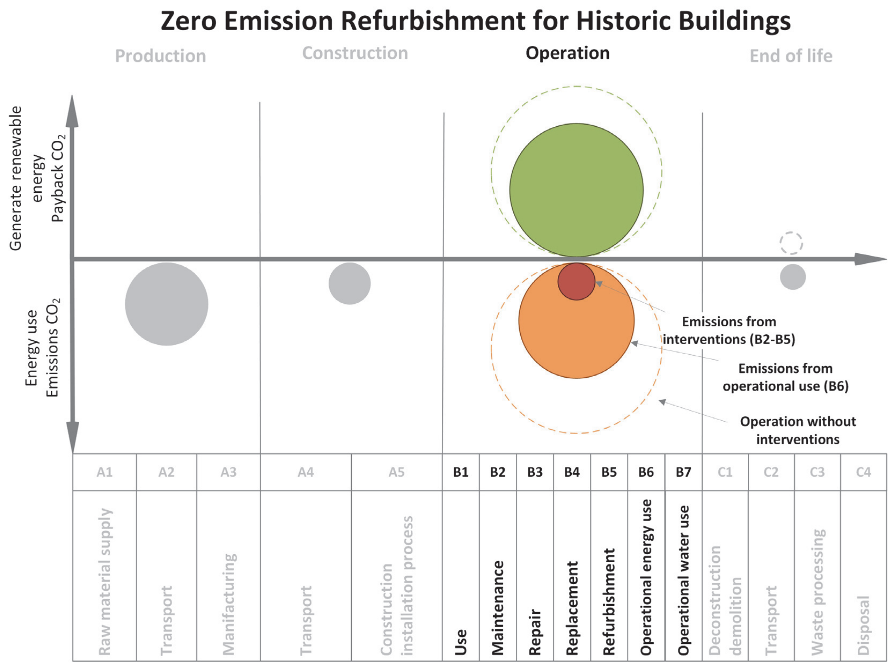


Figure 3.4. Zero Emission Refurbishment (ZER) balance for historic buildings

3.2. Application to a case study

3.2.1. Historic value assessment

The above method has been applied to a typical historic block in the city of Trondheim, which is composed of wooden buildings with different status of decay and level of protection. The block is situated in Møllenberg area, which is a typical historic district in the city built from the 1890s (Figure 3.5). The data for the labelled buildings are provided from the Maps and Surveying Office of the Trondheim Municipality (Trondheim Kommune 2020), and they do not cover the entire block but 28 buildings; however, the following subparagraphs aim to show the steps of application of the ZER method in a broader scale.

Figure 3.5. The block of buildings located in Møllenberg district in the city of Trondheim, Norway

3.2.2. Decay assessment

The decay level is assessed by employing the estimated service life (ESL) values that have been determined for wall components of every building using the modified factor method described in paragraph 2.2.2. The lifespan of the wood products in construction is over 30 years, but for some components, it reaches more than 100 years (Pearson et al. 2012). For a typical timber log wall, it can last 200 years or more, with normal maintenance. The factor values for the calculation of the ESL of building no.1 are shown in Table 3.1.

Table 3.1. Example of calculation of ESL for the building no.1

Subfactor	Conditions	Expert values			Distribution	Factor values		
		Min	Mn	Max		f_{x5}	f_{x50}	f_{x95}
A1: Main material	Normal variation of component	0.70	1.00	1.30	Normal	0.84	1.00	1.16
A2: Insulation	Insufficient quality of component	0.65	0.80	0.95	Normal	0.72	0.80	0.88
A3: Treatment	Good quality of the component	1.00	1.20	1.40	Normal	1.09	1.20	1.31
B1: Design	Good technique, identical design	1.20	1.20	1.20	Deterministic	1.20	1.20	1.20
B2: Sheltering	No sheltering for walls	1.00	1.00	1.00	Deterministic	1.00	1.00	1.00
B3: Decoration	No decoration for walls	1.00	1.00	1.00	Deterministic	1.00	1.00	1.00
B4: Energy effic.	Poor thermal transmittance	0.60	0.80	0.90	PERT distr.	0.69	0.79	0.87
C1: Workmanship	Normal construction, no mistakes	1.00	1.00	1.00	Deterministic	1.00	1.00	1.00
D1: Temperature	Heated building, 18°C ≤ T ≤ 25°C	1.00	1.00	1.00	Deterministic	1.00	1.00	1.00
D2: RH	No risk of condensation, RH≤70%	1.00	1.00	1.00	Deterministic	1.00	1.00	1.00
D7: Mould	Medium risk	0.90	1.05	1.10	PERT distr.	0.97	1.04	1.08
D8: Insects	Very low risk	1.30	1.45	1.50	PERT distr.	1.37	1.44	1.48
E4: Dry days	Medium risk	0.90	0.95	1.10	PERT distr.	0.92	0.96	1.03
E5: Frost days	High risk	0.70	0.85	0.90	PERT distr.	0.77	0.84	0.88
E6: Wet days	Medium risk	0.90	0.95	1.10	PERT distr.	0.92	0.96	1.03
E7: Heavy precip.	Medium risk	0.90	0.95	1.10	PERT distr.	0.92	0.96	1.03
E8: Tropical night	Very low risk	1.30	1.45	1.50	PERT distr.	1.37	1.44	1.48
F1: Type of use	Residential house	0.90	1.00	1.10	Normal	0.95	1.00	1.05
F2: Flux of use	4 apartments, 9 inhabitants	0.90	1.00	1.10	Normal	0.95	1.00	1.05
F3: Surroundings	No heavy activities around	1.10	1.20	1.30	Normal	1.15	1.20	1.25
G1: Maintenance	Scaffolding needed from outside	0.60	0.80	1.00	Normal	0.69	0.80	0.91
G2: Ownership	Owners live in it	0.90	1.10	1.30	Normal	0.99	1.10	1.21
G3: Budget	Surface treatment every 10 years	0.85	1.00	1.15	Normal	0.92	1.00	1.08
TOTAL						**0.37**	**1.53**	**5.40**

The reference service life (RSL) of the existing wall component (wooden cladding, log, insulation, barriers, fasteners) has been assumed 50 years. The service life prediction of the building no.1 for the 50% percentile is therefore 50 × 1.53 = 76.5 years with a confidence interval of ±20.5 years. The calculations are done case by case for all the buildings of the block taken into consideration. The results of the ESL of wall components, together with the general information about the buildings, are given in Table 3.2:

Table 3.2. Information about the buildings of the block

Building no.	Construction year	Protection level	Floor area (m^2)	Wall net area (m^2)	ESL (years)	Decay level
1	1852	C	259.0	162.0	76.5	Low
2	1870	B	166.0	168.9	46.5	Medium-high
3	1879	C	82.0	148.8	57.3	Medium
4	1892	C	154.0	165.6	63.6	Medium
5	1892	C	170.0	124.8	63.6	Medium
6	1895	C	126.0	168.6	72.1	Low
7	1895	C	296.0	190.2	57.3	Medium
8	1896	B	253.0	236.4	56.2	Medium
9	1896	B	135.0	199.6	56.2	Medium
10	1896	C	134.0	152.1	60.7	Medium
11	1896	C	230.0	215.5	60.7	Medium
12	1896	C	576.0	339.4	57.3	Medium
13	1897	C	319.0	171.6	76.5	Low
14	1897	B	573.0	354.4	46.5	Medium-high
15	1897	C	132.0	198.0	57.3	Medium
16	1897	C	406.0	351.0	63.6	Medium
17	1898	C	282.0	208.2	59.6	Medium
18	1898	C	282.0	210.6	59.6	Medium
19	1899	C	424.0	446.8	68.8	Low
20	1899	C	457.0	336.2	74.5	Low
21	1900	C	543.0	395.2	74.5	Low
22	1901	C	306.0	131.6	56.2	Medium
23	1904	C	168.0	115.6	57.3	Medium
24	1910	C	309.0	187.4	63.2	Medium
25	1911	B	270.0	176.0	72.1	Low
26	1914	A	115.0	153.9	56.4	Medium
27	1953	C	359.0	326.4	56.4	Medium
28	1986	C	315.0	303.1	72.1	Low

The ESL values are divided into three categories which correspond to medium-high decay (33÷50 years), medium decay (50÷67 years) and low decay (67÷135 years) (Loli and Bertolin 2018). The categorization has been done using the data distribution of the ESL values for the 28 buildings of the block. The calculations of the ESL values have been performed using the climatic conditions of the CLIMATE FOR CULTURE project for the Recent Past (1960-1990) scenario.

3.2.3. Recategorization of the data

The typical wall section of the wooden buildings in the block is shown in Figure 3.6. Most of the buildings were subjected to interventions in the ’80s by adding a layer of mineral wool from the inside. However, nowadays, the section does not reach the requirements for energy-efficiency (U_{max} = 0.18 W/m^{2}K) according to the actual Norwegian standard TEK17 (Ministry of Local Government and Regional Development 2017). The buildings whose walls have a similar level of decay (small, medium and medium-high decay in the x-axis) and level of protection (A, B and C in the y-axis) are grouped into a 2-D diagram, together with their total area of external walls as shown in Figure 3.7.

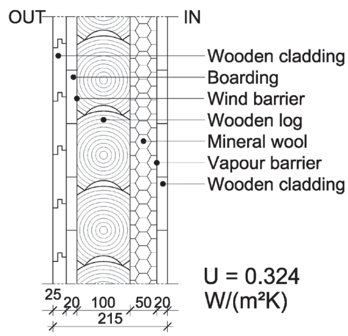


Figure 3.6. The original wall section of the buildings located in the block

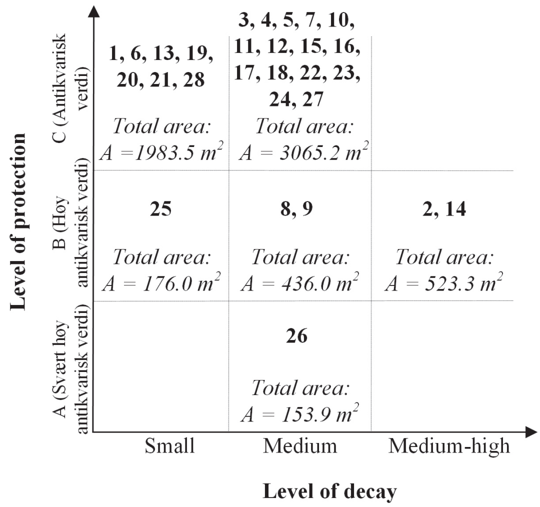


Figure 3.7. Recategorization of the buildings according to the level of decay and status of protection. The number of buildings refers to Figure 3.5

3.2.4. Selection of the intervention

In Figure 3.7, for each of the section groups, the specialists suggest one or more intervention scenarios that enhance the historic value and extend the service life of the components. Besides, medium scale interventions are proposed even for components of a low decay level, with the aim to improve the energy efficiency of the buildings. For some wall sections, especially those with a high possibility to change, more than one intervention scenarios that enhance the wall thermal transmittance are possible. In such cases, the criteria used for the selection of the most appropriate intervention is the carbon footprint of the action. The improved wall section and the carbon footprint of the selected intervention work in 1m^2 unit for each category (as in Figure 3.7) are reported in Figure 3.8.

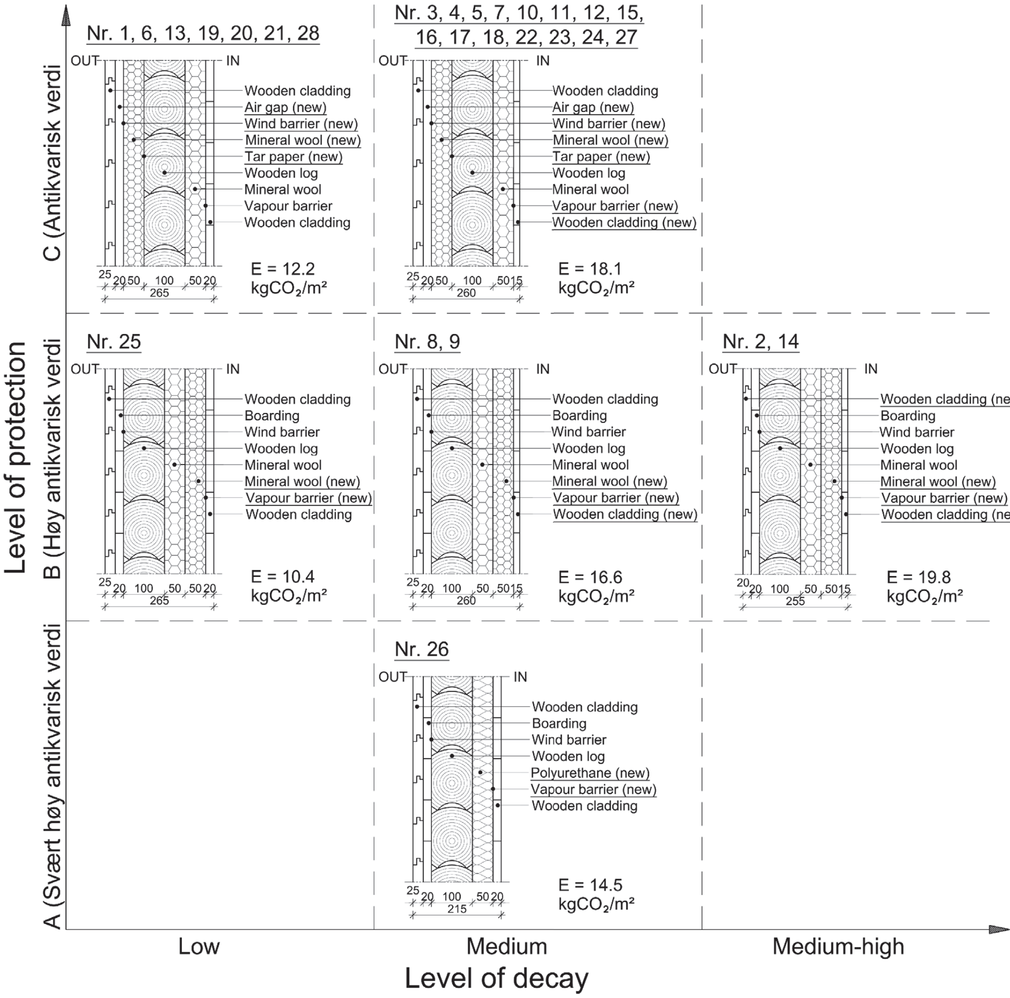


Figure 3.8. Refurbished wall sections for each category and the environmental cost of intervention in 1m^2 of them

The buildings within the class of protection C show higher flexibility of change, so the intervention can be applied from the outside for better insulation of the wall. The suggested interventions for this category fulfil the minimum required U-values. For buildings within the class of protection B, the intervention will be applied from inside by adding 50mm of insulation. In such cases, special attention will be given to avoid the creation of thermal bridges. This type of intervention gets very close to the minimum requirement for energy-efficiency. Regarding the building with the level of protection A, the only suggested intervention is the replacement of the old insulation with a new one with improved thermal capacities. The former insulation is not considered in the right conditions to be applied to other buildings, so it can be disposed to landfill for the end-of-life stage, which increases the emissions cost. The new U-value of the wall does not meet the TEK17 standard value requirement, but notwithstanding it has a significant improvement in respect to the original section.

3.2.5. Calculation of emissions and service life improvement

The next step of the method is the calculation of emissions of the entire intervention works in the walls of the selected block. The amount is achieved by using the formula in equation (16) as follows:

$$E_{i,w} = \sum_{j=1}^{6} A_j \times CO_{2j} = 1983.5 \cdot 12.2 + 3065.2 \cdot 18.1 + 176.0 \cdot 10.4 + 436.0 \cdot 16.6 + 523.3 \cdot 19.8 + 153.9 \cdot 14.5 = 101\ 340 kgCO_{2eq} \quad (21)$$

This result (calculated for the six different groups of wall sections) needs to be added to the emissions of the interventions in windows and roofs calculated by means of equation (16) and (17) to estimate the entire environmental cost of the interventions in the district.

Finally, the service life estimation of the improved wall sections has to be calculated to forecast the time of the new intervention actions over the future. For this, the Far Future scenario which projects the environmental-related variables in the timeframe 2070-2100 needs to be used. The new suggested time of action must consider not only the effect of climate change but also the improvements in the quality of wall due to application of new materials, new construction techniques and improvement of the thermal transmittance of the walls and windows.

Interest also show the results when only the effect of climate change is compared. The new estimations predict that the ESL of the walls will decrease by about 10% only due to climate change; therefore, the status of some buildings (No. 6, 19, 25, 28) with a low level of decay shifts into medium, and some buildings with medium level will shift into a medium-high level of decay (No. 8, 9, 22, 26, 27). These changes are expressed in Figure 3.9, which compares the categorization of the components when applying the Recent Past and Far Future scenarios on the same wall sections. The buildings that shift cell in the diagram because of the decay increase induced by climate change are underlined in Figure 3.9b.

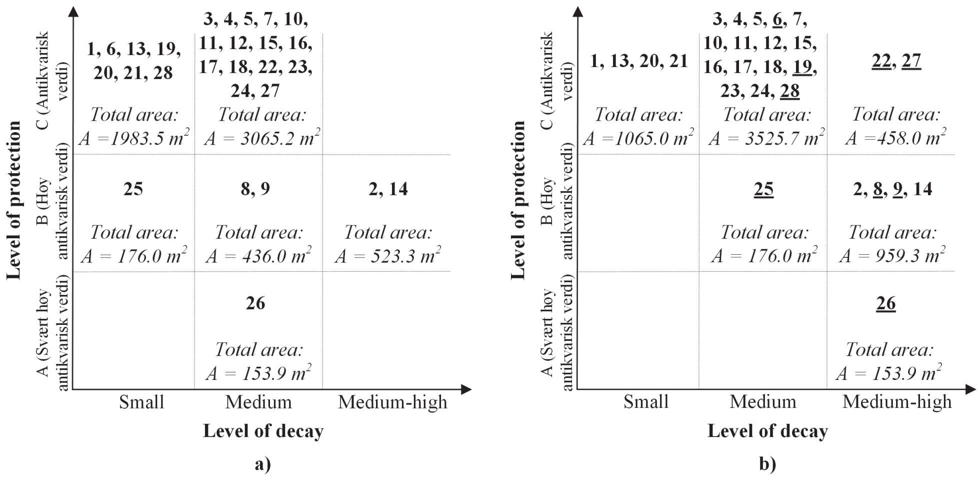


Figure 3.9. Recategorization of the buildings according to the level of decay and status of protection when applying a) Recent Past (1960-1990) and b) Far Future (2070-2100) scenarios

As a simplifying assumption, the original wall section has been considered the same for all the buildings in the case study. The method can be further improved by making a more specific grouping of the wall sections where each grid square in the 2-D diagram can contain more than one section.

3.2.6. Payback approach

The emissions from intervention actions need to be added to the emissions emitted from the buildings during the operation phase after the intervention, as shown in equation (18). It is expected that the suggested intervention actions will improve the energy efficiency class of the buildings. For this, it is necessary to estimate the energy consumption of the improved buildings by using computer modelling software or measuring it directly after the works have been completed. The sum of the emissions from the intervention works in walls and windows (vertical plan) with those corresponding to the reduced operational energy consumption after the intervention (horizontal plan) will serve as a basis for estimating the emissions that should be compensated from on-site renewable energy produced from the block. This calculation offers the basis for the shift toward Zero Emission Neighbourhoods in historic urban districts.

In the block case of study, it was not possible to gather the annual electricity consumption of each building because the energy labelling system considers the data as confidential and need applicable competence requirements to access them (Energimerking 2020). For this reason, the average annual energy electricity consumption of the buildings has been taken from Statistics Norway. The results may not be identical to the specific case, but the example aims to show the path of applying the ZER method at a district scale. According to the statistics, for residential houses build before 2000, the average electricity consumption is 172 kWh/m^2 (Statistics Norway 2020) which corresponds to the level of energy C1 according to the energy efficiency rating certificate as shown in Figure 3.10a.

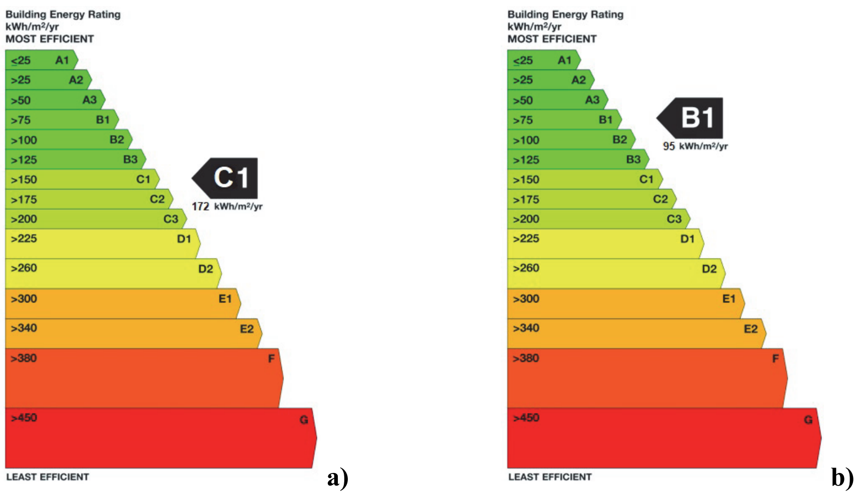


Figure 3.10. The assumed energy consumption of the block of buildings a) before the interventions and b) after the intervention actions

Assuming the annual energy consumption of the buildings is the same, the renewable energy generated from the district would correspond to the total emissions from the operational phase of the block in case of no interventions:

$$E_{ZER}' = E_{op}' = CO_{2e} \times Q_d' \times A_f = 0.132 \cdot 172 \cdot 7841 = 178\ 022 kgCO_2 eq./year \tag{22}$$

where:
CO_{2e} = 0.132 kgCO_2 eq./kWh is the averaged CO_2 eq. conversion factor for **e**lectricity in a long term perspective (Sartori et al. 2012),
Q_d' = 172 kWh/m^2 per year is the annualized electricity **d**elivered to the buildings before the intervention,
A_f = 7841 m^2 is the total heated **f**loor area of the buildings considered in the case study.

The results of the equation (22) should be compared with the emissions from the operational phase of the buildings after the competition of the intervention measures. In practice, these can be done through 3-D energy modelling software of the buildings, or with direct measurements of the energy consumption of the refurbished buildings. In this case study, the improvement will be estimated by comparing the thermal transmittance of the original wall and the wall after the intervention. The original wall had a value of U = 0.32 W/(m^{2}K) while the walls after the refurbishment reach or approach the recommended limit of the TEK17 standard U_{max} = 0.18 W/(m^{2}K), corresponding to a thermal transmittance improvement of 55%. Hence, it is assumed that the average electricity consumption of the buildings after the intervention will be 95 kWh/m^2 which corresponds to the level of energy B1 according to the energy efficiency rating (Figure 3.10b). In this case, the renewable energy generated from the district is expressed as:

$$E_{ZER} = \frac{E_i}{t} + E_{op} = \frac{E_i}{t} + CO_{2e} \times Q_d \times A_f = \frac{101\ 340}{t} + 0.132 \cdot 95 \cdot 7841 = \frac{101\ 340}{t} + 98\ 326 \tag{23}$$

From the comparison of (22) and (23), the buildings reach the same emission results after 1.3 years of operation. Afterwards, the cumulative emissions from the building with refurbished walls will be significantly smaller through time, which would result in both economic and environmental profits (Figure 3.11).

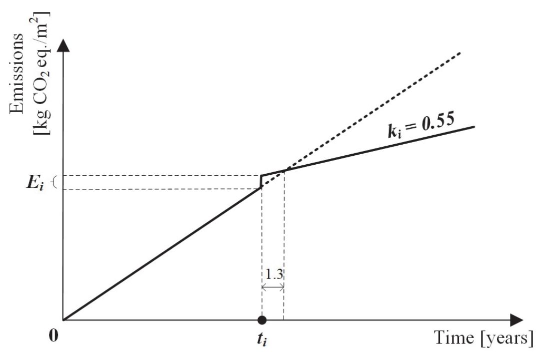


Figure 3.11. Cumulative emissions from the buildings before and after the application of interventions

3.3. Discussions

The transition from Zero Emission Buildings (ZEB) to Zero Emission Neighbourhoods (ZEN) implicates an increasing number of buildings considered under the same study or project. The enlargement of the application scale goes in parallel with an increase of complexity of the calculations; however, the presented framework is flexible and inclusive, it and can be applied to different scales from building, street, block or neighbourhood level. It has the possibility of application in different geographical locations by changing the grading scale of the axes with regards to the decay categorization and level of protection defined from the specific municipality or country. In the application in the case study, the 2-D matrix has a total of nine cells, but this number is flexible and can change according to the circumstances. The framework also has the possibility to be applied to existing buildings with no historic value attributions by categorizing the components only related to one variable: the level of decay of the components.

When the method is applied to a large scale of buildings, it is expected involvement of different materials and components. In such a case, the 2-D diagrams are built for every construction material which can be wood, masonry, stone, concrete, etc. and the environmental results are summarised in the end. In a large scale of application, it is likely to find different components that have the same level of decay and protection. In this case, a specific cell in the 2-D matrix can be split into sub-cells for every different component.

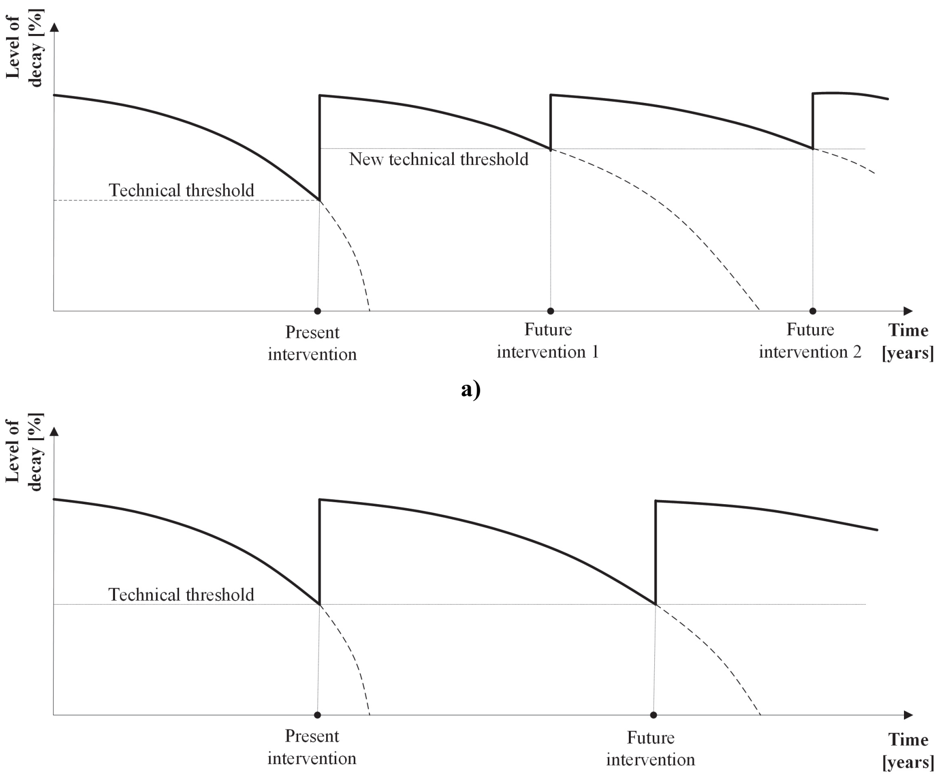
The real benefits of the application of framework are when it is applied in historic districts with buildings that share similar attributes, construction techniques and cultural values because of the high possibility of grouping the components. In these types of districts, the environmental calculations are firstly done for a unit scale of the component (which can be one m^2 or piece) and then directly to the district level. The bypass of the building scale would result in a reduction of time and cost of the calculations. Otherwise, in case of a jeopardised situation, when the district is very heterogenous regarding the type of buildings, the calculations are done from unit scale to building scale and then, to the district scale.

The application of the method in a large scale of buildings ensures, as well, the uniformity of the works throughout the district. This uniformity has not only benefits in the aesthetical aspect, but it ensures the same level of measures regardless of the type of ownership or budget of the owners. A large-scale involvement also makes feasible the application to big projects that can be funded from municipalities, governments or organisations dealing with immovable cultural heritage preservation. Like this, buildings that taken alone do not have significant value but considered on a big scale give the shape to the district and the city will be included and improved.

Ideally, a good intervention would not only keep the same level of decay and protection class but would decrease the decay level and enhance the historical value of the building. In the 2-D diagram, this is expressed by aiming to shift the components to the cells near the origin of coordinates in future interventions. By doing so, the next intervention rounds would result in a smaller environmental cost because the quantity of work demanded in the next rounds would be lower, and the time intervals between interventions would be bigger.

The estimation of the service life should not only be performed to the actual status of the component but also the improved component in order to plan the next round of interventions in the future. The decay assessment for the other round of interventions should have as input the improvements of the first round together with deterioration functions of the materials that will be repaired or changed.

In the example of application, it was shown how climate change would influence the level of decay for the interventions of the future. While it was estimated a reduction of the service life of the components by 10% only because of climate change effects, in reality, it is expected an increase of ESL due to the improvements in the first round of interventions and therefore, a larger timespan of future actions. The results of the second round are essential for the stakeholders to decide according to the budget, deterioration and significance between frequent interventions (maintenance) or more in-depth interventions with large timespans (refurbishment) in the future as shown in Figure 3.12.



a)

b)

Figure 3.12. Comparison of the decision-making process between a) maintenance and b) refurbishment in the future rounds of interventions

The estimation of the environmental impact of future interventions is a challenging task to be completed because the rapid changes in the technology and material science make it difficult to predict how the interventions after several decades will look like and how the emission calculations or targets would evolve.

In the method, the decision-making process between two or more scenarios that reach the same improvement is based on the environmental impact of the action. This driver could have been the economic cost of the work, but since the framework is focused in historic buildings, it is assumed that the monetary aspect should not be a barrier when dealing with the cultural inheritance. However, in everyday practice, especially in public procurement works, the variable that mostly drives the decision of following a specific scenario rather than others, is the economic value of the work. In the 3-D diagram, the monetary aspect is partially considered at the prediction of the level of decay (x-axis), which together with the law restrictions established to retain the historic, cultural and social values of the building (y-axis) and the environmental impact in (z-axis), encompass the pillars of the sustainability in the decision-making process.

4. CONCLUSIONS AND FUTURE WORK

4.1. Conclusions

The Zero Emission Refurbishment method merges the results of two independent grading systems that are needed to decide the type, time and location of the intervention works. The starting point of the method utilises the historic value categorization, performed from governmental institutions, according to the attributes that the buildings hold. The conclusions of this assessment give recommendations about the type of interventions that are allowed, and their limitations related to the buildings' capacity of change. On the other side, the estimation of service life for building components or assemblies suggests the time of the intervention in order to keep good condition of the original material and avoid irreversible decay status. A re-categorization of the above independent outcomes can lead to the selection of intervention scenario works that satisfy both the requirements of conservators/restorers and engineering/material science communities. The re-categorization is done by placing every building envelope component (wall, window or roof section) of the buildings in the case study into a two-dimensional diagram with axes scaled regarding the decay status and level of protection of the component. For each of the different section groups in the diagram (a unit section with a specific level of protection and level of decay), one or more intervention scenarios can be proposed that fulfil both the requests of reducing the decay and keeping unchanged or enhancing their value. When more than one scenario is suggested, the selection of the most appropriate intervention is done by the mean of the environmental impact of the work. Considering that all the proposed intervention scenarios for a component respect the limitations of the cell they are located, then the way how it is achieved becomes significant. By doing so, the method respects the requirements of the global decarbonisation movement, thus turning into a three-dimensional decision-making system.

The novelty of the thesis is not expressed only in the creating of the ZER framework, i.e. placing the building components and assemblies in the 3-D diagram, but results have been achieved in each of the components of the diagram, by studying and setting new categorization systems for every axis with a special focus on historic buildings.

The results of the literature review reveal that previous methodologic frameworks assess the environmental improvements only for the operational phase of the buildings, i.e. before or after the application of interventions while the proposed method highlights the importance of the intervention stages and incorporates the environmental impact of them in the framework. Moreover, the environmental assessment, as the third component of the diagram, holds the same weight in the selection process of suitable interventions together with the physical state and legal protection of the component. The approach of selecting scenarios with low carbon impact makes the environmental cost of the entire intervention process quantitatively small in comparison with the emissions from the operation stage. However, it is the intervention stage that holds a very significant weight because it does not only safeguard the historic value and extend the service life but also the emissions during the operational phase after the intervention depend intensely from it. Sequentially, the overall carbon footprint of the intervention measures, linked with the energy improvement of the buildings after the completion of the works, serve as an indicator for the estimation of renewable energy that has to be generated within the district (e.g. by photovoltaics on suitable roofs) and therefore, for the shift towards Zero Emission Neighbourhoods in historic urban cities.

In the current work, firstly it is presented an overview of the allowed interventions that can be applied to historic buildings and then an equation of how to calculate the amount of the emissions which they are emitting. The categorization of interventions from the amount of emissions and not the quantity or cost of work follows the recommendations of professionals dealing with conservation of immovable cultural properties, i.e. applying minimal technical interventions, interfering as little as possible to the original fabric, avoiding unnecessary replacement of materials and ensuring principles of compatibility, reversibility and retreat-ability in each intervention.

In the ZER method, a strong emphasis is given to the reduction of carbon emissions and therefore, to the climate change mitigation. Additionally, the new equation of service life estimation incorporates the risk induced from the climate of the future, thus stressing the importance of climate change adaptation. The subfactors in the environmental categories can be estimated by using the results of the Recent Part, Near Future or Far Future scenarios, depending on the time when the intervention measures are scheduled to happen. As a result, the expected refurbishment interventions will be planned by considering the predicted climate results, thus increasing the accuracy in the plan of future interventions.

The main research scope of this thesis was to include the main necessary steps and involved stakeholders in the process of planning correctly and effectively sustainable interventions that safeguard the significance of the historic buildings firstly. The Zero Emission Refurbishment framework links together the results of the main communities and experts from different disciplines (conservators, restorers, engineers, urban planners, material science specialists, managers, owners, environmentalists, etc.), sometimes opposing each other, in a methodologic approach. In the presented framework, the work of each community remains independent, and the recommendations and restrictions of the principal involved stakeholders are incorporated in the categorization systems along the axes. By directing the refurbishment process in a methodologic approach, what today is a subjective choice, taken on a case-by-case basis, will become a more scientific and technical assessment, building the path to shift from building scale towards district scale.

4.2. Recommendations for future work

The method has the flexibility to be applied in districts with different size and character of buildings, and it can be further improved through practice and research, maintaining the principle of independence of the involved communities where the output of each community serves as the input for the other. The framework would increase its importance and become a powerful tool for the stakeholders involved in the sustainable refurbishment of historic buildings when the scaling of the axes in the 3-D diagram would be unified regardless the location or category of the buildings involved. For reaching this, it is recommended further research for every grading scale of the diagram and more specifically, in the historic value assessment which can turn into a unique system for the municipalities in a national or international level.

Regarding the decay assessment of the components, further work is recommended not only concerning the grading system but also towards the method of estimation of the decay value. With the introduction of the subfactors, the main quality, environmental and operational characteristics that influence the service life of historic buildings were taken into consideration. However, the estimation can be subject to further improvement to adapt to the new challenges of the intervention process or the particulars of the built cultural heritage under examination. The definition of value for each of the subfactors and their type of distribution ask for further research in the field through the involvement of multidisciplinary experts in data collection, running analysis and laboratory tests. By doing so, the decay assessment can be more exploited and contribute to creating a database for historic buildings to support specialists dealing with heritage site management and preventive conservation.

During the application in the case study, there have been used many assumptions regarding the sections of the walls and the energy consumption of the buildings with the main reason to show the steps of application of the method. The application of the method would become easier with the creation of a "passport" for each building which should include all the input parameters that are necessary for the right application of the framework. This document, together with the enormous help from the computational software, would increase the accuracy and effectiveness in the implementation of the method.

The final calculation of the method indicates the total amount of energy that needs to be generated from the district for achieving ZER balance; therefore, it should be linked with ongoing research regarding Zero Emission Neighbourhoods in smart cities. For reaching the payback approach in existing and historic buildings, renewable energy has to be produced locally on the buildings or on-site to balance out the embodied (from interventions) and operational emissions. A common way to do this is by mounting photovoltaics (PVs) on roofs and façades, and the combination of the PVs with architectural expression in listed and protected buildings needs special attention in future research. Consequently, the method can be further improved by pointing areas of the buildings or district which will serve for the production or storage of the energy and suggesting the type of renewable energy sources according to the geographical location, category of buildings and expected climate change.

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6. APPENDIX

Article 1

Loli, Arian; Bertolin, Chiara. (2018) **Towards Zero-Emission Refurbishment of Historic Buildings: A Literature Review.** *Buildings*. vol. 8 (2).

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Article

Towards Zero-Emission Refurbishment of Historic Buildings: A Literature Review

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Abstract: Nowadays, restoration interventions that aim for minimum environmental impact are conceived for recent buildings. Greenhouse gas emissions are reduced using criteria met within a life-cycle analysis, while energy saving is achieved with cost-effective retrofitting actions that secure higher benefits in terms of comfort. However, conservation, restoration and retrofitting interventions in historic buildings do not have the same objectives as in modern buildings. Additional requirements have to be followed, such as the use of materials compatible with the original and the preservation of authenticity to ensure historic, artistic, cultural and social values over time. The paper presents a systematic review—at the intersection between environmental sustainability and conservation—of the state of the art of current methodological approaches applied in the sustainable refurbishment of historic buildings. It identifies research gaps in the field and highlights the paradox seen in the Scandinavian countries that are models in applying environmentally sustainable policies but still poor in integrating preservation issues.

Keywords: historic buildings; environmental sustainability; conservation; literature review; method; maintenance; refurbishment; Scandinavian countries

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1. Introduction

the renovation potential of buildings in the European Union (EU) is huge. Up to 110 million buildings could be in need of renovation [1] as 35% of the EU's buildings are over 50 years old and, in Europe, there is a slow replacement rate [2].

In the existing built environment, a historic building (HB) is a single manifestation of immovable tangible cultural heritage that does not necessarily have to be a heritage-designated building [3,4]. The historic buildings (HBs) that are not listed or fully protected by countries' legislation may have a significant cultural value in identifying the form of cities, and play a significant role in providing a sense of identity to the community. However, existing materials, building structures and envelope design may limit the choice of interventions to be applied, while the restraints in thermal-performance upgrades may limit their cost-effectiveness. This means that, if compared to recent buildings, these interventions are more demanding in terms of maintenance and adaptation and more challenging in energy-saving during the operational stage.

Nowadays, the preservation of historic buildings is at risk, not only due to natural weathering of their materials but also by the convenience of rebuilding instead of restoring or of developing renovation methods tailored to modern buildings. The topic has recently gained a lot of attention, including the first achievements of planning and executing preservation, protection, maintenance and restoration of immovable cultural heritage in a standardised way [3].

in recent years, several databases (e.g., the Odyssee database used by the European Environment Agency (EEA) [5]), assessment methods (e.g., Building Sustainability Assessment (BSA) [6]) and modelling and evaluations tools (e.g., the SURE Indicator Tool [7]) applicable to different stages of the refurbishment process have been created.

in addition, different sustainability certification systems to assess building performance have been developed. The most important at European level are:

- BREEAM (Building Research Establishment Environmental Assessment Methodology), leading in the EU market (80% of all the EU-certified sustainable buildings) but mostly used in the United Kingdom, where it was created in 1990 [8];
- LEED (Leadership in Energy and Environmental Design) developed in the USA in 1998 [9];
- HQE (High-Quality Environmental) developed in France in 1992 [10];
- Miljobyggnad (environmental buildings) created in Sweden in 2005 [11]; and
- the DGNB (German Sustainable Building Council) system developed in Germany in 2007 [12].

These tools apply a rating method to compare different options in new, converted or renovated buildings; for example, to assess the improvements in energy and materials before and after refurbishment. However, their scoring methods are actually not applicable for the conservation of HBs, as they are not designed to highly rate: (i) the multi-value of immovable cultural heritage; (ii) the significant embodied energy savings within this building stock; and (iii) the energy performance targets achievable through refurbishment.

Decisions on conservation, restoration and retrofitting interventions in HBs need to take into account not only the aspects mentioned in the above paragraph but also a broader range of benefits counting for historic, artistic, cultural and social values or the preservation of authenticity and use of materials compatible with the originals. In such a case, reversible techniques are preferable because, if proven to be inefficient or of low durability over time, they can be replaced without damaging the original material or decreasing artistic and historical value. However, reversible techniques (i.e., maintenance and preservation actions) do not always solve existing restoration problems that require higher levels of interventions of the irreversible type.

Is it possible to save HBs by implementing sustainable-refurbishment actions? What are the existing methods used by heritage scientists, environmental engineers and, generally, decision-makers to plan correct and effective sustainable interventions? Are the two main research communities working on these objectives? What are the gaps in knowledge?

This paper puts into the sustainability specialist and conservators' debate the potential conflict between the need to meet environmental targets—particularly greenhouse gas emissions, e.g., the objective of a 20% energy-saving target by 2020 [13]—and to retain cultural heritage values and resources (Section 1—Introduction). The aim is to clarify such issues through a systematic literature review (Section 2—Methodology). The results indicate a need for knowing, characterizing and summarizing the existing methodological approaches on cultural heritage safeguarding and CO_2-savings potentialities linked to refurbishment (Section 3—Results). Finally, the paper in Section 4 (Discussion and Conclusions) identifies the gaps in the methodological approach that must be addressed in the future. It also highlights the current situation created in the Scandinavian countries that are meritorious, and a model in applying sustainable policies that are nonetheless poor when it comes to integrating preservation issues.

2. Methodology

in research studies, there is a variety of methods that can be applied during a literature review and the choice of the appropriate one is a delicate process because the use of different methods in the same field may appear to have contradictory outcomes [14]. The topic of "sustainable refurbishment of historic buildings" involves different research communities and asks for a review of large bodies of information from different fields. For this reason, the systematic literature review method was selected and applied at the junction between the environmental sustainability and the heritage sectors, as this method guarantees a proper mapping of different areas of knowledge and of relevant research gaps and uncertainties and highlights research needs properly [15].

2.1. Selection of Publications

Identification and counting of existing research publications in the field of sustainable refurbishment of historic buildings was done using the online Elsevier database, Scopus. This platform was selected because it is the world's largest abstract and citation database of peer-reviewed literature i.e., scientific journals, books and conference proceedings, with over 22,000 titles from more than 5000 international publishers [16]. The interests of the two main research communities involved, sustainability and refurbishment specialists, drove the choice of the two initial sets of keywords in the search, using one set for each community. The first set was created to identify the publications related to sustainable methodologies applied to historic buildings by using the keywords "sustainab*" AND "method*" AND "histor* build*"; while the second research results related to interventions aiming at the preservation of historic buildings by using the keywords "preserv*" AND "interven*" AND "histor* build*". The two sets have in common only the category of analysed buildings, i.e., historic buildings, while they differ for the rest. The keywords were written keeping the root of the word and adding the asterisk symbol (*) after it to include all the grammar forms of the word. As the research topic is quite new, the search was performed for scientific publications from the year 2000 until the present day (search performed in September 2017). The search results gave a total number of 274 publications, of which 118 documents resulted from the first set of keywords (sustainability field) and 156 documents from the second set (preservation field). After a first scan, the total number was reduced to 246, removing 9 documents not written in English, 9 duplicate documents, and 10 lecturers' notes or conference proceedings' books. This final list was subject to a document analysis both in term of general characteristics, contents, gaps and needs. The list of the publications considered for the review is provided in the supplementary file.

2.2. Analysis of Publications

the first level in the analysis, i.e., the general characteristics for each document, was retrieved by reading the abstract aiming to identify the following information:

- geographical area;
- type of publication;
- year of publication;
- discipline of the research.

the classification of the documents regarding their discipline served as an input for the second level of analysis i.e., the content characteristics. Within this level, the documents were grouped using the scheme in Figure 1. They were categorised according to the intervention-driving factor i.e., sustainability or the measures to improve the performance of the building. When one document was judged to belong to more than one category, it was assigned to the most relevant field by the authors. From these two main driving factors (orange colour—Figure 1), more precise categories of contents were recognized (green colour in Figure 1) and the classes of environmental (impact) and refurbishment (process), the focus of our paper, were selected for further review. This deep review was the third and last level of analysis, i.e., the content's characteristics. This consisted of full text readings of papers that were assigned to environmental and refurbishment green boxes (Figure 1), in order to understand the objectives and the authors' judgement and track future research needs. Specifically, research products focused on methodological approaches (blue cell—Figure 1) were the ultimate objective of this review as the base on which to build new and effective tools in planning the sustainable refurbishment interventions of HBs in Scandinavian countries.

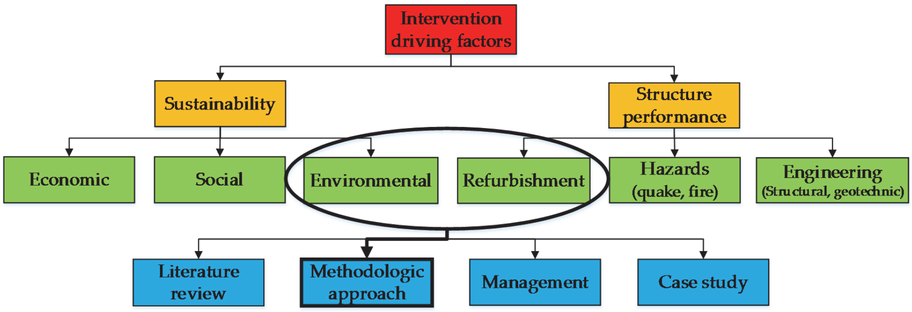


Figure 1. Flow diagram for the content review of the documents. Step 1 groups the documents according to the focus of publication (orange cells), step 2 categorizes them according the field of publication (green cells), and step 3 identifies the type of contribution (blue cells).

3. Results

3.1. General Characteristics

3.1.1. Geography of Publications

the geographical distribution of the documents is defined taking into account the continent and the country of the first author's affiliation. By screening of the entire list it can be seen that 79% (n = 193) of the documents are published by researchers from the European continent, 10% of the documents (n = 25) are published in Asia, and each of the other continents has produced less than 5%. This result reflects the efforts and the financial availability that the European Commission is investing in Framework Programme (FP) for Research and Technological Development in order to develop innovative and effective ways to preserve its cultural heritage. In fact, over the last few decades, the largest EU-funded research initiatives such as the Noah's Ark [17], Climate for Culture [18], EFFESUS [19], 3EnCult [20] and MOVE [21] projects, have demonstrated valuable methodological approaches in the cultural heritage (CH) protection field.

It is interesting to examine the results within Europe. Almost half of the relevant European literature (45%) is published in Italy (n = 86), followed by United Kingdom with 11% (n = 22), Spain and Turkey with 6% (n = 11), Czech Republic with 5% (n = 10), and other countries with less than 10 publications. Regarding northern Europe, the number of publications is very low, with two documents published in the Scandinavian countries (both of them part of the European project EFFESUS [19]) and two documents published from researchers affiliated with the Baltic countries. The results show that the topic is still unexploited and more research should be conducted for the green refurbishment of historic buildings in northern Europe. The geographical distribution is given in Table 1.

Table 1. Distribution of the publications by continent within the two main research communities involved, i.e., the sustainability and conservation specialists.

Continent	"Sustainab"	"Preserv"	Total	Percentage
Europe	84	109	193	79%
Asia	20	5	25	10%
North America	5	7	12	5%
South America	1	8	9	4%
Australia	1	3	4	1%
Africa	1	2	3	1%
Total	113	134	246	100%

3.1.2. Type of Publication

the search has shown that documents were written in all forms of scientific literature, with the journal article being the most found genre (128 documents (52%)). As journal articles are expected to have top-level quality due to rigorous peer-review processes before publication and a larger impact in the research community, they received most attention during the literature-review process. The percentage of publications related to conferences is also considerable with 43% (n = 109) of the documents categorised as conference papers. The other types of publications such as books or book chapters account for less than 5%.

3.1.3. Year of Publication

the sustainable refurbishment of historic buildings is a multi-disciplinary topic that has received a lot of attention among researchers in recent years. In fact, while the number of publications within this field was quite low (n = 2) in 2000, over the last few years that has increased significantly, reaching a maximum in 2015 with 38 publications followed in 2016 with 35. Figure 2 shows the number and the categories of publications per year.

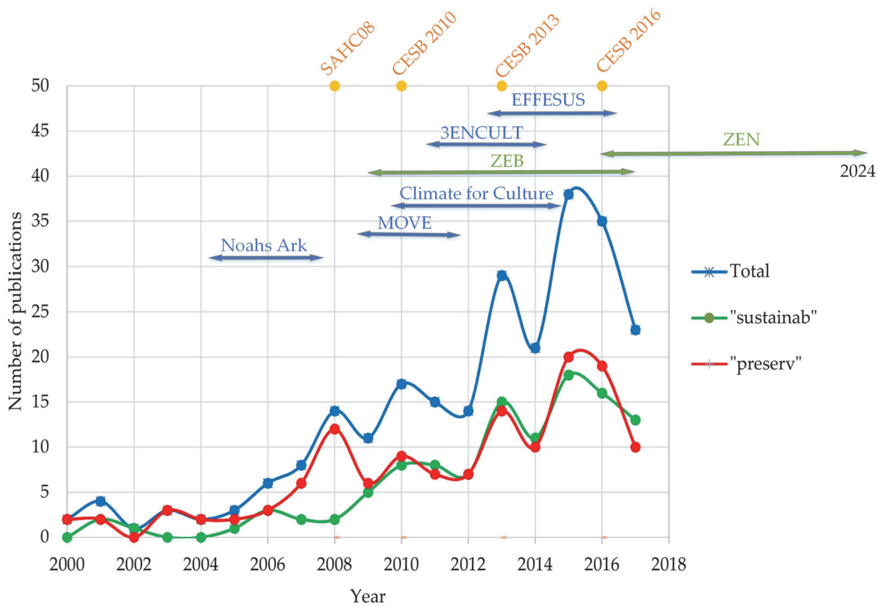


Figure 2. Distribution of documents by year of publication with indication of some major projects and conferences in the field that have influenced the growth of interest in this research topic. The Norwegian research centres for Zero-Emission Building (ZEB) and on Zero-Emission Neighbourhoods in Smart Cities (FME ZEN) are also highlighted.

the graph highlights an increased number of publications in 2008 with regard to the set of search keywords related to interventions (i.e., "preserv*" AND "interven*" AND "histor* build*"). From the data analysis, the increase this year mainly came from publications related to the International Conference on Structural Analysis of Historic Construction (SAHC08). In addition, regarding sustainability issues, the number of publications reflects three fruitful series of conferences—the Central Europe towards Sustainable Building (CESB) event held in Prague, Czech Republic in 2010, 2013 and 2016. The 2015–2016 maximum in the number of publications is not a result of a separate event but rather the effect of the EU framework programme FP7—environment. This EU framework, over a 6-year period (2007–2013), produced a general increase in consciousness of environmental technologies to be used in CH protection and necessary knowledge that resulted in a rise in the number of publications a few years later. Publications in 2017 are counted until early September, the date when the search was concluded.

3.2. Content Characteristics

3.2.1. Field of Publication

the sustainable refurbishment of historic buildings has embraced researchers from different fields and disciplines. The grouping of documents according to their field of publication is reported in Figure 3. In about 34% (*n* = 84) of the listed documents (see supplementary file), the main driver of the publication is the refurbishment process, from maintenance (preservation, conservation) i.e., low-level interventions to renovation and/or restoration i.e., high-level interventions. Within this group of documents (primary driver: refurbishment), 55% (*n* = 47) of the publications focus on energy efficiency and the energy retrofit of historic buildings as part of the global effort to reduce energy consumption [13,20]. a wide variety of passive and active interventions were used to achieve such energy goals, e.g., passive interventions directed to the building envelopes, insulation of roofs and walls, introduction of high-performance windows, and active measures directed at energy-saving improvements linked to equipment maintenance, system controls, change in lighting, and heating, ventilation and air-conditioning (HVAC) systems. Ten documents (i.e., 12% within this driving factor) are, instead, related to the revitalization/reuse of abandoned buildings or their change of use.

the second large sub-group (Figure 3—yellow colours) of listed publications has sustainability issues as its main driver (*n* = 62, i.e., 25%) in accordance with the three main pillars of sustainability: environmental (*n* = 30, i.e., 12%), social (*n* = 23, i.e., 9%) and economic (*n* = 9, i.e., 4%). Although this sub-group is strictly connected with the first, this division was undertaken to maintain the focus of the paper, i.e., to analyse the union and intersection between the physical process of the intervention (sub-group 1 i.e., refurbishment) and the impact of the intervention (sub-group 2 i.e., sustainability). The environmentally sustainable-related documents mainly emphasise the reduction of greenhouse-gas emissions in the construction sector as part of worldwide action towards a decarbonised society [22]. Research in this sector is also devoted to the assessment of the impact of climate change on historic buildings, following the general increased awareness related to the topic and the call for action by the EU community in this field [17,18]. In the review, 15 documents (6%) that treat climate change-related research were identified.

the third large sub-group (i.e., Engineering in Figure 3) includes research contributions dealing with the integrity of the structure and its ability to resist natural ageing and decay. This category of publications has predominantly an engineering and technical character and includes several disciplines, such as structural engineering, geological and geotechnical issues, material sciences, and computer technologies. The number of publications listed in this category is comparable with those regarding sustainability (*n* = 62, i.e., 25%). The result points to two aspects:

1. Conservation and, above all, restoration interventions are conducted when HBs are in a situation of "emergency" i.e., when the risk of partial or complete loss of the building is high due to instability, leaning, rising damp, damage of building materials through moisture, corrosion, salt crystallization, etc.;
2. the value of an HB is often perceived by stakeholders, owners and users as intimately connected with the use and technical performance of the building itself [23].

the last sub-group (i.e., Hazard in Figure 3) refers to publications that intend to preserve tangible CH under natural hazards and catastrophic events (38 publications, i.e., 16% in total). Among those, 33 publications discuss the integrity of historic buildings during and/or after earthquakes. This result reflects the location of the majority of case studies in the Mediterranean Basin, which has a high risk of seismic activity. Although there is a diversity of publications concerning this topic, the majority of them discuss the strengthening interventions before the hazardous event, e.g., base isolation, fibre polymers and other non-invasive techniques with the help of computer simulations and laboratory testing. Only a few of them (3) are focused on post-disaster interventions and efforts to restore as much as possible of the initial buildings. In the list, there are also research documents that aim at the stability of buildings during other hazardous events such as fire (2), erosion (1), floods (1) or wind (1).

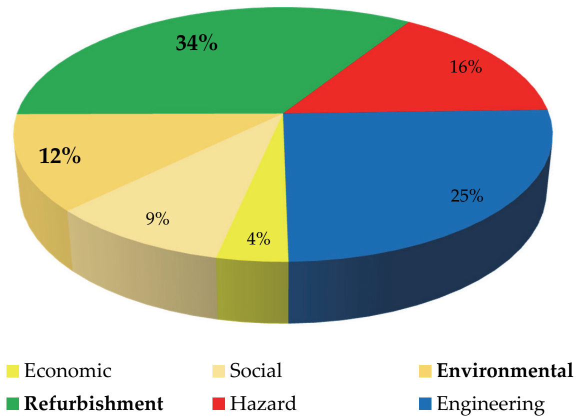


Figure 3. Distribution of the documents by field of publication i.e., content characteristics.

3.2.2. Type of Contribution

Research outcomes dealing with refurbishment processes and the environmental sustainability pillar were identified with respect to four types of contributions, and are reported in Figure 4.

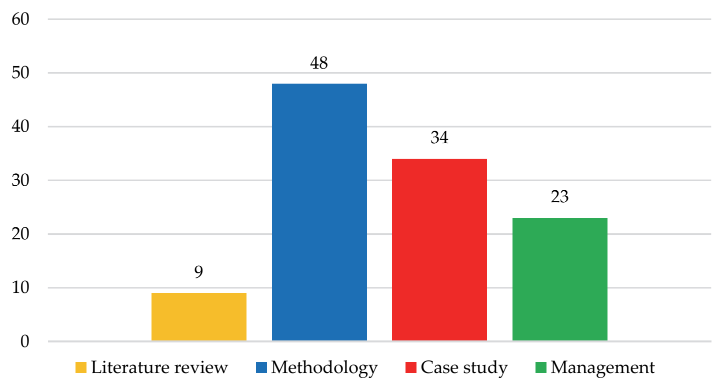


Figure 4. Distribution of the environmental and refurbishment documents by type of publication.

the literature review is the less-used approach when working with sustainable interventions in heritage buildings (i.e., the smallest category, with nine listed documents). At this point, it is quite common to present research results as descriptions of the methodological approaches to be applied during restorations (the largest category with 48 documents). It is also common (n = 34) to use the analysis of data and information gathered on specific case studies, eventually supported by computer simulation, to suggest generalized conservation and/or energy-retrofitting actions on similar buildings in comparable geographical conditions.

Finally, the last type of contribution is mostly focused on the management process, including communication methods and channels used to involve different types of stakeholders (n = 23). This proves the importance, both in the heritage and sustainable sector, of keeping decision makers, owners, and local communities involved in HB conservation projects. Concern about the social aspect from the beginning may positively influence the planning of the interventions (i.e., maintenance, preservation, and refurbishment/restoration), as well as guarantee the long-lasting and effective application of advice coming from the research community.

3.2.3. Methodological Contributions

Documents presenting methodological approaches (48 papers, marked with italic in the supplementary file) to apply during refurbishment processes were further screened to pinpoint achievements and gaps in the field (Figure 5a). The first document in this category was published in 2008. This shows how research into developing a methodological approach is still in its early phase and has recently gained increasing interest. About 54% of these documents (n = 26) describe methodological approaches that deal with intervention processes, while 31% of them (n = 15) focus on energy-retrofit measures and energy-efficiency evaluation after the refurbishment process (e.g., [24–27]). Four publications (8%) present conservation methods that take into account the effects of future climate-change scenarios [28,29] and the evaluation of microclimate conditions [30,31] in the building. Finally, two documents primarily focus on the carbon footprint calculation after intervention [32,33], and one publication discusses the methodology in the decision making process [34].

the 26 documents that describe a methodological approach in maintenance and refurbishment were further categorised according to the levels of intervention (Figure 5b). Three categories were used: low (preservation and conservation), middle (refurbishment and rehabilitation), and high (renovation and restoration). The actions of the first category refer to maintenance interventions, while the middle- and high-level interventions are performed during deeper adaptation processes. From the analysis, 14 documents (54%) describe methods referred to a low level of interventions i.e., preservation (e.g., [35,36]) and conservation (e.g., [37,38]) using the rule of minimum intervention and as much as possible non-destructive techniques. Five publications (19%) have as a primary driver mid-level interventions (i.e., refurbishment, rehabilitation) (e.g., [39–41]) while seven documents (27%) present methodological approaches applied to deeper interventions and the full restoration of decayed or abandoned buildings (e.g., [42–45]).

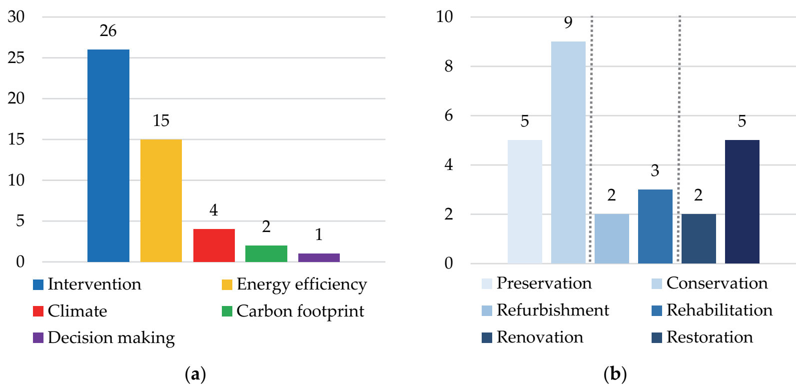
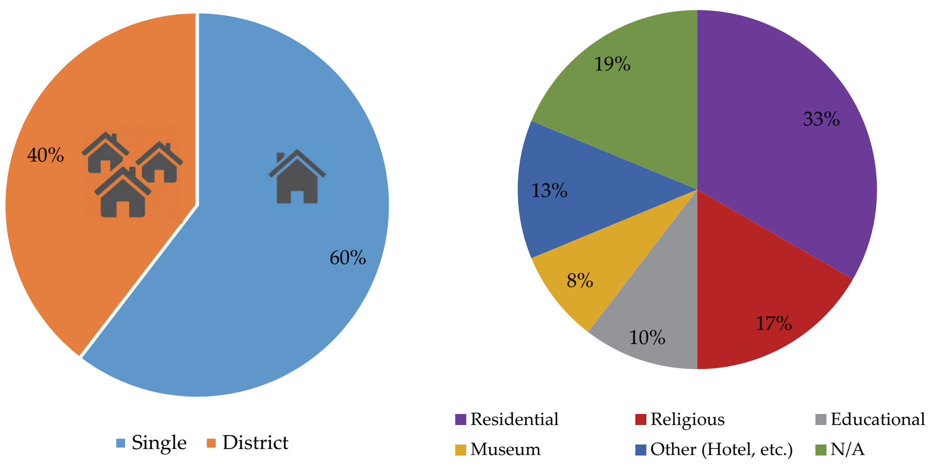


Figure 5. Findings from the systematic literature review: (**a**) categorisation of the documents presenting methodological approaches by primary driver; (**b**) categorisation of the documents describing a methodologic approach in maintenance and refurbishment by level of intervention.

A further analysis was made regarding the type of methodological approach used to achieve the sustainable refurbishment of historic buildings. The results underline a huge variety of approaches used in the field in recent years. The most common approach was the multi-criteria assessment method that was applied in buildings for both energy-efficiency improvement [46] and for interventions [35,44,47]. Decision-makers, using this assessment, have the ability to rank different interventions in order to select the most effective and appropriate actions. Criteria eventually in conflict—that create awareness about conservative interventions—can be also identified. Particular methodological approaches were: maturity matrix assessment [48], multi-attribute value theory (MAVT) [42], methodology for energy-efficient building refurbishment (MEEBR) [25], the functionality index [39], or other methods that require the use of computer simulation or numerical methods. This diversity and heterogeneity of tools shows the importance of using cross-disciplinary, multi-criteria, multi-index, multi-level procedures to develop an effective method/tool able to plan and assess different levels of sustainable interventions depending on the conservation needs, type of building, and climate conditions.

3.2.4. Further Findings

Further analyses of the data gathered from the listed papers allowed the type of building and level of applied interventions to be determined, as well as the building materials subject to alterations. For example, no method was identified that can tailor sustainable interventions on buildings' façades, although in HBs the front walls are often representatives of much of the aesthetic and architectural value and constantly exposed to climate and anthropic-induced decay. The majority of the methods (60%, i.e., $n = 29$) (e.g., [44,47]) were applied to single (as a whole) buildings while the rest (40%, i.e., $n = 19$) to interventions at district level (e.g., [34,49]) (see Figure 6a). Regarding the occupancy of the building, about 33% focus on residential buildings ($n = 16$, e.g., [48,50]), 17% on religious buildings ($n = 8$, e.g., [45,51]), 10% on educational buildings ($n = 5$, e.g., [24,25]), 8% on museums ($n = 4$, e.g., [31,32,46]) etc. (see Figure 6b).



(**a**) (**b**)

Figure 6. Findings from the systematic literature review: (**a**) categorisation of the scale of intervention at building (blue) or district level (orange); (**b**) categorisation of the building by its function.

It is interesting also to analyse the type of the materials that constitute the building subject to intervention. More than 40% (i.e., $n = 19$) are brick buildings that require interventions to improve mortar and plaster conditions and to reduce energy consumption through the addition of insulation.

Sixteen documents (i.e., 33%) focus on the refurbishment of stone buildings with interventions directed towards thermal insulation of the walls and application of chemical agents against moisture, while less than 10% (i.e., n = 3) of documents propose suggestions for the refurbishment of timber buildings. The findings are summarised in Table 2, with some examples of the most common interventions performed.

Table 2. Categorisation of publications by primary building constructive material, number of related publications, and most common performed interventions.

Material	Number	Level of Intervention		
		Low	Middle	High
Stone	16	Re-opening blocked wall doorways and removal of false ceilings to enhance authenticity	Treatment with chemicals to inhibit plant growth and fungal infestation	Enhancement of window airtightness and thermal resistance; thermal insulation of ground floor and roof; internal thermal-insulating plaster
Masonry	19	Maintenance and minimal brick substitution with compatible material	Repairing the roof with thermal insulation and waterproofing slabs	Insulation of the roof and floors; superposition of certified frame windows to the existing ones
Wood	3	Monitoring campaign to assess the state of preservation	Replacement using original technique	-
Concrete	1	-	-	Change of windows; envelope insulation addition; heat-recovery intervention; new ventilated facade
Not Applicable (N/A)	9			

4. Discussion and Conclusions

This review offers insights into the state of knowledge on sustainable refurbishment of HBs and reports how these topics are being explored globally. Its ultimate aim is to influence scholars belonging to the two communities of experts on sustainability and conservation of cultural heritage by further increasing science-based knowledge within the field and influencing decision-making in safeguarding heritage in a society that demands better energy management. This systematic review shows that such topics were incorporated in research agendas since 2006, demonstrating growing interest with an increasing production of research papers. However, current research is geographically limited to Europe and still has some significant gaps in knowledge, as recognized and analysed in the following sub-section.

4.1. Knowledge Gap and Research Needs

First, almost all the published methodological approaches evaluate the actual performance of the buildings and suggest the application of interventions to improve their energy performance and related environmental impact. Environmental sustainable improvements are always assessed during the operational phase i.e., after the conclusion of interventions. No methods are proposed to assess the environmental impact of the refurbishment process itself.

This identified gap is driving our future work on the assessment of the environmental footprint of different refurbishment scenarios by developing a methodological tool that will respect conservation principles i.e., the adoption of minimal technical interventions (avoiding unnecessary replacement of historic fabric), compatibility, and reversibility. The refurbishment scenarios, while ensuring the best preservation, have the potential to become a powerful tool in optimizing the re-use of original materials, planning the time of intervention, and reducing its cost. In fact, they can be developed to take advantage of embodied energy, to recognize areas most vulnerable to climate-induced decay, and to focus interventions on minimum waste production, and thereby on the whole to increase a building's lifetime.

Second, all the published methods for refurbishment processes are fragmentary with a focus on different stages or procedures and based on the partial needs of different stakeholders. In our perspective, there is a call for a multi-disciplinary, inclusive method able to confront and link different issues that can help stakeholders in:

- revealing and improving the protection of the historic, cultural, and socio-economic value of the building;
- identifying levels of intervention from monitoring results on the state of conservation and on structural health;
- reducing costs of building management without trying to compromise on the comfort for occupants;
- applying preparedness measures for HB in order to face slow cumulative and/or immediate drastic hazards;
- selecting new materials for interventions based on types and properties compatible with already existing materials;
- using a life-cycle assessment (LCA) approach to find optimal combinations that maximize the reuse of materials and their lifetimes, thus reducing the carbon footprint of interventions.

Such inclusive and effective sustainable-refurbishment processes can take place given the close cooperation of professionals from different fields such as urban planners, architects, engineers, heritage scientists, conservation specialists, buildings owners, and decision-makers involved in heritage management. From the perspective of planning a long-term building management strategy, its use provides benefits for both the conservation of HBs and the reduction of environmental impact.

Due to the complexity of the field, the methodology will first be applied to regions with similar climatic conditions and to historic buildings with similar architectural attributes. Later, it will be further developed into a tool to be applied in different built environments and places.

Third, the research should be performed in a broader spatial context for monumental buildings, i.e., extending the method to the neighbourhood scale, as this would result in time and cost savings in adaptation processes. In a district perspective, it is more efficient and economical to categorise the buildings and give solutions for each category than to treat them one by one. Moreover, in towns and cities, buildings with no outstanding historic and architectural value by themselves may, taken as a whole, represent an important part of the country's heritage [52]. This wider-scale approach of increasing the number of buildings subject to refurbishment would enhance the achievement of ambitious energy-efficiency targets and would significantly improve the living conditions of the inhabitants. Furthermore, it would upgrade the image of the cities and the incomes through leisure and tourism.

4.2. the Scandinavian Paradox

Finally, this review pointed to the Scandinavian paradox. In Norway, more than 300,000 buildings from before 1900 have been identified, and about 6000 buildings are protected under the Cultural Heritage Act [53]. In Denmark, the number of protected buildings as of 2016 was about 7000 [54]; while in Sweden there are 1500 sites identified as protected (containing many more buildings) [55]. However, the number of papers published in international peer-reviewed journals from researchers affiliated to Scandinavian institutions was very low and they all resulted from the EFFESUS EU project. It was in the interest of the authors to underline the contribution obtained by Scandinavian countries in the results depicted by this literature review. This accentuates the need for future research work and broader dissemination strategies to develop a methodological approach that targets zero-emission refurbishment of historic buildings.

the major publications from the Norwegian governmental institutions that deal with the preservation of cultural heritage, such as the Norwegian Institute for Cultural Heritage Research (NIKU) [56] and the Directorate for Cultural Heritage (Riksantikvaren) [57], are transmitted as reports and, therefore, cannot be traced in a Scopus database search. Moreover, some of them are written in Norwegian, which makes them not easy accessible to researchers of other countries. However, the database search has indicated that even Scandinavian research bodies have devoted very little attention to new methods to effectively maintain and refurbish historic buildings through conservative actions and/or to develop environmental friendly, science-based tools to increase such practice. The existing publications are mainly national reports that, although they contain valuable results in the field [58], have limited dissemination potential due to the language and type of publication.

the literature review has shown that Norway is keeping to traditional established refurbishment and maintenance methods without asking for innovative, science-based approaches. Conservators and researchers in this field want to build further knowledge about maintenance and restoration, collect information on what has been done in the course of the last few years on the usage of traditional handicrafts, and develop "new" knowledge concerning the use of different traditional materials (e.g., results from the "Stave Church Preservation Programme" funded by Riksantikvaren over the 2001–2015 period [59]).

Research on such "new" knowledge concerning the use of traditional material is required in Scandinavia to preserve wooden historic buildings that have high maintenance demands. A detailed knowledge is required to understand the (i) properties of original, aged materials, restored materials and new/created composite materials (e.g., assembling new and aged materials); (ii) changes in building performances (e.g., air-exchange rates, thermal transmission) that include the aesthetic and physical impacts on the existing structure; and (iii) alterations in decay rates or duration of interventions.

An international research project that involves the Norwegian University of Science and Technology (NTNU), NIKU, Riksantikvaren, the Getty Conservation Institute, and the Polish Academy of Science, focuses on the preservation of Stave Churches in Norway and historic wooden buildings in the Scandinavian countries. In the next few years (2018–2021) this will answer some of the questions about the sustainable management of heritage buildings with a long-term perspective. [60]

On the other hand, Norway and the other Scandinavian countries are the most active countries aiming at zero emissions for new construction [61,62] or in developing energy-retrofitting measures for existing buildings, even at a large scale (e.g., district level) [19,63]. This means that:

- Sweden is one of the countries in the EU that, since 2005, has created an energy and sustainable certification scheme for commercial and residential buildings [11], while the large stock of residential buildings in Europe is not certified yet [64].
- in the Scandinavian countries, an increasing number of new constructions, residential or not, are targeted to be nearly zero-energy buildings before 2020 i.e., to balance any CO_2 emission caused by the use of electricity (or other energy carriers) during the building's operation with onsite generation of renewable energy [65].
- in Norway, projects involving dozens of public and industrial partners as well as a large number of pilot projects have been funded since 2009 with industry and governmental support to enable the transition to a low-carbon society. These research centres are: the Research Centre on Zero-Emission Buildings (ZEB) 2009–2017 [61] and the Research Centre on Zero-Emission Neighbourhoods in Smart Cities (FME ZEN) 2016–2024 [62].

the energy-efficiency renovation rate in Norway is at the maximum level compared with that in the 13 countries of the European Union where data are available. It reaches 2.5% a year, while in other countries it varies in a range from 0.5% to 2.0% a year [66–68], with a typical figure being 1% (about 250 million m^2) per year [69]. If retrofit actions are blindly applied to historic buildings without complete knowledge of the challenges involved, in a short time uncontrolled decay will increase the risk of losing valuable historic buildings and will require a huge economic effort to repair the damage caused.

Supplementary Materials: the following are Available online at www.mdpi.com/2075-5309/8/2/22/s1.

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Article 2

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Sustainable interventions in historic buildings: A developing decision making tool

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ABSTRACT

Integrating multi-criteria approaches for reducing greenhouse gas emissions while, at the same time, ensuring long-term maintenance of existing buildings, is a challenge that needs to be faced by both the present and future generations. The core objective of this paper is to integrate a life cycle approach within the framework of building conservation principles to help decision makers dealing with "green" maintenance and adaptation interventions of historic buildings. The proposed approach identifies conservation principles to respect, it considers low, medium, high levels of intervention, and it analyses the impact of interventions in terms of emissions and energy consumptions that should be compensated – while the historic building is in use – with on-site renewables. The method, in the whole, allows the comparison of different intervention scenarios and the selection of the most sustainable one over a long-term management perspective of the historic building. The benefits are twofold: under the conservative perspective, for helping in choosing the right time of interventions, in reducing the decay rate, in using materials that endure longer and are compatible with existing fabrics; under the environmental perspective, for helping in reducing the carbon footprint, in supporting conservation needs through a minimal intervention approach, and in encouraging materials reuse and renewable energy systems.

1. Introduction

Nowadays, the imperative to limit globally the concentration of greenhouse gases (GHG) in the atmosphere to 450 ppm [1], the Paris agreement [2] and the review of the Directive 2010/31/EU [3] on energy performance of buildings by the European (EU) Commission, ask for larger reduction of the emissions in the building sector.

In the cultural heritage sector, a historic building is defined as a single manifestation of immovable tangible cultural heritage in the form of an existing building that in addition manifests significance (i.e. historic, artistic, cultural, social and economic value). Historic buildings do not all have legislation protection or heritage-designation [4]. The heritage-designation of a building can be in the form of legislation protection i.e. "listing", "scheduling" or inclusion in conservation areas or UNESCO World Heritage Sites. Depending on the form of designation, a heritage building can be referred to as "monument". The majority of historic and heritage buildings has at least twice as long life spans of an existing building with no or low significance estimated in 60 years [i.e. standard life span (SLS)]. They need appropriate high quality interventions to ensure satisfactory long-term performance and aesthetic continuity and are demanding sustainability mainly driven by environmental and economic reasons. Nowadays, efforts to achieve a "green label" for historic buildings in use, partially reflect the initiative of the individual heritage institutions, the national laws on the categorization of protected buildings, and the policies for implementing the use of renewable energy sources in different countries. In the future, cumulatively, for the stock of existing and historic buildings exceeding the SLS, the potential for reducing the CO_2 emissions by systematically adopting decisions based on selection of environmental sustainable intervention options is huge.

In time of climate change and over-exploitation of resources, on a wider scale, the preservation of historic city centres will require new conservation solutions and tools tailored specifically to this category of buildings. These expected "sustainable refurbishment tools" have to consider the state of conservation, the historic, cultural, and economic value of historic buildings. They have to use such information to plan maintenance and/or refurbishment at the right time and hierarchy in order to retain the significance, and minimize both the materials decay and the carbon emissions during interventions.

What is actually missing in developing a "sustainable refurbishment tool" is an inter-disciplinary research to decision-making that integrates perspectives of the cultural heritage preservation

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with those of a better energy management. Energy management aspects related to energy saving in historic buildings were extensively developed in literature and in research projects over recent years. The main outcomes being cost-effective retrofitting actions to secure higher benefits in terms of comfort [5–10]. Differently, energy management aspects to reduce greenhouse gas using criteria met within a Life Cycle Analysis have been poorly investigated in historic buildings interventions [11].

The cultural heritage preservation demands essential principles as the highest quality of refurbishment work to keep the cultural value unchanged while usually neglecting the environmental and economic costs of the intervention. The energy management through reduction of energy-and emissions deals with the use of new technologies and materials with the target of reducing the economic and environmental impact, sometime neglecting the historical and cultural value. If the knowledge remains sector-based there is a risk that the gap between heritage scientist, conservators, life cycle assessment (LCA) experts and energy – and emissions specialists deepens.

2. Research aim

The core objective of the paper is to combine the perspective on preservation of historic buildings with that on greenhouse gas (GHG) emissions reductions (Section 3) in order to develop a comprehensible and shared method for sustainable interventions on buildings of heritage significance that need special consideration (Section 4). The research need is addressed through:

- the analysis of the allowed interventions and the conservation principles to respect;
- the identification, at different level of interventions (i.e. maintenance, repair, replacement and refurbishment), of the major contributors to emissions and the potentialities for their reduction.

The result is a semi-quantitative evaluation framework to reach zero emission refurbishment (ZER), which can be a starting tool for decision-makers to select the intervention that ensures the historic significance of the building while at the same time promotes the reduction of the emissions and energy use. ZER has the potential to be further developed and used for planning a long-term strategy for the management of historic buildings, choosing the right interventions based on the recognized value and state of decay, and the right application time for prolonging the historic building lifespan (Section 5).

3. Material and methods

The method used to develop a ZER tool that fits with the requirements of the heritage preservation, is based on the following five steps:

- a comprehensive survey of the definitions of the most used interventions (Section 3.1), i.e. the set of actions that result in a physical change to a building element and/or fabric and that are generally applied when the element and/or the fabric is approaching/exceeding the end of its standard service life. The survey was conducted systematically analysing the “Terms and definitions” used in the European Committee for Standardization (CEN) – Technical committee 346: “Conservation of Cultural Heritage” [4,12–16];
- identification and characterization of the allowed interventions in a historic building (Section 3.1). Allowed interventions have to retain a building or its parts in a condition in which it can both perform its required function and retain its heritage significance i.e. the combination of historic, cultural, and artistic value or significance for past, present or future generations. This identification was made through an extensive literature review on the conservation measures and actions aimed at safeguarding cultural heritage and their significance [17–26];
- identification of terms and definitions adopted in the field of professionals and “energy and emission specialists” (e.g. building life cycle stage, zero emission building architecture, and low carbon solutions) to understand the applicability to interventions in historic buildings (Section 3.2). The terms and definitions came from the results of the research activities performed over eight years (2009–2017) at the research centre on zero emission building [27] in Trondheim, Norway. We specifically addressed our survey on the ZEB centre definition of zero emission buildings, the main emission concerns, the life cycle emissions, the emissions balance, the relative importance of embodied emissions and the common calculation procedures [28];
- classification of the level of interventions, based on effects on heritage value of historic buildings (Section 4.2). This classification was based on the rating (i.e. low, medium, high) of the allowable conservative interventions. First, the level of actions adopted in an intervention was evaluated – following a LCA approach – on the base of use of new material (i.e. material production, transport) and on waste treatments. Then, this rating was examined in term of possible impact on changing the heritage value. Minimal interventions, stability, reversibility, compatibility and durability of the intervention were guidelines in performing such estimation [29–31];
- use of the LCA framework [28,32–34] in the proposed method to reach a zero emission refurbishment (ZER) balance (Sections 4.1 and 4.3). Synthesis of the compiled information through the development of a comprehensive approach is presented in form of an equation to calculate the emissions, which can be used by a large research community. The level of intervention is correlated with the carbon footprint of this specific lifecycle stage to determine the renewable energy that has to balance the emissions from both the intervention and normal operation phase (see Section 4 for an extensive explanation).

The material used in this research is based on:

- the know-how made available by international and up-to-date projects in the identified research fields (e.g. ZEB [27,35], EFFESUS [6,36], DIVE [37], 3ENCULT [38]);
- the definitions related to the protection of cultural properties from the European Committee for standardization (CEN) – Technical body CEN-TC-346: Conservation of Cultural Heritage [14,39];
- the research needs described in the scientific literature [11].

3.1. Definitions of interventions for historic buildings

The set of interventions that can be applied to an existing building with elements that have signs of weakness, deterioration or hazardous conditions (e.g. fabric preservation) and may not work properly or have a low level of performance (e.g. energy efficiency and comfort conditions) are described in Table 1. An intervention, for definition, is any action other than total demolition or deconstruction. Demolition is outside the due scope of this work and it is reported in Table 1 as reference to a not permitted action in historic buildings.

The whole classification system for interventions that can be applied to existing buildings during their performance management process [41] is reported in Fig. 1. These interventions can be

Table 1
Definitions of interventions applied in the performance management of existing buildings. Identification of the interventions permitted on historic buildings with historic, cultural, and/or artistic value (Y = yes; N = no).

Type of intervention	Definition of intervention – application on existing buildings	Application to historic buildings (Y or N)
Preservation	Act/process of applying measures necessary to sustain the existing materials, form, and integrity minimizing decay. It is part of the ordinary maintenance. It includes indirect measures e.g. monitoring as process of measuring, surveying and assessing changes of material properties and environmental factors over time	Y – It recognizes the historic building or an individual component as a physical record of its time, place and use, protecting its heritage value and keeping it in a proper state [40]
Conservation	Action/s applied directly on a building fabric to prolong its life without the loss of authenticity and significance [40]. It includes preventive and remedial conservation thus involving both maintenance and stabilization interventions	Y – Interventions aimed at safeguarding the character-defining elements to retain heritage value and extend building lifetime. Interventions have to be physically and visually compatible, identifiable through inspection and documentation. Chemical or physical treatments, if appropriate, have to be as gentle as possible
Maintenance	Routine, cyclical, non-destructive interventions (i.e. combination of technical, administrative, and managerial actions) during the life cycle of a building to secure its uninterrupted use at the desired level of activity [40]. It includes both preservation and preventive conservation actions	Y – Maintenance aims at keeping the historic building in an appropriate condition to retain significance, slowing the deterioration, and increasing a bit the performance level. It entails periodic inspection, routine, cyclical non-destructive cleaning, and refinishing operations
Repair	Action/s applied to a building or part of it to recover functionality and/or appearance (original condition). Minor repairs of damaged or deteriorated materials can be part of maintenance	Y/N – In historic buildings, repair is a remedial conservation intervention to recover functionality and/or appearance of deteriorated materials. Repair, based on evidence, to respect heritage significance is preferable to replacement. In case of use of new materials, they have to match the original in composition, design, colour and texture
Refurbishment	Action/s that modify an existing building to bring it to an improved, acceptable condition. It includes both interventions to enhance building envelope appearance/ function (i.e. facelift – superficial or refit - cosmetic), and extensive maintenance/ repairs interventions to reach modern standard (e.g. energy retrofitting)	Y/N – Refurbishment in a historic building is allowed when respect the construction techniques, material and heritage significance. Any exterior alteration/ new addition needs to be distinguishable and compatible with historic material, feature, size, scale and proportion
Replacement	Construction operations that replace an entire character-defining feature with new material. Replacement is conducted when the level of deterioration/decay on existing materials precludes repair, as action in connection with a change of use, or as an upgrading of the building	N – In a historic building, the replacement of a character-defining feature, of intact or repairable historic materials is not allowed
Rehabilitation	Act or process of making possible a (new) compatible use for a property. It can include element of modernization as well as some extension works with even major structural alterations	Y/N – Rehabilitation of a historic building has to propose a contemporary use compatible with its character defining elements and heritage value. It has to interpret the property value with minimal changes to its distinctive materials, features, and spaces
Renovation	Action/s, driven by law/regulations requirements, to upgrade components, elements and systems (including energy efficiency) to the today's level. It can include stabilization and consolidation works as damp proofing measures and timber treatments	Y/N – Renovation to upgrade a historic building up to the today's comfort levels is generally not a conservation action as it cannot fully respect its significance. Modern materials and technical installation can be no compatible with original materials, finishes, character-defining features and original energy performance
Restoration	Action/s to bring the existing building back to a former condition. It is normally restricted to major adaptation work to derelict or ruinous buildings. It can include substantial reconstruction works of part/s of the building	Y/N – Restoration of a historic building involves risk of loss of historic and artistic value due to the modification of character-defining features. It reveals and recovers the state of a historic building or of an individual element as it appeared at a particular period in its history and it can result in removal of features from previous historic periods
Demolition	Action/s of removing existing materials and/or part/s of the building. It cannot be defined as an intervention, i.e. a physical change or alteration of a building	N – Demolition is an option that cannot be considered for a historic building as all the efforts to retain its historic, artistic, cultural and social value have to be guarantee over the time to present and future generations

grouped in two main categories: maintenance and adaptation. They refer respectively to:

- any intervention that maintains performance and is better applied to historic buildings to retain the value embodied in the historic fabric;
- any work to a building beside maintenance to change its function, capacity, or performance.

Within the specific category of historic buildings, all maintenance interventions (blue colour in Fig. 1) are admitted, while, concerning adaptation, only those labelled in red if preserve the significance and respect the conservation requirements (see Section 3).

Usually, both maintenance and adaptation are applied when an existing building is below its minimum acceptable standard, either to increase its condition up to its original status or to achieve an optimal standard (e.g. building energy efficiency classes). The same is not always possible for historic building (see Table 1) due to restrictions deriving from legislative protection and the need to preserve unchanged their character-defining features and significance.

3.2. Integration of LCA theory in the proposed method

In recent years, significant attention was given to reducing energy use in existing buildings [42], and to propose energy retrofitting measures in historic buildings (e.g. EU research projects 3ENCULT [38] and EFFESUS [6]). Most of the research efforts focus on the performance and energy efficiency of the building after the intervention works but little or no attention has been directed towards the potential to balance – in existing and historic buildings – the emissions related to the intervention process itself. The concept of "green maintenance" in historic buildings has been proposed from Forster et al. [43] to support the maintenance decisions on a life cycle basis. Our scope is to explore further this approach by quantifying the emissions from all types of interventions that can be applied to a historic building and to balance these emissions during the normal operation of the building through renewable energy systems.

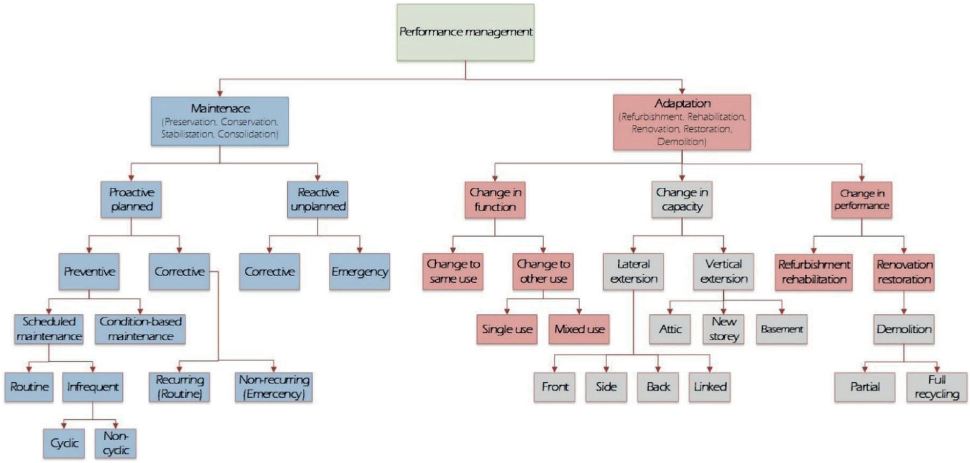


Fig. 1. Interventions that can be applied to an existing building [41]. All types of maintenance interventions can be applied to historical buildings (blue) while only interventions in red can be applied during adaptation process if they preserve the significance.

To face this issue, and to highlight common and/or diverging needs between new and historic buildings, the terms and definitions used by experts in assessing the emissions in the life cycle (LC) stages of a building, are shortly presented here. These definitions were developed by the ZEB Centre and the EU Committee for Standardization: sustainability of construction works in EN15978:2011 [14]. They refer to new and existing buildings and are constituted the following:

- product stage [A1 to A3]: accounts for emissions from the production of raw materials, transportation to manufacturing sites, and manufacturing emissions. In the case of a historic building this stage is not included, as the emissions from producing materials were in the past;
- construction stage [A4 and A5]: emissions related to the preparation of the ground, building erection, and waste/waste treatment during the construction process. No emissions for a historic building in this stage, being constructed in the past;
- use or operation stage [B1 to B7]: emissions occurring when users occupy the building, i.e. energy and material use during that time. Historic buildings have emissions in this stage;
- end of Life (EoL) stage [C1 to C4]: emissions when a building has ended its use stage and needs to be either restored (i.e. both disassembled and reconstructed) or demolished. Historic buildings may have some emissions in this stage.

Through the analysis of the above stages, a simplified life cycle CO_2 balance was proposed by the ZEB centre for a ZEB pilot building (Fig. 1b – online material) [27,44–46] and presented in form of an equation (1) by Dokka et al. 2013 [28,47]. Equation (1) allows the calculation of the CO_2 balance and the future payback period for the construction and use of a new building:

$$\Delta CO_2 = CO_{2p} + CO_{2mo} + CO_{2e}{}^{*}(Q_d - Q_e) \quad (1)$$

where, as reported in [44], the terms referred to are:

CO_{2p} emissions from the annualized Production and construction (p) stage [kg CO_2 eq/m^2 per year] referred to A1–A5 stages.

CO_{2mo} annualized Material emissions during Operation (mo) stage, i.e. product stage replacement only in ZEB pilot building [kg CO_2 eq/m^2 per year].

CO_{2e} averaged CO_2 equivalent emission factor for Electricity (e) [kg CO_2 eq/kWh].

Q_d annual electricity Delivered (d) to the building [kWh/m^2 per year].

Q_e annual electricity Exported (e) to the grid from the building [kWh/m^2 per year].

In Section 4, equation (1) is adopted to calculate the emissions balance for existing and historic buildings. The users of the method should take into account its limitations, as follows:

- the implementation of this tool will enable comparative analysis to be undertaken on several intervention scenarios (see examples reported in Section 4.3) within the same region;
- the region specification, i.e. the equation is partially focused on Norwegian conditions where the only source of energy is the electricity. In case of other sources of energy, the equation may be adapted accordingly by replacing electricity with the other sources like natural gas (m^3 gas), etc. and should be adjusted to local energy supply conditions;
- the estimation of the CO_{2e} factor (for both electricity production and distribution) for emissions from present towards the near future;
- the normalized value used in the calculation of the embodied emissions from production and replacement of materials used in the building that is the floor area over a SLS of 60 years (i.e. new building SLS).

4. Results

4.1. ZER balance and payback approach for existing and historic buildings

The quantitative method presented here for the first time, which refers to the zero emission refurbishment (ZER) balance, shifts the emphasis away from intervention financial costs towards CO_2 expenditure on maintenance and adaptation interventions. This decision-making approach helps supporting the conservation needs of historic buildings as it encourages a minimal intervention-based approach. It allows the calculation of the emissions released during the intervention modules from B2 to B5 (see Fig. 1a and b – online material) [12]. The modules are (B2) maintenance, (B3) repair, (B4) replacement, and (B5) refurbishment. Module B1 (use), which encompasses the emissions during the normal use of the building components, is not relevant for this study. The impacts of energy and water needed for the operation of the building (respectively B6 and B7), although high emission contributors, are not considered because the research is expressly focused on the emissions of building interventions.

The time span of the proposed LCA equation, aiming a zero emission refurbishment balance, is the time-period of the interventions process (generally some months to few years in major interventions). The intervention impact should be considered to the zero emission building balance [either directly to the overall emissions over the whole reference period (usually life time of the building) or as annualized value to equivalent yearly emissions].

For an existing building, (the system boundary includes all stages representing the remaining service life and the end-of-life stage of the building), the management of the emissions during interventions helps to:

- estimate the emissions related to ordinary and extraordinary maintenance;
- choose the type of intervention (and calculate the expected emissions) based on architectonic and design features and actual and expected performance (e.g. energy efficiency and comfort level);
- increase the building lifetime, preferring repeated mild interventions as scheduled maintenance or unscheduled corrective actions taken at the first appearance of decay on materials;
- take advantage of existing materials (e.g. increase material reuse during adaptation interventions);
- produce, when allowed, energy using renewable sources to compensate for operational and embodied emissions during the maintenance and adaptation interventions.

For an historic building, that is defined as an existing building that in addition manifests cultural, historical, aesthetic, social and economic values [4], the system boundary includes all stages representing the remaining service life of the building. The end-of-life stage is not considered because it is not a recommended solution for this category. It can be considered only during the intervention processes for the components that need to be replaced. Actions on historic building differ from interventions on existing buildings because they have stricter requirements regarding the type of interventions allowed (Table 1). The selection of the right action depends on the complexity of the different historical layers, building values, state of conservation, and levels of protections. In general, they have to respect the following conservation principles:

- execution of initial (and even repeated annual inspections to update the conditions and refine the plan of interventions) condition survey to assess the state of conservation and the cultural significance of a historic building [48–50];
- adoption of minimal technical interventions, i.e. interfering as much as necessary to allow an item to retain a state of use, but as little as possible in order to avoid unnecessary replacement of historic fabric, thereby ensuring principles of compatibility, reversibility and retreat-ability in each intervention;
- adoption of planned management, in particular through preventive conservation, i.e. a management approach that preserves cultural significance by continuous improvements, rather than by 'after damage' restoration [51];
- identification of the state or condition to be achieved (e.g. the preservation of cultural significance), developing a general awareness (i.e. quality control and well-executed craft-based technique to avoid lack of historic, artistic, and/or cultural value after the interventions) [51];
- respect for historic patina to enable the continuity of aesthetic integrity to be achieved while simultaneously sustaining a workforce of traditionally trained, craft-based workers [52,53].

If interventions fit within the conservative principles, they are generally of high quality, more compatible with the existing fabric and endure longer than insensitive, often inappropriate repairs. The proposed equation (2), is used to estimate the CO_2 emissions for each level of a building management intervention (i.e. low, medium and high) once the building's conditions are assessed at a certain time i (i.e. subscript: condition, i). Levels of interventions and what they include are defined from the boundaries of the Use stage [16] considering only intervention modules (B2–B5).

The equation works for both interventions on existing and historic buildings and is defined as:

$$CO_{2_{ZER},i} = [CO_{2_{pn}} + CO_{2_t} + CO_{2_i} + (CO_{2_e}{}^{*}Q_{el}) + CO_{2_{EoL}}]_i \quad (2)$$

As stated earlier, equation 2 works only for the LCA stages B2–B5 of the standard ZEB definition. Emissions during a general adaptation intervention are calculated for each sub-stage (i.e. addenda in the equation) of the process as:

CO_{2pn} emissions from the production (p) stage of new (n) building components used during the intervention [kg CO_2 eq/m^2];

CO_{2t} emissions from the transport (t) stage of building components used during the intervention [kg CO_2 eq/m^2];

CO_{2i} emissions during the intervention and installation:(i) process (cleaning, repair, replacement, construction of small components) occurred to the building [kg CO_2 eq/m^2].

CO_{2e} averaged CO_2 equivalent emission factor for electricity [kg CO_2 eq/kWh].

Q_{el} total supplementary electricity delivered to the building before or during the intervention process for constant control of chronic conditions of deterioration [kWh/m^2].

CO_{2EoL} emissions from the waste management and the end of life (EoL) stages of the removed components and ancillary products to repair and/or substitute [kg CO_2 eq/m^2].

Specifically for historic buildings, the reuse of materials has a high potential to both preserve the building significance and decrease emissions by minimising the use of new materials and the end of life of the old ones.

The three different levels of intervention (low, medium, and high) are defined visually in Figs. 2–4, respectively. Each figure refers to one or more Life Cycle intervention stage/s in the standard definition [14] but shows the increased complexity by adding new submodules specifically designed for historic buildings (eq. 2 and symbol "*" in Figs. 2–4). These submodules are defined using the boundaries of the modules B2–B5 in the standard [14] as follow:

- from A1* to A3*: emissions from the production of new materials used for interventions [CO_{2p} in equation 2];
- A4*: emissions from the transport process of new materials during the intervention [CO_{2t} in equation 2];
- A5*: emissions during the intervention process i.e. during the operation of construction, installation, and replacement with new and repaired materials [CO_{2i} in equation 2];
- B1*: emissions from the electricity consumed from the building for constant control of chronic conditions of deterioration in order to maintain the performance of the building fabric and building-integrated technical systems (e.g. emissions of monitoring campaign) [$CO_{2_e} * Q_{el}$ in eq. 2];
- from C1* to C4*: emissions from deconstruction, transport, waste processing and disposal during the end of life of a component that needs to be replaced, repaired, or refurbished [CO_{2EoL} in eq. 2].

Results for each submodule generate the emissions during an intervention process (B2–B5 – standard definition [14]) and they should be added to the emissions from the normal use of the building (B1, B6 and B7 – standard definition [14]).

A low change level (Fig. 2) consists of maintenance works (Module B2 in the standard definition [14]). Preventive conservation

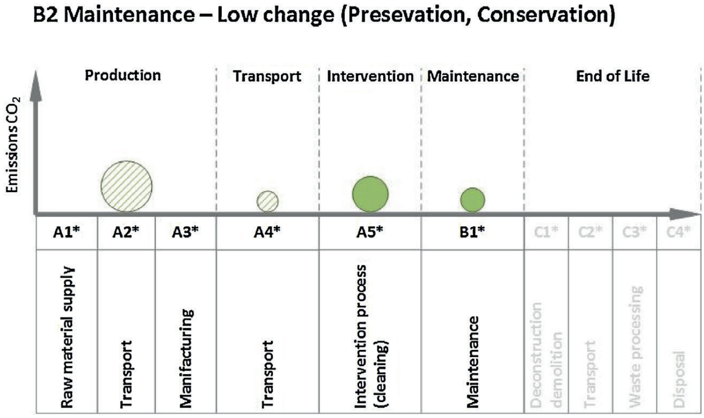


Fig. 2. CO_2 emitted (green) during low change interventions. Emissions during preventive conservation derive from the periodical cleaning and maintenance phase (solid green circle) while emissions from remedial conservation derive from the use of new materials (green striped circles). Application on existing and historic buildings from [14].

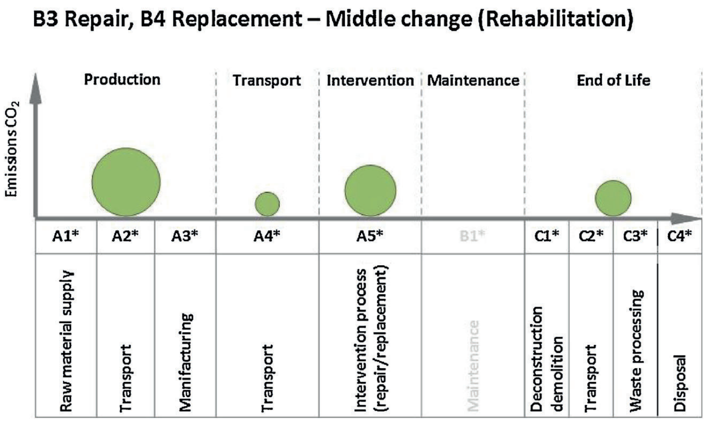


Fig. 3. CO_2 emitted (green) during medium change interventions. Generated emissions derive from the use of new materials in higher amounts than during low change interventions. Application on existing and historic buildings from [14].

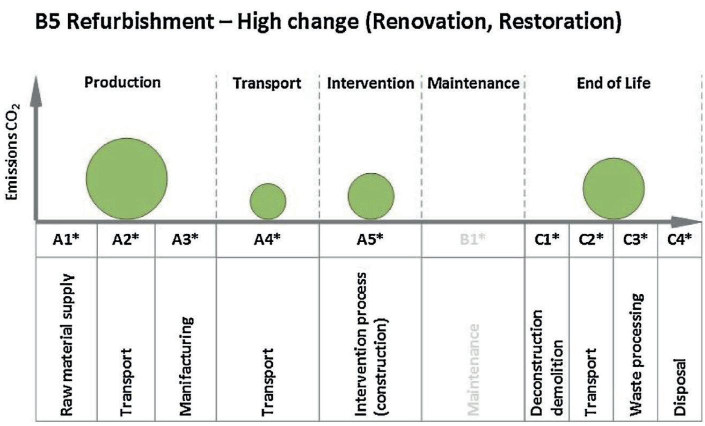


Fig. 4. CO_2 emissions (green) during high change interventions. Application on existing and historic buildings from [14].

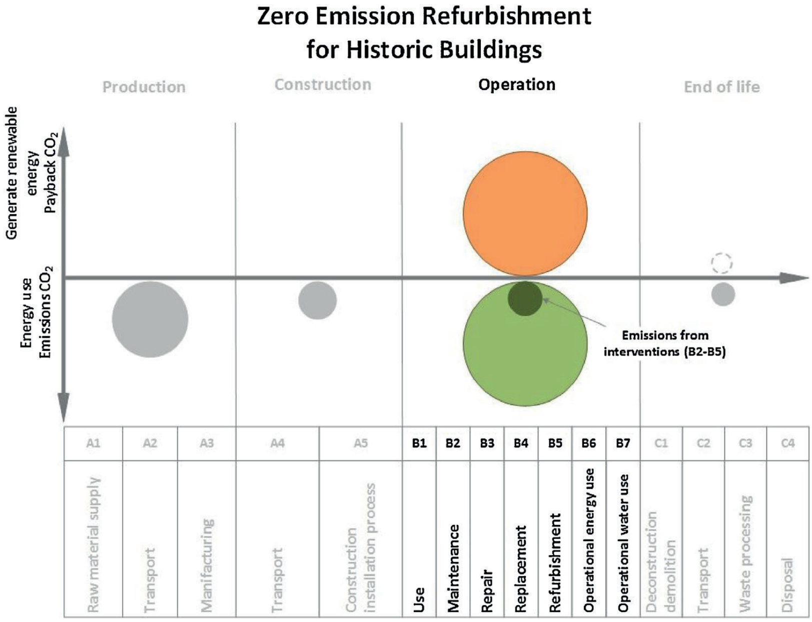


Fig. 5. Zero emission refurbishment balance for historic buildings. The emissions during the interventions are included in the emissions from the normal operation of the building in order to calculate the payback.

actions in a maintenance plan are defined according to the boundary conditions of this module and include emissions during the periodical cleaning process of a building (A5*) and processes for maintaining the functional and technical performance of the building fabric and technical systems e.g. monitoring campaigns (B1*). In case of deeper interventions that require use of new components needed for maintenance (e.g. remedial conservation works such as stabilisation and consolidation i.e. an improvement of internal cohesion of a deteriorated element usually involving addition of material), the emissions during these components production and transportation are also considered (A1*–A4*).

Medium change level (Fig. 3) refers to adaptation works (modules of repair (B3) and replacement (B4) in the standard definition [14]). For existing and historic buildings, this level refers to repair and rehabilitation categories and these stages include emissions during the production, transportation of new materials used in the repair/replacement process (submodules A*). During the adaptation work, some original building components may need to be substituted, so the emissions of these waste management and the end-of-life stage, should be also considered (C1*–C4*).

The highest level of interventions (Fig. 4) (the refurbishment (B5) module in the standard definition [14]) includes deeper actions than the possible repair and replacement of damaged materials (medium level). It may include construction of new building components that respects the fabrication technique and are compatible with original materials. Referring to the EN 15978:2011 boundaries, refurbishment works (i.e. renovation and restoration) include emissions from the manufacture and transport of new materials (A1*–A4*) and emissions during the installation and construction of items in the building as part of the refurbishment process (A5*). Also the emissions from the treatment of the removed components (C1*–C4*) has to be considered.

For historic buildings, due to the importance of the quality in the execution of interventions and material compatibility to original, more rationalized and life-cycle-emission-optimised emissions from use of local materials are expected than for the same level of intervention in existing building with low significance where higher embodied and/or transportation emissions are the consequence of cost-optimised interventions. The total emissions should be compensated with on-site renewable energy generation in order to reach a zero emission refurbishment (ZER) balance (Fig. 5). The energy should be generated while the existing and historic buildings are in use. In case of existing buildings, the emissions of the end-of-life stage should be also included for the payback balance.

As seen in Fig. 5, the total emissions to be balanced from the renewables are the sum of the emissions during the operational use of the historic building (operational use energy B6 as major contributor) with the emissions during the intervention processes (equation 3).

$$CO_2 = t^{*}CO_{2e}{}^{*}Q_{d,i} + CO_{2_{ZER}} \quad (3)$$

where:

t time of building operation in years.

CO_{2e} averaged CO_2 equivalent emission factor for Electricity (e) [kg CO_2 eq/kWh].

$Q_{d,i}$ annual electricity Delivered (d) to the building after the intervention i [kWh/m^2 per year].

$CO_{2_{ZER}}$ emissions from the intervention stage [kg CO_2 eq/m^2] [see equation (2)].

The amount of emissions from the intervention process may not be significant in comparison with emissions from operational use of the building but the selection of the right intervention process has big importance firstly in retaining value embodied in the historic fabric and secondly, for the energy efficiency in case the intervention improves the performance of the building itself. The energy performance after the intervention is expressed through a coefficient of intervention k_i, which is the ratio of the energy demand of

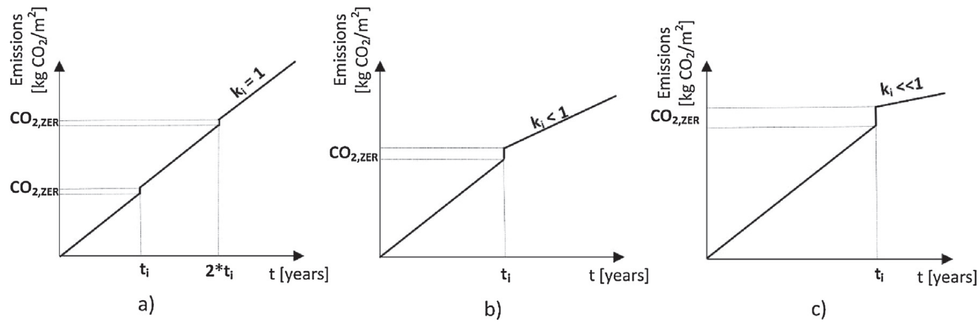


Fig. 6. Cumulative CO_2 emissions to be paid back from renewable energy sources after intervention of: a: maintenance; b: repair, replacement; c: refurbishment.

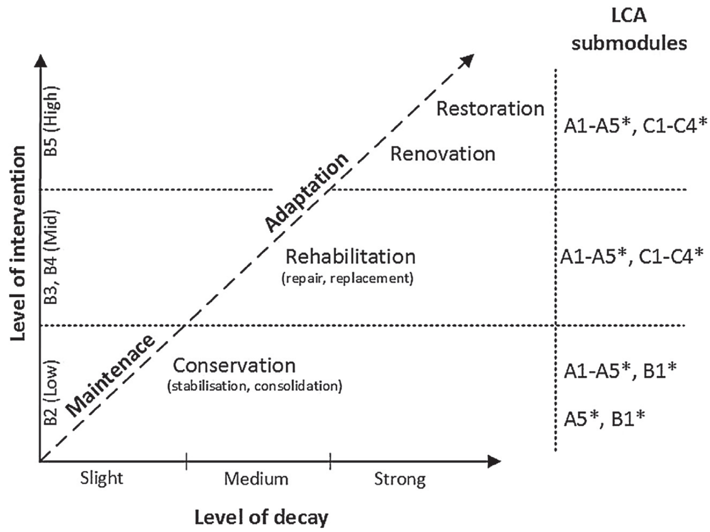


Fig. 7. Relationship between level of decay (LoD) and levels of interventions that can be applied to historic buildings. LCA stages to take into account during low, medium and high levels of interventions (column on the right).

the building after the intervention process to the demand before the intervention (i-1):

$$k_i = \frac{Q_{d,i}}{Q_{d,_{i-1}}} \qquad (4)$$

where $Q_{d,i}$ is the annual electricity delivered to the building after the intervention and $Q_{d,_{i-1}}$ is the energy demand before the intervention [kWh/m^2 per year].

According to the level of the intervention, the coefficient k_i can have two values:

- $k_i = 1$ for low change (maintenance) interventions that do not reduce the energy demand of the building;
- $k_i < 1$ for medium or high change interventions that improve the energy performance of the building.

Schematic relations between the service life of an historic building and the total emissions to be generated from renewables before and after each type of intervention (Fig. 6). Fig. 6a shows the emissions after a low change (maintenance) periodic intervention (at time t_i) that does not reduce energy demand; Fig. 6b and c express respectively the reduction of the energy demand after a medium change (repair, replacement) or a high change intervention (refurbishment).

During the service life, an historic building may be subject of more than one intervention process. In this case, the equation (3) is transformed into the equation (5) that includes all the possible interventions i applied to the building:

$$CO_2 = \sum_{i=1}^{n} (t_{i+1} - t_i)^* CO_{2e_i}{}^* Q_{d_i} + \sum_{i=1}^{n} CO_{2,ZER_i}$$
$$= \sum_{i=1}^{n} (t_{i+1} - t_i)^* k_i{}^* CO_{2e_i}{}^* Q_{d_{i-1}} + \sum_{i=1}^{n} CO_{2,ZER_i} \qquad (5)$$

where:

$(t_{i+1} - t_i)$ time of building operation until the next intervention occurs [years].

$k_i = \frac{Q_{d_i}}{Qd_{i-1}}$ coefficient of each intervention i.

CO_{2e_i} averaged CO_2 equivalent emission factor for Electricity [kg CO_2 eq/kWh].

Q_{d_i} annual electricity demand after the intervention i [kWh/m^2 per year].

$Q_{d_{i-1}}$ annual electricity demand before the intervention i [kWh/m^2 per year].

$CO_{2_{ZER},i}$ total emissions from each interventions i [kg CO_2 eq/m^2].

4.2. *Relationship between level of decay and levels of interventions*

The relation expressed in Fig. 7 links the level of decay (LoD) that may be also expressed as a condition degree of an existing and historic building or of a building element, with the type of recommended intervention. Based on visual inspection, type of material, possible degradation agents, description and extent of symptoms, the LoD is classified as an index belonging to one of the three classes. As an example, a simplified numeric evidence is applied here to the management of historic (wooden) buildings, as follows:

- LoD 1: slight symptoms, e.g. paint worn, moss on roof tiles and few broken rood tiles;
- LoD 2: medium symptoms, e.g. localized damage caused by minor wet rot infestation in panel board requiring repair;
- LoD 3: strong symptoms, e.g. leaking roof with consequent damage and major damage caused by fungal or rot infestation.

Apparently, minor symptoms may hide unforeseen damages. In addition, when grading the condition for a group of components, the grade shall correspond to the most damaged part (that hence as a higher weight in the rating), to one or more individual symptoms or to an overall evaluation of a set of symptoms.

The level of recommended interventions is also subdivided in 3 classes as already described in the text (i.e. low = maintenance, e.g. preventive conservation and cleaning; medium = rehabilitation, e.g. moderate repair and/or further investigation and maintenance and high = restoration, e.g. major intervention based on diagnosis). The numerical relation connect the class of LoD with the same class of level of intervention to avoid to overdo, to keep the addition or removal of material at minimum and to not compromise the authenticity thus maintaining the approach of minimum intervention.

The interventions of maintenance and adaptation in the plot are related to the submodules (symbol "*") presented in the paper.

4.3. *Application of the equation to two simplified scenarios of intervention*

The proposed decision-making tool for reaching ZER is illustrated in two simplified refurbishment scenarios as examples of mid-level intervention processes (repair/replacement) applied to a historic building in Norway. The emissions are calculated for interventions applied to an external wooden wall that need to fulfil the new heat transmission requirements. The original wall, typical of Scandinavian historic wooden buildings built at the beginning of 20th century, is reported in section in Fig. 8.

Calculation of the thermal transmittance (U-value) of the original wall was done using the standard EN ISO 6946:2017 [54] resulting in U = 0.298 W/(m^{2}K), while according to the Norwegian standard TEK17 [55], it should be below 0.18 W/(m^{2}K). Therefore, two refurbishment scenarios were proposed to improve the thermal transmittance of the original wall in value 0.171 W/(m^{2}K) which results in the reduction of transmission losses through the wall by 43%. The two scenarios, with the sections after the refurbishment works together with the list of intervention processes, are reported in Fig. 9. The interventions are done from the internal part of the wall in order to keep unchanged the original external facade.

New products used during the intervention are underlined in the figure while the installation processes that are considered for calculation of emissions (A5*) are shown in bold in the list of work processes. The emissions of other installation processes are not considered, as they require use of craft-based techniques, i.e. technology that is based on hand tools and/or transition work rather than in the use of tools that require energy-consumption. The processes in italic are given for the materials that will be processed later as waste.

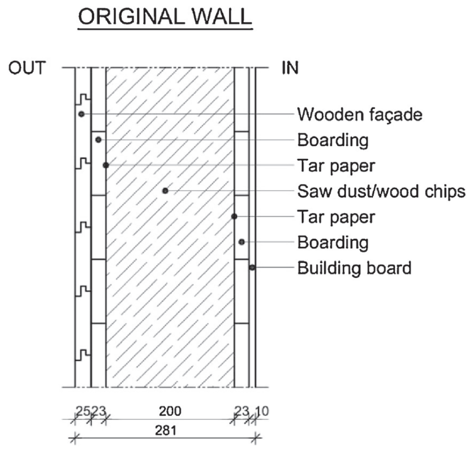


Fig. 8. The section of the original wall with the description and the dimension of its components in millimetres. The outdoor and indoor wall exposition is also highlighted.

The scenario 1 comprises the emissions during the production of the new materials (A1*–A3*), their transport to the building site (A4*) and the emissions during the installation process (A5*) while the scenario 2 includes all the above, and the emissions during the end-of-life cycle of the waste materials (C1*–C4*). The calculations to apply the proposed ZER equation (2) to the two refurbishment scenarios have been done using the ecoinvent 3.1 database [56] with the help of OpenLCA software [57].

The result, for the scenario 1 is:

$$CO_{2_{ZER},1} = \left[CO_{2_{pn}} + CO_{2_t} + CO_{2_i}\right]_1 = 19.51 + 0.24 + 0.10 = 19.85\, kgCO_{2eq}/m^2 \quad (6)$$

while for the scenario 2 is:

$$CO_{2_{ZER},2} = \left[CO_{2_{pn}} + CO_{2_t} + CO_{2_i} + CO_{2_{EOL}}\right]_2 = 10.76 + 0.44 + 0.14 + 0.97 = 12.31\, kgCO_{2eq}/m^2 \quad (7)$$

The scenario 2 has a better environmental impact, even though it requires use of more amount of new material.

The proposed ZER equation is finally applied to calculate the total emissions from the replacement of insulation considering the real dimension of the historic building, i.e. on 125.8 m^2 of total external walls. The total emissions from the replacement of insulation are:

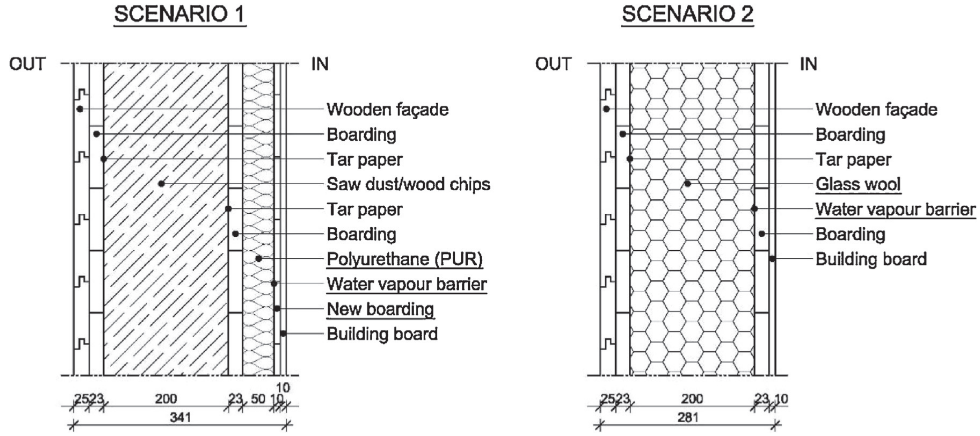
$$CO_{2_{ZER},2} = 12.31^{*}125.8 = 1548.6\, kgCO_{2eq} \quad (8)$$

In case there would have been required only a maintenance intervention (i.e. low-level intervention), e.g. paint of the internal side of the walls, the emissions for this process would have been:

$$CO_{2_{ZER},3} = \left[CO_{2_{pn}} + CO_{2_t}\right]_3 = 1.94 + 0.04 = 1.98\, kgCO_{2eq}/m^2 \quad (9)$$

and for the whole surface:

$$CO_{2_{ZER},3} = 1.98^{*}125.8 = 249.1\, kgCO_{2eq} \quad (10)$$



Scenario 1: Additional insulation:

1. Remove building board
2. **Add thermal insulation (PUR)**
3. **Add water vapour barrier**
4. **Add new boarding**
5. Reinstall building board

Scenario 2: Replacement of insulation:

1. Remove building board
2. Remove boarding
3. ***Remove tar paper***
4. ***Remove saw dust/wooden chips***
5. **Add thermal insulation (GW)**
6. **Add water vapour barrier**
7. Reinstall boarding
8. Reinstall building board

Fig. 9. The new sections of the wall after two intervention scenarios and the list of the applicable intervention processes. Bold refers to the processes that give emissions. Italic refers to materials that will be processed, later, as waste.

The ZER amount must be added to the total emissions from the annual operational phase of the building to calculate the payback from the onsite renewable energy sources. In the case of this building with two floors of 335.6 m^2 surface in total and the annual energy consumption before the intervention of 172 kW h/m^2 (corresponding to emissions factor 132 gCO_2eq/kWh), the total emissions to be compensated through the years are:

$$CO_{2,3} = t^*CO_{2e}{}^*Q_{d,3} + CO_{2_{ZER},3} = t^*0.132^*(172^*335.6) + 249.1 = 7619.5^*t + 249.1\,kgCO_{2eq} \quad (11)$$

where t is the number of years that the building will operate until the next refurbishment occurs.

When applying the second intervention scenario, for transmission losses through the walls up to 36% of the total losses, the new annual energy consumption should be:

$$Q_{d,2} = 172^*(1 - 0.43^*0.36) = 145.4 kWh/m^2 \quad (12)$$

and the coefficient of intervention:

$$k = \frac{Q_{d,2}}{Q_{d,3}} = \frac{145.4}{172} = 84.5\% \quad (13)$$

The total emissions to be equalized from the renewables during the years are:

$$CO_{2,2} = t^*k^*CO_{2e}{}^*Q_{d,3} + CO_{2_{ZER},2} = t^*0.845^*0.132^*(172^*335.6) + 1548.6 = 6438.5^*t + 1548.6\,kgCO_{2eq} \quad (14)$$

From the comparison of (11) and (14), the building reaches the same emission results after 1.1 years of operation following both interventions. Afterwards, the cumulative emissions from the building with better-insulated walls will be in smaller amounts through the time, which would result in both economic and environmental profits.

5. Discussion

The selection of the right intervention to retain the value embodied in a historic fabric is one of the greatest challenges for conservators for present and future time. However in the near future, with climate change and world energy crisis, to connect the level of conservative interventions in historic building with minimal environmental impact interventions, can become even more a challenge. This is an emerging research field where still no guidelines exist targeted to reduce carbon emission.

This paper proposes for the first time a decision-making tool composed of mathematical equations, and scenarios method for assessing emissions during maintenance and adaptive interventions in historic buildings. It follows a methodological approach that uses material life cycle data and “cradle to grave” techniques within the framework of building conservation principles.

Even if the proposed decision-making tool doesn‘t consider an holistic assessment of energy refurbishments of historic buildings, however it has the potentiality to be used for maintenance and repair scenarios as demonstrated extensively in Section 4.

It is however undoubted that further research is needed to adequately integrate the increased complexity of selecting maintenance and adaptation works for historic buildings. The main issues to take into account are:

- to formulate a mathematical expression that better return the constraints coming from the status of protected buildings where the selection of interventions have to first guarantee conservative principles;

- to formulate a multi-criteria approach that can take into account the multi-value (i.e. cultural, historic, aesthetic, social, economic) of a historic building when assigning a grade to choose the most appropriate "green conservative intervention";
- to overcome difficulties in finding complete database on materials and processes used during intervention in historic buildings;
- to overcome the lack of studies on "payback" using on-site renewable energy in existing and historic buildings.

6. Conclusions

Integrating multi-criteria approaches to decision making for reducing GHG emissions while, at the same time, ensuring long-term maintenance of existing buildings, is a challenge that needs to be faced by both the present and future generations. This paper covers important steps towards the creation of an effective zero emission refurbishment (ZER) tool for decision makers dealing with maintenance and adaptation interventions of a special category of buildings i.e. the historic buildings. The result achieved is a first attempt to develop a quantitative balance approach to assess "green conservative interventions" of maintenance, repair and refurbishment while historic buildings are in use, compensating the total emissions with on-site renewable energy generation. This method has the potentiality to become an effective tool for decision-makers when choosing among allowed/possible measures, different levels of interventions based on the legislative protection and/or the recognized values, and state or rate of decay in a historic building. The proposed decision-making tool uses equations and scenarios to estimate emissions for a set of feasible interventions as exemplified in Section 4. In the perspective of planning a long-term "green" management strategy for historic buildings, the use of a life cycle approach – within the framework of building conservation principles – provides benefits for both (1) the conservation of historic buildings e.g. choosing the right level and application time of interventions, reducing the decay, applying correct interventions and increasing the quality of used materials, and (2) the reduction of environmental impact e.g. supporting conservation needs with a minimal intervention based approach, reusing materials, and encouraging the use of renewable energy to payback even the emissions from interventions.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.culher.2018.08.010.

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Article 3

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Indoor Multi-Risk Scenarios of Climate Change Effects on Building Materials in Scandinavian Countries

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Abstract: Within the built environment, historic buildings are among the most vulnerable structures to the climate change impact. In the Scandinavian countries, the risk from climatic changes is more pronounced and the right adaptation interventions should be chosen properly. This article, through a multidisciplinary approach, links the majority of climate-induced decay variables for different building materials with the buildings' capacity to change due to their protection status. The method tends to be general as it assesses the decay level for different building materials, sizes, and locations. The application of the method in 38 locations in the Scandinavian countries shows that the risk from climatic changes is imminent. In the far future (2071–2100), chemical and biological decays will slightly increase, especially in the southern part of the peninsula, while the mechanical decay of the building materials kept indoors will generally decrease. Furthermore, the merge of the decay results with the protection level of the building will serve as a good indicator to plan the right level and time of intervention for adapting to the future climatic changes.

Keywords: climate change scenarios; mechanical decay; biological decay; chemical decay; wood; masonry; Scandinavian countries; indoor climate

1. Introduction

The Scandinavian countries are predicted to be affected by climate change not only limited to the temperature increase [1]. In Norway, long-term climate projections up to the year 2100 have demonstrated that the country will face a significant increase of annual temperature, precipitations, floods, and mean sea level while the winter snow cover and the number of glaciers will be substantially reduced [2].

It is unavoidable that the climatic changes will affect humans and their living environment. The risk assessment of building materials and components serves as a basic step for defining the adaptation measures that need to be applied in buildings to adjust them to the "new" climate. In this context, several studies have been carried out to assess the decay level of the Scandinavian building stock induced by climate change regarding the type of constructive material: wood [3,4], masonry [5,6], and concrete [7].

Within the built environment, historic buildings are among the most vulnerable structures due to their relatively older age and un-renewable values that they represent. The report from UNESCO World Heritage Centre states that the impacts of climate change are affecting many and are likely to affect many more World Heritage sites, both natural and cultural in the years to come [8]. The topic has gained a lot of attention in the last decades with many studies focused on the intersection between the climate change and cultural heritage management [9]. The objective of these research studies is to assess the potential impact of the climate change in heritage sites and propose strategies to face the future risks [10–12]. In addition, many international projects at European level have been running or are ongoing with the primary goal to alleviate the negative effects of the decay induced by climatic changes [13,14].

Due to its severity, the impact of the climate change has obtained high attention in the Scandinavian cultural heritage sector where intergovernmental meetings with a focus on conservation, planning, and management of the cultural environment have been held [15]. Their scope is to assist the cultural heritage managers in adapting to climate change and to strengthen the collaboration between the Scandinavian countries [16]. To this aim, a step-by-step methodology is proposed in this article for helping the heritage owners and managers to evaluate possible climate-induced risk on building materials and take precautions against it [17].

The achievements of the materials science researchers and cultural heritage specialists regarding the effects of climate change are important, but they should be merged to find suitable adaptation interventions that satisfy the demands of both communities. The scope of our article is to link the majority of climate-induced decays that can affect historic buildings with the level of legislative adaptation intervention (small, medium, large) allowed to them in one multidisciplinary method. The use of available data from the European project Climate for Culture (CfC: 2009–2014) [18] is enhanced in the proposed method. The data are used to estimate the total level of decay in a range of 16 buildings, with different sizes and construction materials, with the purpose to quantify the comprehensive effects of the expected climate change in the far future (2071–2100). The simulations provide information to cultural heritage managers and help the stakeholders to understand the type of structure that resists better, in natural conditions, to climate change impact and the geographical locations that are more exposed to risk in the Scandinavian region. This type of information is extremely valuable because, after the merge with the protection level of the building, it serves as a good indicator to plan adequate adaptation interventions and implement them with the necessary level of urgency.

2. Materials and Methods

2.1. Climate for Culture Project

The European project Climate for Culture, which investigated the potential impact of climate change on Europe's cultural heritage assets, particularly on historic buildings, provided high-resolution risk maps that identify the most urgent outdoor risks for European regions until 2100 but also risks for indoor collections [13]. These maps are the output of climate change scenarios coupled with building simulations at the European scale and serve as a powerful tool for preventive conservation and decision-makers that deal with cultural heritage [19]. The maps, through the colour codes, show the level of risk, both for outdoor and indoor environments, for 16 building types and 19 environmental variables. The results of the project can be used to understand how the climatic changes affect the buildings in natural conditions (without the use of indoor heating, ventilation, and air conditioning (HVAC) systems) in relation to their geographical location, building size, window size, and constituting material.

2.1.1. Description of Buildings and Climatic Data

In the CfC project, the general assessment and map creation process has been carried out using the following specifications:

- Emission scenario

The impact of climate change on historic buildings was evaluated using the high-resolution regional climate model REMO [20] which provides climate change projections for entire Europe at 12.5 km spatial resolution. Two emission scenarios were applied in the project. The first is the mid-line A1B scenario [21], which considers a CO_2 emission increase until 2050 and a decrease afterwards. The second is the more recent Representative Concentration Pathway 4.5 Emission Scenario (RCP4.5) of the Intergovernmental Panel on Climate Change (IPCC) assessment report 5

(AR5) [22]. This scenario is based on long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover, which stabilizes radiative forcing at 4.5 watts per metre squared (approximately 650 ppm CO_2 equivalent) in the year 2100 without ever exceeding that value.

- Locations

Climate data assessment and simulations were calculated for a regular grid that covers entire Europe including the Mediterranean region.

- Time windows

The climate data were produced for all the climate-induced variables from hourly data elaboration over two 30-year time windows: 2021–2050 (Near Future) and 2071–2100 (Far Future), maintaining the period 1961–1990 (Recent Past) as a reference period (Table 1).

Table 1. The time windows used for simulations in the Climate for Culture project.

Recent Past (RP)	Near Future (NF)	Far Future (FF)
1961–1990	2021–2050	2071–2100

- Future indoor climates and risk assessment

The outdoor climate influences the cultural heritage structures, both in terms of outdoor and the indoor environment [13]. The future climate predictions explained above were used to create the risk maps for the outdoor environmental variables, which provide important information for decision makers to plan outdoor adaptation measures. These climate change predictions linked with building simulations allow the estimation of indoor climate variables (temperature T, relative humidity RH) and indoor damage variables for mechanical, chemical and biological decay using an automated method [23]. The risk induced indoor by climate change is assessed by the combination of indoor climate data with the damage functions of the variables [24].

- Buildings

Indoor climates of historic buildings were modelled and simulated following two different approaches. The first consisted of the development of a full-scale multizone dynamic hygrothermal whole building simulation while the second used a simplified hygrothermal building model. The first model gives more detailed results about the temperature and relative humidity inside the building, but it has a high development cost and takes long simulation time. The simplified model provides reliable results within a short simulation time and for this reason, it was applied in the CfC project to predict indoor temperature and relative humidity. It has the restriction to be effective to buildings without active HVAC systems and to request all the necessary measured values for the parametrisation of the model [13]. Through this model, it was possible to perform simulations on 16 generic sacred buildings, virtually located in all the grid cells, for producing indoor climate data and risk maps. The general layout of buildings is composed of a rectangular floor plan, a gable roof, and long walls in the North-South direction with windows only on the long walls. Each of the buildings is unconditioned and their matrix is a combination of their volume (small/large), window area (small/large), structure (heavyweight/lightweight), and moisture buffering capacity (MBP) (low/high) as given in Table 2.

Table 2. Generic sacred building matrix.

		Heavyweight		Lightweight	
		Low MBP	**High MBP**	**Low MBP**	**High MBP**
Small Building	**Small Window**	Building 1	Building 2	Building 3	Building 4
	Large Window	Building 5	Building 6	Building 7	Building 8
Large Building	**Small Window**	Building 9	Building 10	Building 11	Building 12
	Large Window	Building 13	Building 14	Building 15	Building 16

2.1.2. Indoor Deterioration Variables

The variables, according to the CfC results, for each mechanism of indoor deterioration (mechanical, chemical, and biological) and assigned to different building materials (wood, masonry, and concrete), are reported in Tables 3 and 4 [25].

Table 3. The main variables to estimate indoor deterioration in wooden buildings.

Mechanical Damages	Chemical Degradation	Biological Deterioration
Panel (base material)	Lifetime multiplier	Mould
Panel (pictorial layer)		Insects
Jointed element		
Cylindrical element		

Table 4. The main variables to estimate indoor deterioration in masonry and concrete buildings.

Mechanical Damages	Chemical Degradation	Biological Deterioration
Salt crystallisation cycles	Lifetime multiplier	Mould
Thenardite-Mirabilite cycles [1]		
Freeze-thaw cycles		
Frosting time		

[1] Only for concrete structures.

A short explanation for the indoor decay-linked mechanisms, according to the CfC deliverable D4.2 [24], is given as follows:

- Mechanical risk for wooden elements: panels, jointed elements, cylindrical elements

The *RH* of the air affects the moisture content (MC) in a wooden element. As the moisture content changes, so do the dimensions of the element, which set up internal stresses that lead to deformations. At low stresses, the wood behaves elastically, with reversible deformations while above a certain threshold of strain (the yield point), the deformation becomes plastic, the change is not reversible anymore and the material fails. The damage functions used in CfC for this type of elements are based on Marco Martens' interpretation [26] of studies by Mecklenburg, Bratasz, and Jakiela [27–29]. Different response times are used in the algorithm to smooth out the *RH* fluctuations in order to represent better the moisture changes experienced in the substrate of different building elements in wood. The strains induced by the expected changes are calculated and a final assessment is made to evaluate if the resultant strain falls in the area of elastic (green code), plastic (orange code), or failure (red code) response.

- Mechanical risk for masonry and concrete

Salt-crystallization cycles. Damage from salt crystallization occurs at the interface between air and the object, or beneath the surface of the object. The surface gets covered by a mass of small crystals that destroy the visual integrity or disfigure the natural appearance of masonry or concrete. When this occurs below the surface, the visible result is surface disruption and loss of material. The damage function for stone weathering is studied from Grossi et al. [30] and predictions in the context of climate change are discussed in the atlas of Noah's Ark project [31] and reported by Lankester and Brimblecombe [32]. The damage function used in CfC for calculating the number of cycles counts the transition that occurs in a range around 75% *RH* (independently from the temperature) as this is the threshold of deliquescence of the sodium chloride.

Thenardite-Mirabilite cycles. Similarly, the porous stone might be destroyed due to the pressure exerted during the transition from the thenardite (Na_2SO_4) to the mirabilite ($Na_2SO_4 \times 10H_2O$) that occurs with the inclusion of 10 molecules of water in the hydrated crystal. Mirabilite exerts a very high crystallization pressure on the porous wall causing the damage of stone. A pressure of about 10 MPa occurs when the *RH* increases across value described by a critical $RH = 0.88 \times T + 59.1$. Repeated cycles may accumulate stress and in the long-term, they may cause severe decay. The damage function used in CfC counts the transition that occurs in the thenardite-mirabilite system and estimates a green code for up to 60 cycles; orange code for 60–120 cycles and red code over 120 cycles.

Freeze-thaw cycles. When water goes from liquid to solid phase within a porous masonry element or in a structural crack, it increases in volume, which can cause damaging stress. If this stress is repeated in a cyclic way, the brick or stone becomes weaker, and eventually delaminates and spalls. The theoretical background of freeze-thaw cycles is discussed by Camuffo [33] and in the atlas of Noah's Ark project [31]. The damage function counts the number of cycles between $T < -3$ °C (freeze) and $T > +1$ °C (thaw) that occur in one year. The results of CfC maps indicate a green code for up to 30 freeze-thaw cycles, orange code for cycles between 30 and 60 and red code for more than 60 cycles during the year.

Frosting time is considered the total amount of time (in hours) during the year when the air temperature (outdoor or indoor) is below zero degrees Celsius. The effect of frosting time over cultural heritage materials has been studied by Camuffo [33]. Separately, this variable is not helpful to predict material damage but it may serve as an indicator for further investigations. Frosting time can be a useful parameter in sub-zero temperature zones (many zones in the Scandinavian countries) where it determines the penetration risk of the ice front through the building wall. The level of risk according to CfC maps is estimated green for up to 2400 h/year, orange for frosting time between 2400 and 4800 h/year, and red for more than this value.

- Chemical risk

Lifetime Multiplier (LM) is the ratio between the predicted lifetime of the material subjected to the environmental conditions and the predicted lifetime at standard conditions of 20 °C and 50%RH. When $LM > 1$, the material will last longer than the standard conditions (green code) while for $LM < 1$, the rate of deterioration is greater and the lifetime shorter. The level of $LM < 0.5$ (half of lifetime), is defined as the threshold of high risk and is illustrated in red.

The calculation of the *LM* for different types of materials is done using the Equation (1) derived by Michalski [34]:

$$LM = \left(\frac{50\%}{RH}\right)^{1.3} \times e^{\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{293}\right)} \quad (1)$$

where *RH* is the relative humidity [%], *T* is the absolute temperature [K], E_a is the activation energy [J mol^{-1}], and *R* is the constant of gas (8.314 [J mol^{-1} K^{-1}]).

In the calculations, the value of activation energy (the least possible amount of energy which is required to start a reaction) is considered 59.24 kJ mol^{-1} for wood and 42.5 kJ mol^{-1} for masonry and concrete. The values are taken as average because the activation energy can vary for a different range of materials. The equation does not consider the effects of very low or very high *RH* but it can be a good indicator of the decay rate if the *LM* will increase or decrease in the future.

- Biological risk

Mould growth is an extensive problem that implicates the human health and the integrity of the material. The effects on heritage items can vary from light powdery dust to severe stains, which weaken and disintegrate the substrate material. It is assumed that at temperatures above zero degrees Celsius and relative humidity above 70% the mould spores can germinate. The rate of growth depends on the climatic conditions, type of material but also the accumulation of dirt and dust in case of inorganic materials. The CfC maps have been developed using the Sedlbauer isopleths system [35] and they consider a growth rate of less than 50 mm/year as safe (green), a growth rate between 50 and 200 mm/year as possible damage (orange), and an annual growth rate greater than 200 mm as damage (red).

Insects can be another cause of damage to heritage items. The damage can be caused by certain moths and beetles and some forms of insects such as silverfish and booklice. The risk of damage from insects depends on relative humidity for some species and on temperature for most insect types. The key factors in assessing risk are climatic conditions, type of insect, and the vulnerability of the organic material such as wood. The insects' activity is present in temperatures of 5–30 °C but below 15 °C, their damage is limited [36]. The results for the CfC project have been achieved by calculating the annual degree-days over 15 °C ((days × $(T - 15)$) with $RH > 75\%$ and $T < 30$ °C for humidity dependent insects and $T < 30$ °C for temperature dependent ones.

2.2. Risk Assessment

The tool presented here tends to be general as it assesses the total decay level for the building materials. For this reason, the results of all decay-linked variables explained in the Section 2.1.2 and simulated in the CfC project, will be used as input to assess the overall deterioration of different building materials. The level of decay for each variable is divided into 6 category levels: very low, low, medium, medium-high, high, and very high. The threshold values for each decay level are established from the description of the variables in the CfC deliverable D4.2 [24] and the colour code of the risk maps from the project output which considers the likelihood and the impact of the decay. The boundary value for each level is shown in Table 5.

Table 5. The table of risk assessment for the main deterioration variables.

Variable Name	Unit	Very Low	Low	Medium	Medium-High	High	Very High
Panel—base material	[-]	0.333	0.667	1	1.333	1.667	2
Panel—pictorial layer	[-]	0.333	0.667	1	1.333	1.667	2
Jointed element	[-]	0.333	0.667	1	1.333	1.667	2
Cylindrical element	[-]	0.333	0.667	1	1.333	1.667	2
Salt crystallisation cycles	[no/year]	30	60	90	120	150	180
Thenardite-Mirabilite cycles	[no/year]	30	60	90	120	150	180
Freeze-thaw cycles	[no/year]	15	30	45	60	75	90
Frosting time	[h/year]	1200	2400	3600	4800	6000	7200
Lifetime multiplier—Wood	[-]	1.5	1.25	1	0.75	0.5	0.25
Lifetime multiplier—Masonry	[-]	1.5	1.25	1	0.75	0.5	0.25
Lifetime multiplier—Concrete	[-]	1.5	1.25	1	0.75	0.5	0.25
Mould growth	[mm/year]	25	50	125	200	400	600
Insects—humidity dependent	[DD/year]	500	1000	1500	2000	2500	3000
Insects—temp. dependent	[DD/year]	500	1000	1500	2000	2500	3000

Firstly, the level of risk is weighed for each decay-linked variable using the thresholds given in Table 5. In the second step, depending on the constituting building material, the risk is evaluated for each mechanism of deterioration: mechanical, chemical, and biological. When more than one decay-linked variable is needed to evaluate the level of deterioration of a specific mechanism (e.g., mechanical decay), the highest risk level among the variables determines the risk level of the entire mechanism. This assumption has been made by assigning the same importance to each-decay linked variable due to their likelihood and associated impact. The third and last step is the assessment of the total level of decay of the building, based on the rating of the three deterioration mechanisms computed in the second step. The same assumption as in the previous step is used, i.e., the mechanism with the highest level of risk determines the total level of decay of the building.

2.3. Historic Significance Assessment

In parallel with the decay assessment, the other stage that deals with the assessment of the historic values of the buildings, should be performed. While the first stage covers the technical and physical characteristics of the building, the significance assessment highlights the social, artistic, and cultural aspects of it. The assessment of the character-defining elements (CDEs) is very important prior to take adaptation actions in historic buildings because it safeguards the values that need to be preserved and avoids incorrect or irreversible interventions [37].

On this background, a tool named DIVE (Describe, Interpret, Valuate, and Enable) has been developed for assessing the historic significance of buildings and suggesting the potential field for actions/interventions [38]. The method is a result of two international projects "Sustainable Historic Towns: Urban Heritage as an Asset of Development" (SuHiTo: 2003–2005) [39] and "Communicating Heritage in Urban Development Processes" (Co-Herit: 2007–2008) [40] with partners from Finland, Lithuania, Norway and Sweden and it emphasizes the importance of collaboration between cultural heritage professionals and decision-makers.

The name of the method is an acronym of the four main stages of it that are connected like links in a chain (Figure 1). DIVE is an interdisciplinary and participatory methodology that involves different target groups from both the public and private sector. The tool has been applied to different cultural environments in North Europe like in the towns of Jakobstad in Finland, Naujoji Vilnia in Lithuania, Odda and Tromsø in Norway, Arboga in Sweden, etc. [40].

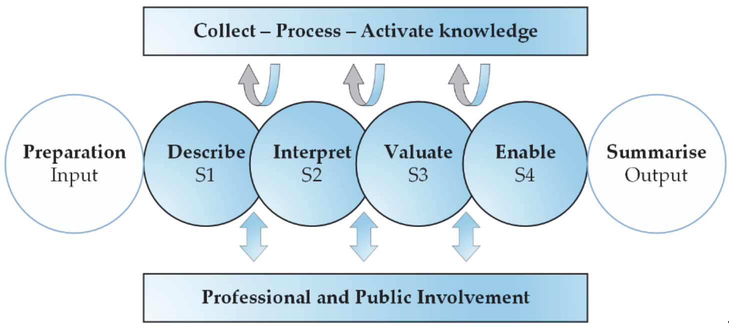


Figure 1. Structure of the DIVE approach.

The output of the method enhances the simultaneous importance of preserving social, cultural, and physical features of the buildings in the future development of historic urban districts by stating the attributes that carry a primary role and those that are of secondary importance. The recommendations are given for every attribute (shape, windows, ceiling, stairs, walls, etc.) that are grouped into four main categories: exterior, interior, structure, and use of the building. The analysis tends to categorise the buildings according to the values that they represent as well as the scale of interventions (capacity to change) allowed on them [38].

According to DIVE output, the capacity of a building to change can be of a small, medium or large scale (e.g., preservation of the window frame, replacement by keeping the same format and proportions or replacement with a new window). Meanwhile, during the application of the method in case studies, the applied grading system results with six intervention levels by adding also intermediate levels: none to small, small, small to medium, medium, medium to large, and large corresponding to the levels of protection: very high, high, medium-high, medium, low, and very low [41].

3. Results

3.1. Matrix of Selection of Adaptation Intervention

Finding the best adaption intervention scenario in historic buildings is a complex process because it has to boost the historic value of the building, to decrease the damage of the decay processes, and, at the same time, to satisfy the increasing demands regarding the minimisation of carbon footprint and energy use. For this reason, the intervention should take into consideration three important parameters: level of protection that safeguards the significance of the historic building, level of decay in the building and the environmental impact of the intervention by minimizing the use of new materials and energy. The environmental impact has a substantial contribution towards the minimization of the climate change impact and should be considered throughout the selection of the adaptation intervention [37].

A possible adaptation scenario in an historic building should be able to respond properly to the expected level of climate-induced decay. In addition, the level of intervention should decrease the expected damage in a conservative approach. This can be achieved by linking the results of the risk assessment (Section 2.2) with the historic value assessment (Section 2.3). The proposed matrix that connects the levels of decay with the levels of legislative protection in historic buildings is given in Figure 2.

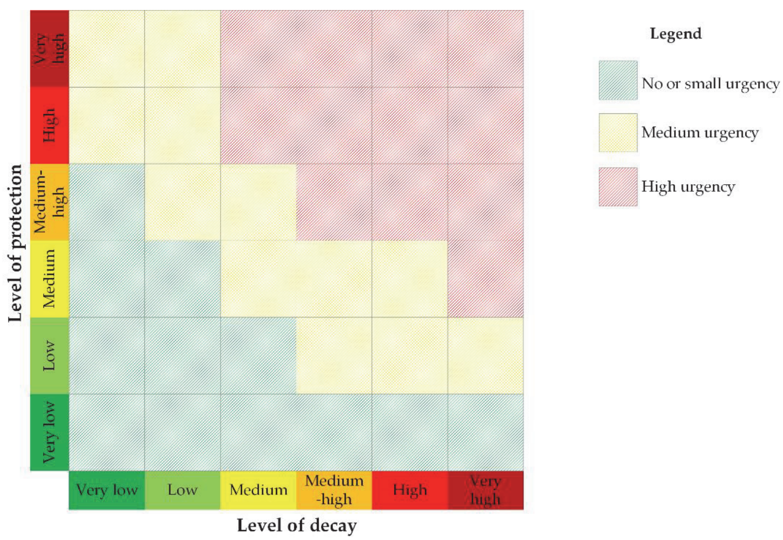


Figure 2. The link between the levels of decay and the levels of protection in historic buildings. The colour code highlights the urgency need for adaptation interventions.

The matrix is an useful tool for the decision-makers because it represents the limits of effectiveness of an adaptation intervention by considering both the level of deterioration and the scale of intervention allowed to the structure. Figure 2, through the colour codes, indicates the urgency needs before planning and implementing adaptation interventions. The riskiest situations (red nuances in the right-upper side of the matrix) can occur when a very valuable historic building is subject to natural hazards or catastrophic events such as earthquake, fire, floods, wars, etc. or in heavy conditions due to continuous disuse and lack of maintenance. In such cases, the legislative requirements of small interventions (e.g., ordinary maintenance and cleaning) cannot solve the strong symptoms of decay and therefore, higher level of interventions is required with urgency. The intervention target should be primarily directed towards the stability of the structural elements in order to avoid the collapse of the whole structure and the loss of the cultural heritage.

When the deterioration level is high or very high, the judgement can confirm (green nuance) or exceed (yellow and red nuances) the scale of the allowed interventions, depending on the protection category of the building [42,43]. However, examples of wrong, heavy or useless invasive interventions on architectural heritage sites exist after disastrous events [44] or as a result of wrong decision-making processes (e.g., the refurbishment case of the Matrera castle in Spain where smooth concrete walls were added to the original stone structure). Safety interventions, necessary to avoid collapses during the aftershocks or long disuse of the building, can hide or reduce the value of the original historic building when no compatible or durable materials are used. After such interventions, the return of the structure to the original form can be more difficult and expensive.

When the level of decay does not affect the load-bearing capacity of the structure but comes as a result of natural weathering (up to medium-high decay), the selected intervention should maintain the historic attributes of the building, through the applications of both preventive conservation measures and non-destructive interventions [45,46].

In the left-lower side of the matrix, the green area reports the "ideal" situation, i.e. when the building itself has not many CDEs at risk and/or when the decay level is not high to be kept under control using conservative interventions. However, bad conservative practices can fall even in the green area of Figure 2. These overdoing practices, common when adapting a historic building to modern use (e.g., change of use or capacity) or to new comfort requirements, do not always fit with the original design of the building and have the additional risk to use unnecessary economic and environmental resources.

3.2. Influence of Climatic Changes to Future Interventions in the Scandinavian Countries

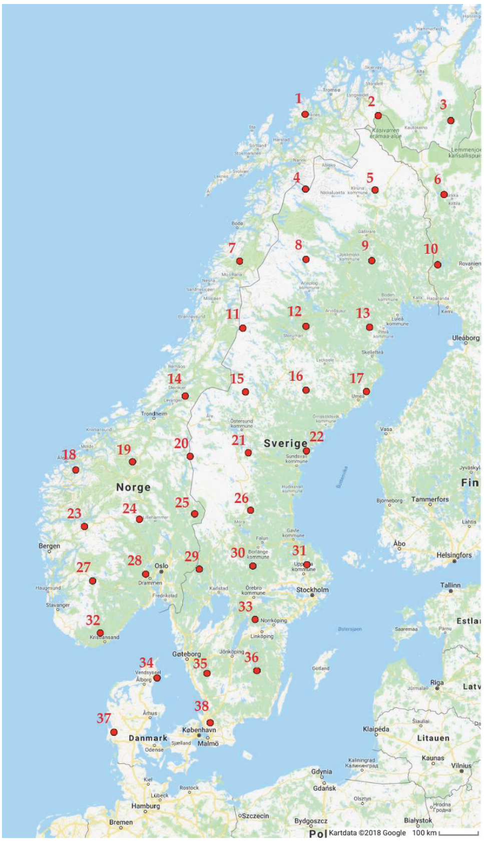
The climate change effect will affect the deterioration level in historic buildings depending on the geographic location and type of constructive material [31]. For this reason, cultural heritage managers have to plan and implement adaptation actions that can work effectively for the years to come [47]. An effective adaption intervention has to consider not only the actual situation of the building but also the effects of the climate change over an extended period. In the following example, the level of decay is estimated over two time windows: the Recent Past (RP) and the Far Future (FF) to evaluate the expected effect of climatic changes over building materials. Thirty-eight locations in the Scandinavian countries are extracted from the general European and Mediterranean grid of the CfC project. The coordinates and the labels of each location are provided in Table 6.

For each location, data from the 16 generic sacred unconditioned buildings are taken from the CfC project simulations in term of indoor conditions. In the project, the choice of working with scenarios in unconditioned buildings (without indoor HVAC systems) was made because the climate change effects can be more clearly identified indoors and due to the limitations of the simplified simulation method. The values of the variables are taken from the RCP4.5 emission scenario, because it is the most recent one.

3.2.1. Decay-Linked Variables

Charts that visualize the connection between the decay-linked variables and the geographic location of the buildings are created for the RP and FF time windows and collected in Supplementary Materials. In the charts, only the set of dots has a numerical meaning; however, the dots of the same building are connected with lines and colour codes to facilitate the reading and allow distinguishing the values among buildings sizes and materials. The charts in Supplementary Materials are presented for each climate-induced variable in relation to the time window, geographical location, material, and size of the building.

Table 6. The map and the coordinates of the 38 locations extracted from the Climate for Culture project (image generated from [48]).

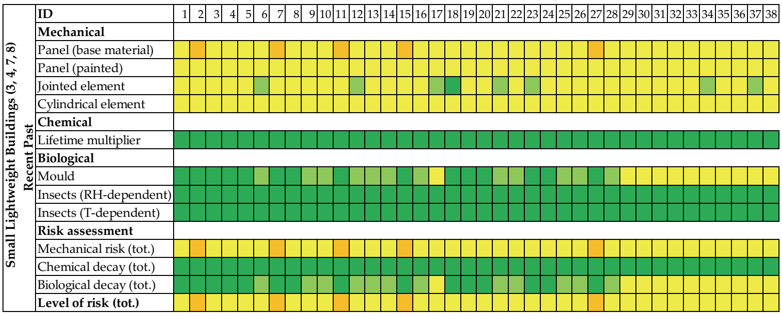


Map	ID	Lat.	Long.	Country
	1	69.2898	17.5711	Norway
	2	69.2659	21.1079	Norway
	3	69.1791	24.6277	Norway
	4	67.9698	17.5926	Sweden
	5	67.9471	20.9522	Sweden
	6	67.8647	24.2975	Finland
	7	66.6144	14.4121	Norway
	8	66.6498	17.6118	Sweden
	9	66.6282	20.8133	Sweden
	10	66.5496	24.0026	Finland
	11	65.2960	14.5712	Sweden
	12	65.3298	17.6291	Sweden
	13	65.3092	20.6884	Sweden
	14	63.8928	11.7972	Norway
	15	63.9774	14.7152	Sweden
	16	64.0099	17.6447	Sweden
	17	63.9901	20.5754	Sweden
	18	62.2671	6.5031	Norway
	19	62.4467	9.2598	Norway
	20	62.5775	12.0436	Sweden
	21	62.6587	14.8462	Sweden
	22	62.6899	17.6589	Sweden
	23	60.9630	6.9321	Norway
	24	61.1359	9.5886	Norway
	25	61.2618	12.2690	Norway
	26	61.3399	14.9660	Sweden
	27	59.6575	7.3273	Norway
	28	59.8244	9.8912	Norway
	29	59.9457	12.4764	Sweden
	30	60.0210	15.0762	Sweden
	31	60.0499	17.6838	Sweden
	32	58.3510	7.6928	Norway
	33	58.7020	15.1779	Sweden
	34	57.1994	10.4305	Denmark
	35	57.3127	12.8455	Sweden
	36	57.3829	15.2722	Sweden
	37	55.7352	8.3487	Denmark
	38	55.9958	13.0108	Sweden

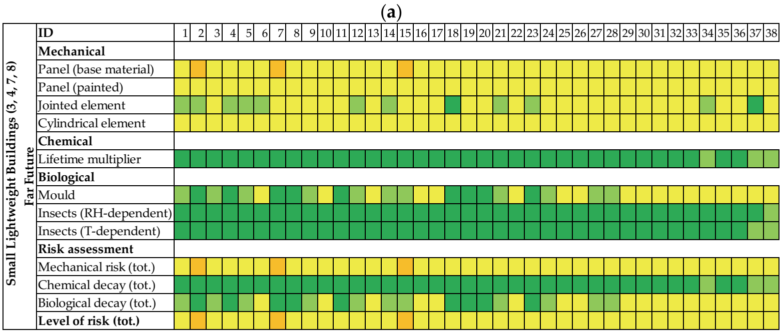
3.2.2. Level of Decay

Wood is the dominant structural material of the constructions in the Scandinavian countries. The decay assessment for wooden buildings is computed using the CfC data related to lightweight buildings for both small (3, 4, 7, 8) and large (11, 12, 15, 16) building sizes (see Table 2). For structures in masonry or concrete, the decay level is assessed using the CfC data related to heavyweight buildings regarding the two size groups: small (1, 2, 5, 6) and large (9, 10, 13, 14). The decay assessment is performed for each group of four buildings using the methodology described in Section 2.2, for both the RP and FF. Given a specific location, the level of a decay-linked variable is evaluated considering the highest value of the variable within the group of four buildings that represents a specific building material and size.

The results of the risk assessment for each mechanism of deterioration (mechanical, chemical and biological) and for the total level of risk regarding small/large and light/heavyweight buildings in the two time windows are reported in Figures 3–6, using the risk assessment colour code (Table 5).

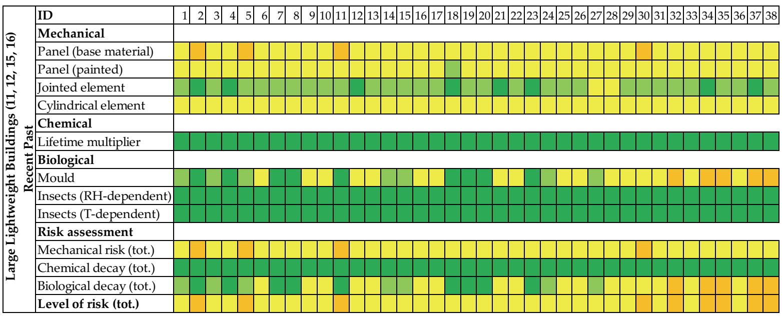


(**a**)

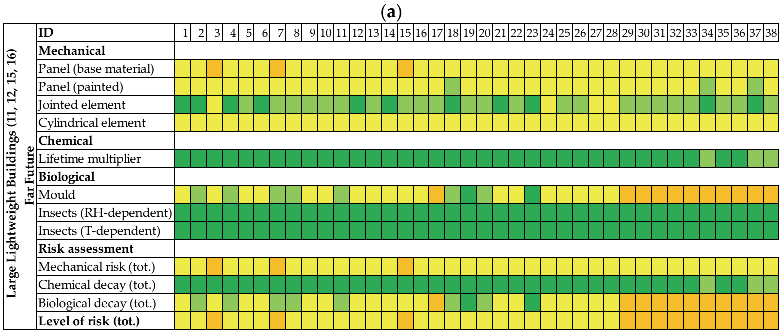


(**b**)

Figure 3. Risk assessment matrix of the deterioration of small lightweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

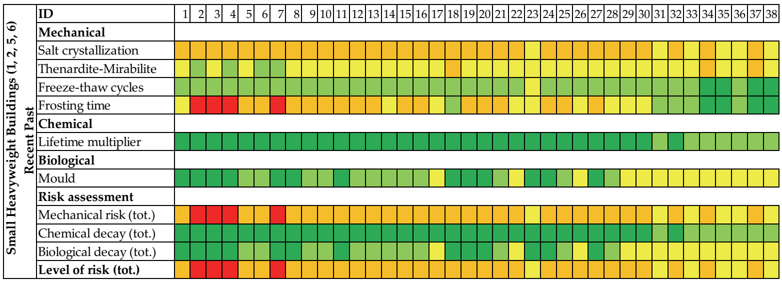


(**a**)

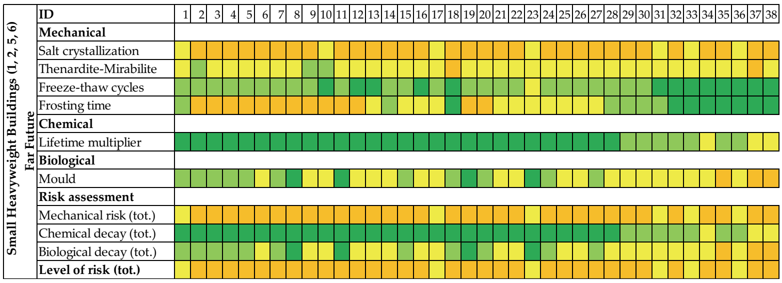


(**b**)

Figure 4. Risk assessment matrix of the deterioration of large lightweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

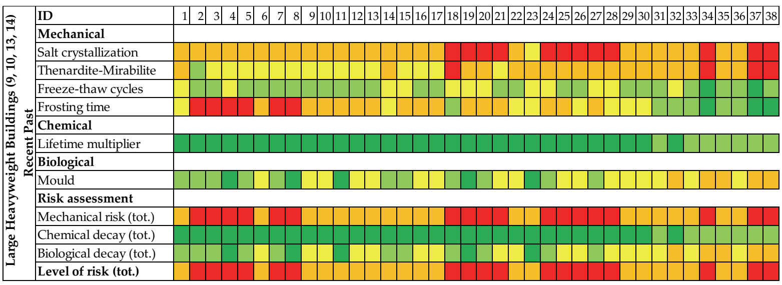


(**a**)

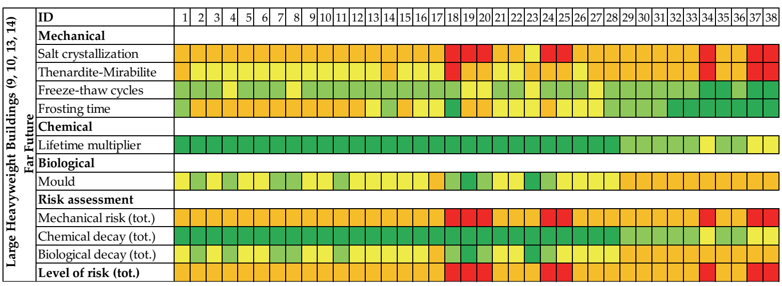


(**b**)

Figure 5. Risk assessment matrix of the deterioration of small heavyweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).



(**a**)



(**b**)

Figure 6. Risk assessment matrix of the deterioration of large heavyweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

From an overview analysis of the graphs in Supplementary Materials and the risk matrices, which summarize the single types of risk and the total level of risk, it is noticed the following:

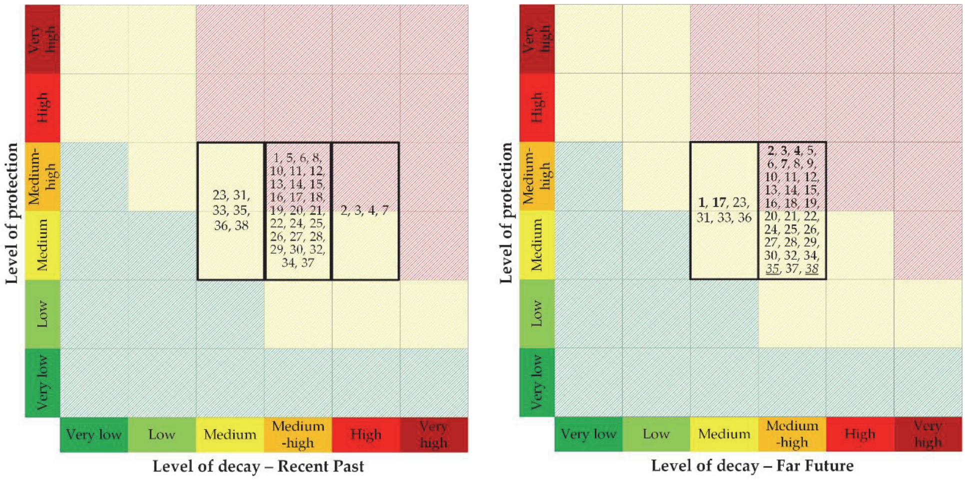
- In Scandinavian countries, the mechanical deterioration indoor in all types of buildings has a general decrease in the Far Future, although the decay remains in the ranges of medium to high risk.
- The chemical and biological risks increase. The former, exemplified by the lifetime multiplier indicator, remains in the range of low decay, except for the last locations in the map, corresponding to the south of Scandinavian Peninsula and Denmark (ID: 29–38) where the risk increases to a low or medium level. In the other ID points, the increase is still distinguishable, but it remains within the same level of risk for the buildings.
- The biological risk increases the number of locations in which the decay will fall in low, medium, and medium-high, especially in western Sweden, south of Scandinavian Peninsula and Denmark.
- Regarding the risk level over the Recent Past (1961–1990), high level of risk (red colour) in the indoor environment is noted only for heavyweight buildings, which resemble the masonry or concrete constructions. This level is caused by the mechanical damage in the building materials and has a throughout geographical distribution: in northern Scandinavian Peninsula (ID: 2–5, 7–8) due to the frosting time, while in central and southern parts of the peninsula (ID: 18–21; 24–28; 34; 37–38) due to the salt crystallization by sodium chloride and the transition from thenardite to mirabilite. In the Far Future (2071–2100), the risk tends to decrease because of the climatic changes, e.g., the risk due to frosting time in the northern peninsula will have a transition from high to medium level (ID: 2–5, 7–8).
- Specific effects of the climate change are also noted when the sizes of the buildings are compared. In all the three deterioration mechanisms, the level of risk in large buildings (ground floor area larger than 320 m^2) results higher in comparison with small buildings, regardless the time window, constituting material, and the geographical location. In the Far Future, the decay risk of large lightweight buildings in the southern part of the peninsula (ID: 29, 32, 34–35, 37–38) will be medium-high due to climate change while small buildings in the same locations will face medium risk. Regarding heavyweight buildings in the Far Future, large ones will be disposed to high risk in central and southern areas (ID: 18–20, 24–25, 34, 37–38) while small buildings in these areas will remain at medium-high risk level.

3.2.3. Level of Intervention

The overall scenarios of the climate change effects on building materials, reported in each multi-risk table, can be used from the stakeholders to choose the urgency of the adaptation interventions that need to be implemented on historic buildings. This is achieved by linking the level of total decay of the buildings with the level of protection and adaptation interventions permitted by law. By applying the matrix in Section 3.1, the stakeholders can compare the actual urgency level (RP) on specific building materials, sizes, and locations in Scandinavian countries with those expected over the Far Future.

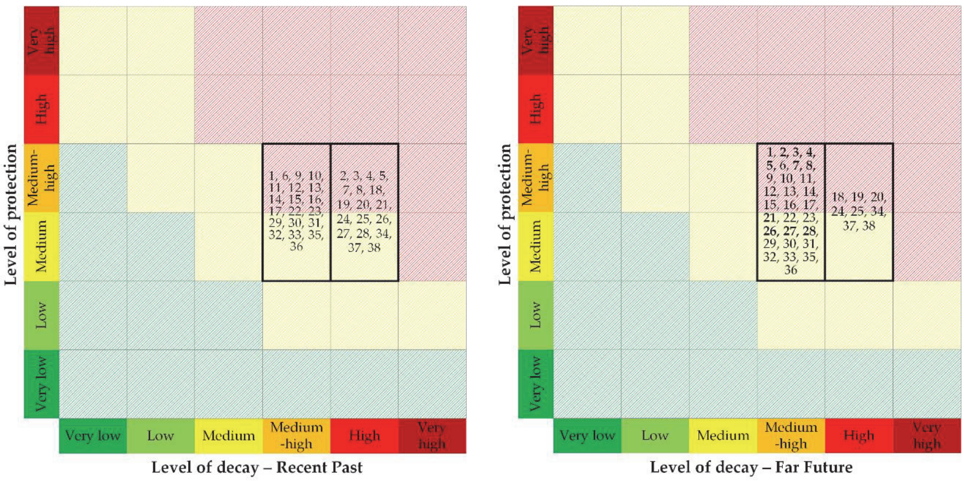
The locations in the Scandinavian countries, where interventions are required to minimize the risk of losing CDEs in historic heavyweight buildings, are inserted in the matrices in the Figures 7 and 8. The level of protection of the buildings according to the legislation is considered medium and medium-high in all the locations, which resembles small to medium and medium capacity to change.

Figure 7 shows the urgency levels of small heavyweight buildings to adapt measures that minimize the decay over the RP (Figure 7a) and the FF (Figure 7b) in relation to their ID locations. Over the RP, decay conditions in most of the locations (except ID: 23, 31, 33, 35, 36, 38) require adaptation measures to be implemented with high urgency when the level of building protection is medium-high. Over the FF, the buildings will experience a total decay reduction, with a consequent lower need for urgent adaptation interventions. At the opposite, small heavyweight buildings located near Göteborg and Malmö (ID: 35, 38, underlined) will shift from medium to medium-high risk of losing CDEs, requiring higher priority in adaptation and a higher level of intervention than those needed actually to counteract the decay.



(**a**) (**b**)

Figure 7. The urgency of interventions in small heavyweight buildings for each ID location in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100). (Underlined locations in FF: higher decay induced by climate change. Bold locations in FF: lower decay induced by climate change).



(**a**) (**b**)

Figure 8. Urgency of interventions in large heavyweight buildings for each ID location in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100). (Bold IDs in FF: lower decay induced by climate change).

Figure 8 demonstrates the urgency of adaptation interventions that need to be applied on large heavyweight buildings in the 38 locations, for both the RP and FF climate-induced decay scenarios.

In Figure 8b, the adaptation interventions over the Far Future will have the same class of urgency as during the Recent Past but the interventions will be proposed for a lower level of decay in ID locations: 2–5, 7, 8, 21, 26–28 (in bold). From a comparison between Figures 7b and 8b, the decay level in the Far Future will remain extensively medium-high for both building sizes but in some locations it will be high for large buildings (ID: 18–20, 24, 25, 34, 37, 38) and medium for small buildings (ID locations: 1, 7, 23, 31, 33, 36).

4. Discussion

The proposed method at Section 2.2 has been applied to assess the total risk of climate-induced decay on building materials preserved in an indoor unconditioned environment of different dimensions. The thresholds, used in the quantification of the decay level, have been defined using the CfC risk assessment method that evaluates the impact and the likelihood of different types of decays through the use of damage functions. The threshold values are average and they can vary for a different range of materials due to their physical and mechanical characteristics or aggressiveness of the environment.

The same approach can also be feasible for assessing the risk of decay outdoors using the outdoor CfC maps and the variables that better estimate damage mechanisms induced by climate and weather conditions.

The main objective of the matrix proposed in this article is to find suitable adaptation interventions that fulfil both the physical state of the original material (to reach a minimum level of decay) and its historic value (to minimize the risk of losing CDEs). Using the proposed matrix, three types of intervention needs can be identified as follows:

1. No or small urgency of adaptation interventions rather than those allowed by the legislation (green colour in the matrix). This level is expected for existing buildings that are neither listed nor protected, as they have no specific need to guarantee the conservation of CDEs.
2. Medium urgency of adaptation interventions (yellow colour in the matrix) is expected for historic buildings that are listed. Within this category of buildings, the ongoing climate change effect will require, in the next decades, implementation of different levels of intervention than those admitted by the legislation, for responding effectively to the expected decay.
3. High urgency of adaptation interventions (red colour in the matrix) is expected for fully protected historic building, monuments and UNESCO sites. Within this category, new adaptation interventions have to be planned and implemented to respond both to the preservation of their valuable CDEs and to intervene with urgency in post-disaster situations.

Within the same matrix cell, more than one adaptation action can be recommended. In this case, the life cycle assessment (LCA) method can be applied as an effective decision-making tool to choose eventually the scenario with the lowest environmental impact. This decision leads to the choice of the greenest intervention, thus avoiding contributing to further the climate change. The environmental assessment can be a consequent component that completes the intervention selection process on historic buildings. Considering carbon footprint of the intervention reduces the impact of the climate change and makes the entire process three-dimensional where each component (level of decay, level of protection and level of emissions) is independent of each other but a correct combination of them achieves satisfactory results to answer the needs of cultural heritage preservation in the time of climate change.

5. Conclusions

Due to climate change impact, the cultural heritage management sector will face new challenges in the future (e.g., more info on identification, documentation and mapping of heritage sites with increased vulnerability to climate change will be needed). The main aim of the presented article is to enhance the use of already existing Climate for Culture results in order to create a tool (matrix) that provides information to cultural heritage managers regarding the urgency of intervention and the effectiveness of measures supported by legislation in reducing the level of decay.

The merge of the expected decay results with the level of protection of the building serves as a good indicator to enhance the reaction capacity and to plan the right level and time of intervention for adapting to the future climatic changes. By directing the adaptation intervention process in a methodologic approach, what today is a subjective choice, taken on a case-by-case basis, would become a more scientific and technical assessment.

The application of the method in 38 locations in the Scandinavian countries shows that the increase of temperature and relative humidity throughout the region will increase the conditions for biological growth of mould and insects as already confirmed from other researches in the field [16]. This risk is imminent in the region where about 90% of the structures and the majority of historic buildings are built from wood, especially in the southern areas where the climatic conditions are more favourable for growth. The climatic changes will affect also the structures that have iron elements due to the increase of risk for corrosion. While the biological and chemical deteriorations show an increasing trend in the far future, the mechanical decay will face a general decrease for all types of building materials indoors.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/8/9/347/s1. The charts of climate change decay variables in relation to the geographical location, time window, material, and size of the building.

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Article 4

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Service life prediction of building components in the times of climate change

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Abstract. Buildings components and assemblies are prone to decay over time due to the inherent characteristics of the materials, environmental conditions and operational use of them. For this reason, it is very important to know the right time and type of maintenance and adaptation interventions that need to be applied to the specific compounds. The answer to the above issue can be given through the service life prediction (SLP) of the components by using standardized calculation methods.
In historic buildings, the process of SLP takes significant importance because these buildings hold non-renewable cultural heritage value and therefore, the interventions should be performed in a way that preserves the original material and value while enhancing the service life. Nowadays, for such buildings that are predicted to live for centuries, the SLP needs to be corrected by considering the effects of climate change in the construction materials.
The paper presents an overview of the application of the well-known factor method in the estimation of the serviceability of the building components, with a special focus on historic buildings impacted by climate change. The technical compatibility, economic viability, use of the building and the indoor/outdoor environments are considered during the assessment of the service life, which is strictly linked with the level of decay. It gives a short explanation of the factors that constitute the method by including the effects of climate change and an example of application to a specific case study in Norway.

1. Introduction

Buildings are prone to both keep materials and components intact and in-use, and to achieve comfortable living requirements. For this reason, it is very important to plan the time milestones of the intervention actions over a long-term horizon. To this aim, the service life prediction (SLP) is an important tool to apply prior to any type of interventions to the structures. The general framework of the SLP for both the new constructions and the existing buildings is expressed in the international standard ISO 15686-1 [1]. Given the variety of structures and materials constituting the built environment, it is of primary importance to set up methods, which use basic data and can be applied to several scenarios under different exposure and user conditions [2]. The factor method, with its constituent factors, as described in the ISO 15686:8, allows such inherent flexibility [3].
The application of the method estimates the service life for a specific component or assembly (in years) by considering its technical conditions in the environment where the component or assembly is located and with its peculiarity of use. When applied to historic buildings, the assessment of the SLP becomes an important heritage management tool to prioritize interventions so that both the integrity and the historic value of the materials is maintained and maximized. The built environment is constituted by different layers such as the site, the structure, the building envelope, the services, the indoor space into

the building, etc. The layers have different rates of change that vary from eternity (site) to a few years (sensitive material/component) [4]. When dealing with historic buildings, beside buildings with indoor sensitive collections (out of the scope of the present work), the layer that holds most of the cultural value is the building envelope. This layer, apart from the historic value, is in direct contact with natural and anthropic degradation agents (e.g. radiation, precipitation, wind, pollutants, etc.) and shows a higher rate of decay. Therefore, its conservation has substantial importance because it does not only preserve the value but the improvement of the building envelope influences the energy performance of the structure, increases the living comfort and reduces the monetary cost and environmental impact. For this reason, this article is focused on the façade of the buildings, more specifically in the estimation of the lifetime of the outer walls of historic buildings.

Following the recommendations of the standard, the SLP method has been applied to different building components such as wooden façade [5], ceramic and stone wall claddings [6, 7], wooden windows [8], thermal insulations systems [9], external paint finishes [10]. This article gives an overview of the use of the factor method in historic buildings by including the most important parameters that influence the level of decay and the building significance. It introduces new correction components and criteria that consider the need of keeping a longer service life for historical materials and their sensitiveness to climate change, as well as subfactors which consider the technical compatibility, the economic viability and the proper use of the building. The method needs to be further refined, especially when dealing with the determination of the list and the value of subfactors used for the analysis. This implies the need for further multidisciplinary research and laboratory tests to validate the results. However, the application of the same methodology to a large group of buildings can be a suitable tool for their categorisation, even though the predicted results can have discrepancy from the real case studies. Finally, an example of a user-friendly SLP application – that does not require huge mathematical background or programming simulations – is reported to a case study in Norway.

2. Materials and methods

2.1. Factor method

There are many ways for calculating the SLP but according to the report "Performance-based methods *for* service life prediction", they can be divided into two main procedures: factor methods and engineering design methods [11]. According to the factor method, the service life (in years) is calculated by multiplication of a reference service life (RSL) with different modifying factors, which consider the deviation from reference conditions as reported in equation (1):

$$ESL = RSL \cdot f_A \cdot f_B \cdot f_C \cdot f_D \cdot f_E \cdot f_F \cdot f_G \tag{1}$$

where ESL = estimated service life; f_A = factor A: quality of components; f_B = factor B: design level; f_C = factor C: work execution level; f_D = factor D: indoor environment; f_E = factor E: outdoor environment; f_F = factor F: in-use conditions; and f_G = factor G: maintenance level.

The factor method is a useful tool for estimation and comparison of the lifetime of materials and assemblies, and it is in continuous improvement through new definitions of the necessary input data for RSL and factor values. In the process of the estimation of ESL, the attention is given to the definition of the RSL, as well as the value of every single factor. According to the standard, the specific values of the factors are independent of each other, and it should be aware that the components are not mixed or taken into consideration multiple times. In our work, to better underline the criteria or important components (called subfactors) which influence the service life of external layers of historic buildings, each factor of equation (1) (f_i with *i* from A to G) is further constituted by *j* number of subfactors (with *j* from 1 to n) as reported in equation (2):

$$f_i = f_{i_1} \cdot f_{i_2} \cdot \ldots \cdot f_{i_n} = \prod_{j=1}^{n} f_{i_j} \tag{2}$$

2.2. List of components

In Table 1 it is given a list of the main subfactors that are considered when evaluating the service life of assemblies in a historic building. The list has been compiled by taking into account the results of the literature review [2, 12-14] and of the EU project Climate for Culture (CfC) [15] with a special focus in impacts of climate change on cultural heritage buildings. The table is not to be considered as exhaustive but can be subjected to further improvement and adaptation with respect to the specific case studies.

Table 1. List of subfactors to be considered during SLP of outer components in historic buildings.

Aspect of interest	Factor	Subfactor
Inherent quality characteristics	A – Inherent performance level	A1 – Quality of the original material A2 – Quality of the later material A3 – Quality of the treatment *A4 – Manufacturing* [a] *A5 – Transportation* *A6 – Storage*
	B – Design level	B1 – Technique of design B2 – Sheltering B3 – Decoration B4 – Energy requirements
	C – Execution level	C1 – Level of workmanship *C2 – Implementation of the project* *C3 – Conditions of the site*
Environment	D – Indoor environment	D1 – Temperature (M, W) [b] D2 – Relative humidity (M, W) D3 – Freezing-Thawing cycles (M) D4 – Salt crystallisation cycles (M) D5 – Thenardite-Mirabilite cycles (M) D6 – Time of wetness (M) D7 – Mould (M, W) D8 – Insects (W)
	E – Outdoor environment	E1 – Freezing-Thawing cycles (M) E2 – Salt crystallisation cycles (M) E3 – Time of wetness (M, W) E4 – Dry days index (M, W) E5 – Frost days index (M, W) E6 – Wet days index (M) E7 – Heavy precipitation index (M, W) E8 – Tropical night index (M, W)
Operation conditions	F – Usage conditions	F1 – Type of use F2 – Flux of use F3 – Surrounding activities
	G – Maintenance level	G1 – Easy of maintenance G2 – Type of ownership G3 – Budget limitations

[a] Subfactors in italics apply to new buildings.

[b] Subfactors with index (M) apply to masonry buildings and with (W) to wooden buildings.

For existing components, the evaluation is done only for the actual conservation status of the components, which means that some subfactors that apply to new materials or the project implementation phase such as manufacturing, transport, storage, site conditions, etc. are not included (or taken equal to 1) in the estimation. Such subfactors are reported in italics in the table and they can be considered during service life calculations of new buildings, or new additional construction works in existing buildings during restoration interventions. In addition, most of the historic buildings, due to their year of construction, have been built with external façade that does not meet the actual thermal conductivity requirements of the latest design codes. In fact, in several cases in existing buildings, the improvement of energy efficiency is the driving factor in retrofitting or refurbishment interventions.

While inherent quality characteristics and operation conditions do not depend on the type of the material, the environmental factors (D and E) can influence the level of the decay with regard on the type of material with whom they interact. The indoors and outdoors climate-induced risks manifest themselves on historical materials and components as mechanical, chemical and biological agents of deterioration and they are represented by a set of sub-factors as indicated in the CfC project [16]. The values of these subfactors, for every risk component linked to a specific climatic area and type of the building, have been determined in this work using the threshold values and the risk maps results of the project [17]. In Table 1, the index (M) represents climate-induced decay components affecting masonry and stone buildings, while the symbol (W) for subfactors affecting wooden buildings. For building components that are estimated to live for decades, the value of SLP can be corrected by introducing a correction factor that considers the effects of climate change in construction materials. This can be achieved by using the results of the Near Future (2021-2050) or Far Future (2071-2100) scenarios for determining the subfactors for the indoor or outdoor environment.

The climate conditions, the atmospheric agents (heavy rainfall, hail, wind, etc.), the type and condition of the landscape (e.g. risk-prone areas, vegetation, etc.) as well as the type and frequency of activities conducted in the adjacent area (e.g. pollution, road with traffic density, delivery areas, etc.) can affect the conservation of building materials through similar mechanisms (e.g. mechanical decay caused by freezing-thawing cycles or crystallization-deliquescence cycles in the presence of water and salts; chemical decay caused by pollutants; biological decay caused by vegetation, mould and pest infestation; etc.).

Type of use and flux of persons entering the building influence directly the indoor microclimate. A high concentration of people in one room leads to change in temperature and relative humidity and therefore, influences microclimate conditions in the proximity of building materials which in turn, act on triggering indoor decay mechanisms. This is an important factor to be considered in historic buildings subjected to mass tourism which can be affected by direct wear of materials and by indirect decay caused by microclimate modifications. On the other hand, a no-use of the building may preserve the components from wear or tear, but it will influence their service life because of the lack of preventive conservation and scheduled maintenance.

In historic buildings, the maintenance process has, therefore, significant importance because it keeps monitored the rate of decay, it keeps the original material in optimal status, and it prevents the loss of cultural heritage value extending the service life of the materials and structure in general. In most of the cases, a good practice in historic building's maintenance increases the cost of the action (compared to the cost of maintenance in an existing building with no significance) because of the careful selection of materials which need to be compatible with the original ones or the careful choice of interventions which must be reversible and implemented by craftsmen with unique expertise. These approaches can be economic and inherent performance barriers for most of the owners and heritage managers. Decision-makers, to minimize the risk of stacking in a "no-action" situation, should plan in advance a range of adaption actions under different budget scenarios so that they can choose in a balanced approach between maintenance and budget [13]. Depending on the preservation target and the budget, the heritage managers should select among actions that aim to keep the estimated service life of material and building components the same as the reference one (preventive maintenance); to improve the service life of the component (rehabilitation) or to increase their service life significantly (renovation, restoration).

The prediction of the decay rate on building components becomes, therefore, a necessary step to determine the time of the intervention action before the component or structure reaches the end of technical/functional service life. The categorisation of decay levels (small, medium and high) becomes the starting point in suggesting refurbishment interventions and the frequency of application.

3. Application of the method

3.1. Description of the building

The factor method has been applied here to estimate the service life of an external wall of a historic building in the city of Trondheim in Norway. The prediction of the service life in years forecasts the level of decay of the wall, and therefore, it suggests the level of intervention that needs to be applied over the time to come.

In the city of Trondheim, apart from the listed buildings (named Fredet and marked with letter F), there is a large number of protected buildings (Vernet) which are categorised in three main groups (A, B and C) according to the value that they represent [18]. The building (Figure 1) is situated in the Møllenberg area, and it has legislation protection of level B. In this category, fall the buildings that have high significance and possess peculiar features. In such cases, intervention works are recommended to be applied from inside in order to hold the original value of the external façade. The external wall is built of wooden material (log-construction), and it has an additional insulation layer of 50mm which has been added in the 80s (Figure 2).

Figure 1. View of the main façade of the building.

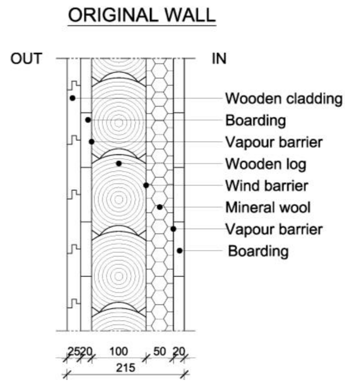

Figure 2. Section of the wall.

3.2. Prediction of the service life

In Table 2 it is given the condition status for each subfactor category that should be considered for the estimation of the service life. Based on the conditions of the wall section, three values have been assigned for each subfactor: the minimum, the most-likely (mode) and the maximum value together with the likely shape of the statistical distribution (e.g. deterministic, normal, log-normal) by using the recommendations from the literature and results of previous research in the field [2, 5]. By using the above information, the values of the subfactors can be estimated for different percentiles of occurrence. In the example, three percentile values (5%, 50% and 95%) have been calculated, following the suggestions of the ISO 15686-8 standard. The most used fractions (50% of the subfactor values) fall under the median value, while 5% and 95% fall respectively above the minimum value and under the maximum value. For the environment-related categories, the values of subfactors and types of distribution have been dispensed by using the maps of the European project Climate for Culture [15]. The effect of climate change has been included by using the projections for the variables in the Far Future scenario (2071-2010) over the Trondheim area.

Table 2. Fractional values of subfactors used for the service life prediction distribution.

Subfactor	Conditions	Factor values			Distribution
		f_{x5}	f_{x50}	f_{x95}	
A1 – Quality of the main material	Normal variation of the component	0.84	1.00	1.16	Normal
A2 – Quality of the insulation	Insufficient quality of the component	0.72	0.80	0.88	Normal
A3 – Quality of the treatment	Good quality of the component	1.09	1.20	1.31	Normal
B1 – Technique of design	Good technique, identical design	1.20	1.20	1.20	Deterministic
B2 – Sheltering	No sheltering for walls	1.00	1.00	1.00	Deterministic
B3 – Decoration	No decoration for walls	1.00	1.00	1.00	Deterministic
B4 – Energy requirements	Poor thermal transmittance	0.69	0.79	0.87	Log-normal
C1 – Level of workmanship	Normal construction, no mistakes	1.00	1.00	1.00	Deterministic
D1 – Temperature T	Heated building, 18°C ≤ T ≤ 25°C	1.00	1.00	1.00	Deterministic
D2 – Relative humidity RH	No risk of condensation, RH≤70%	1.00	1.00	1.00	Deterministic
D7 – Mould	Medium risk	0.97	1.04	1.08	Log-normal
D8 – Insects (RH-dependent)	Very low risk	1.37	1.44	1.48	Log-normal
E4 – Dry days index	Medium risk	0.92	0.96	1.03	Log-normal
E5 – Frost days index	High risk	0.77	0.84	0.88	Log-normal
E6 – Wet days index	Medium risk	0.92	0.96	1.03	Log-normal
E7 – Heavy precipitation index	Medium risk	0.92	0.96	1.03	Log-normal
E8 – Tropical night index	Very low risk	1.37	1.44	1.48	Log-normal
F1 – Type of use	Residential house	0.95	1.00	1.05	Normal
F2 – Flux of use	4 apartments, 9 inhabitants	0.95	1.00	1.05	Normal
F3 – Surrounding activities	No heavy activities around	1.15	1.20	1.25	Normal
G1 – Easy of maintenance	Scaffolding needed from outside	0.69	0.80	0.91	Normal
G2 – Type of ownership	Rental house	0.79	0.90	1.01	Normal
G3 – Budget limitations	Surface treatment every 10 years	0.89	1.00	1.11	Normal
Total		0.29	1.25	4.63	

The assumed reference service life of the wall in residential buildings is considered 50 years [19]. The result of service life estimation is achieved by multiplying the total factors of the percentile 50% with the reference service life as given in equation (3):

$$ESL_{50} = RSL \cdot f_{50} = 50 \cdot 1.25 = 62.7\,years \quad (3)$$

The service life for our case study is estimated 62.7 years with a standard deviation of 8.6 years. This value is calculated by considering the projections of the climate-induced decay components in the Far Future (2071-2100) scenario. In case the calculations are performed using the measured data of the Recent Past (1961-1990) reference scenario, the values of climate-induced risk subfactors and therefore, the values of percentiles, are different as reported in Table 3, with changes also for the other subfactors that however remain within the same risk value range.

Table 3. Fractional values of environmental subfactors if the Recent Past scenario is applied.

Subfactor	Conditions	Factor values			Distribution
		f_{x5}	f_{x50}	f_{x95}	
D1 – Temperature T	Heated building, 18°C ≤ T ≤ 25°C	1.00	1.00	1.00	Deterministic
D2 – Relative humidity RH	No risk of condensation, RH≤70%	1.00	1.00	1.00	Deterministic
D7 – Mould	Low risk	1.12	1.16	1.23	Log-normal
D8 – Insects (RH-dependent)	Very low risk	1.37	1.44	1.48	Log-normal
E4 – Dry days index	Medium risk	0.97	1.04	1.08	Log-normal
E5 – Frost days index	Very high risk	0.57	0.64	0.68	Log-normal
E6 – Wet days index	Low risk	1.12	1.16	1.23	Log-normal
E7 – Heavy precipitation index	Medium risk	0.92	0.96	1.03	Log-normal
E8 – Tropical night index	Very low risk	1.37	1.44	1.48	Log-normal
Total $f_D \times f_E$		1.17	1.78	2.56	

In the Recent Past scenario, the multiplication of the subfactors of environment categories ($f_D \times f_E$) for the 50% percentile is 1.78 instead of 1.60 that it was when using the Far Future projections. For the Recent Past, considering the subfactors of other categories the same, the product of the entire subfactors is 1.39 (instead of 1.25 for the Far Future), which corresponds to an estimated service life of 69.6 years. From the results, it can be noted that the climate change impact is expected to reduce the ESL by about 7 years.

In the current situation, the house of our case study is rented to the students, and the maintenance does not follow the real needs of the structure. If the owners lived in the building, the maintenance would be more scheduled, and the estimated lifetime would increase to 69.7 years, with an increase of 10% from the first calculation. Another increase in the lifetime is predictable when the budget of the owner allows surface treatment of the façade every 5 years instead of approximately 10 years as it is now. In this case, the estimated lifetime of the wall section would reach 75.3 years (20% higher than the reference calculation of 62.7 years).

The house serves as a residential house. It has a central location in the area and in case of its transformation into a commercial building, the number of people getting access to it would increase the damages caused by wear and tear. For this scenario, the expected service life will drop by 15% with an estimation of 53.3 years.

The differences between the above scenarios are highlighted in Figure 3 for a better understanding of the importance of the subfactors in the process of service life prediction.

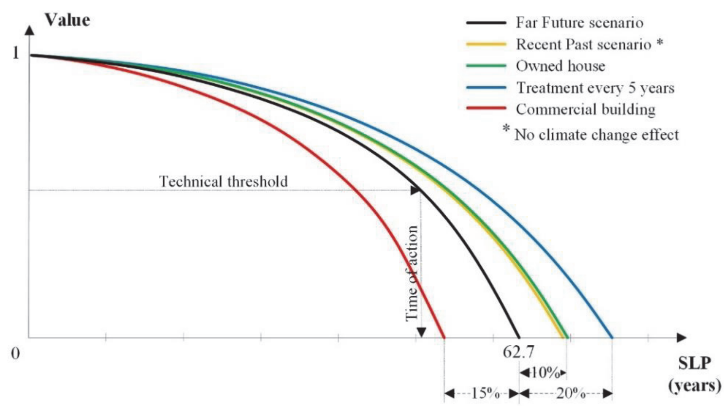

Figure 3. SLP values for different scenarios in the case study building.

4. Discussions and Conclusions

The factor method applied at a wall of a historic building in Trondheim estimates the service life of the component in years. By setting a technical threshold, the calculated value is necessary to determine the time of the intervention action in the wall prior to a high level of decay which would not only degrade the material but also will influence the cultural value of the component. The factor method is a practical method to calculate the service life of new or in-use building components; however, the experts have expressed their reserves towards the method and suggest the improvement of it [20]. One of the biggest issues of the method is the difficulty to determine the factors and therefore, the uncertainty of the results. Another critique of the method is that it considers the factors independent from each other, which may not always be appropriate. However, when applying the same method (with the same marge of uncertainty) to a large built environment, e.g. a street or district level, from the results, it can be recognized the components that are in a higher risk of degradation, even though the estimation of the lifetime may not be accurate in an absolute sense. In a district scale, where the same level of inaccuracy is applied, the prediction allows the grouping of the components with similar values of service life, thus enabling the application of similar refurbishment interventions to components with similar decay status. In the presented framework, strong emphasis is given to the aspects of indoor and outdoor environments. The subfactors in these categories are estimated by using the results of the Far Future scenario (2071-2100), which considers the climate change impact on building materials in the Trondheim area as calculated by the EU project Climate for Culture. As a result, the expected refurbishment interventions will be planned by considering the predicted climate results, thus increasing the accuracy in the plan of future interventions.

The application of this modified factor method serves to identify the areas that are more vulnerable to decay and take actions before the process becomes irreversible. With the introduction of the subfactors, the main quality, environmental and operational characteristics that influence the service life of historic buildings are taken into consideration. The table of subfactors (Table 1) can be subject to further improvement in order to adapt to the new challenges of the refurbishment process or to the specifics of the cultural heritage under examination. From the example of application, apart for the effect of climate change, it could be noticed that the ESL is sensitive to parameters like use of the building, type of ownership, budget limitations, etc., but it can also be influenced by design solution, conservative conditions of original material or level of craftsmanship. The definition of the value for each of these subfactors and their type of distribution ask for further research in the field through the involvement of multidisciplinary experts in data collection, running analysis and laboratory tests. By doing so, the method can be more exploited and contribute to creating a database for historic buildings to support specialists dealing with heritage site management and preventive conservation.

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Article 5

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Refurbishment of historic buildings at a district scale: *Enhancement of cultural value and emissions reduction potential*

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Abstract. The historic buildings have a significant value in providing a sense of identity to the cities and the community. On the other hand, due to their age, they show the highest ratio of living discomfort and energy consumption. Therefore, their refurbishment is a very important process because, if done right, it will not only reduce their energy demand and increase the living comfort but will also strengthen the social and cultural benefits through leisure and tourism.

In the city of Trondheim, as in many other European cities, the historic buildings have been erected in different architectural periods, which manifest diverse historic and technical features. A categorisation of the wall sections of historic buildings has been done for each city's development period regarding their construction material and technique, building functionality and protection status.

The scope of the article is to estimate the potential for reduction of greenhouse gas emissions at a street/neighbourhood/city level prior to applying large-scale intervention measures. This can be achieved by proposing refurbishment alternatives for wall and window sections that preserve the historic value and at the same time, approach or even meet the actual technical standards. Afterwards, the carbon footprint of the refurbishment action itself and the environmental benefits after the refurbishment (operational phase) is estimated for each category of wall sections. The environmental results, multiplied with the total surface of sections carrying the same attributes, give the overall potential of reduction for the entire group of buildings. Based on this, the on-site renewable energy that would lead to achieving zero-emission targets can be calculated. The framework is also important because it does not treat each building separately, but it suggests refurbishment scenarios for specific categories of buildings built in different historical periods.

1. Introduction

By definition, a historic building is a single manifestation of immovable tangible cultural heritage in the form of an existing building [1]. In addition, a historic building manifests significant cultural, artistic, and social values which gives a specific scope to its refurbishment process. For spreading the refurbishment of historic buildings at an urban scale (street, neighbourhood or city), the definition should encompass not only the very valuable historic buildings (the so-called monuments) but also a large number of buildings in European towns and cities which are far less important from a historical and architectural point of view but, taken as a whole, represent an important part of heritage [2]. By doing so, the intervention process at district scale will incorporate residential buildings or relatively recent buildings, which have protection status from governmental institutions.

However, due to the wide range of required expertise and the complexity of the interdisciplinary research, the overall intervention process in historic buildings is a complex issue that needs to be effectively resolved. Generally, the affected groups of stakeholders attempt to make decisions in their favour and sometimes the collaboration among different categories of stakeholders seems complicated for lack of an integrated framework and interconnected vision covering the different perspectives. Moreover, an extended literature review concluded that sustainable improvements are based on the operational phase i.e., after the conclusion of interventions and no method considers the environmental impact of the refurbishment process itself [3].
The European projects related to maintenance of historic buildings are primarily focused on energy efficiency solutions [4, 5], as suggested from the directive of the European Parliament [6]. Regarding environmental impact, a framework that considers the carbon emissions in the selection of interventions has been proposed for the maintenance of masonry building [7]. This paper discusses further the importance of the environmental approach in the decision-making process, in order to select the most suitable adaptation interventions which can be applied to diverse categories of buildings. Indeed, the built environment has different attributes depending on the location, materials, history, time of construction, esthetical features, etc. Systematic and clear categorisation of the built environment according to the construction techniques, architectural values, buildings maintenance and performance conditions might be a helpful step to insert the process of refurbishment in a standardized path that is understandable to each practitioner.
To achieve satisfactory results from plan to practice, it is required strong cooperation from specialists of different fields such as urban planners, architects, engineers, researchers, building conservators, buildings owners and others involved in heritage management [8]. This article aims to group the main attributes, meaningful for historic buildings, into three main categories: technical, heritage significance and environmental impact related. The combination of the scale of material decay and its historic value would lead to the suggestion of appropriate refurbishment works that retain significance while the environmental impact of the work during and after refurbishment would be the driver for selection of sustainable scenarios.

2. Materials and methods

As the name "sustainable refurbishment of historic buildings" indicates, the involved groups of interest can be grouped in three main categories: the materials' science community (service life and risk assessment specialists), cultural heritage specialists (historians, architects, governmental institutions) and the sustainability community (with a special focus on environmental impact). Each of the main communities evaluates the built environment in specific aspects and the results are commonly expressed in grading systems regarding respectively the level of decay, historic value classification and amount of environmental impact.

2.1. Decay assessment

Buildings are prone to changing requirements over long periods and it is very important to work with the time rather than against it. For this reason, service life prediction (SLP) is an important process prior to interventions that should be applied to existing buildings [9]. There are many ways for calculating the SLP but according to the report "Performance-based methods for service life prediction" [10], the methods have been divided into two major groups: factor methods and engineering design methods. The application of the methods estimates the service life for a particular component or assembly (in years) by considering specific technical conditions. According to the factor method, the service life (in years) is calculated on the basis of the following equation:

$$ESL = RSL \cdot f_A \cdot f_B \cdot f_C \cdot f_D \cdot f_E \cdot f_F \cdot f_G \qquad (1)$$

where ESL = estimated service life; RSL = reference service life; f_A = factor A: quality of components; f_B = factor B: design level; f_C = factor C: work execution level; f_D = factor D: indoor environment; f_E = factor E: outdoor environment; f_F = factor F: in-use conditions; and f_G = factor G: maintenance level.

The service life prediction is strictly connected with the decay assessment process because the indoor and outdoor environment can create a proper state for decay. The level of decay (in %) is linked with the value of the SLP (in years) through polynomial functions as shown graphically in Figure 1.

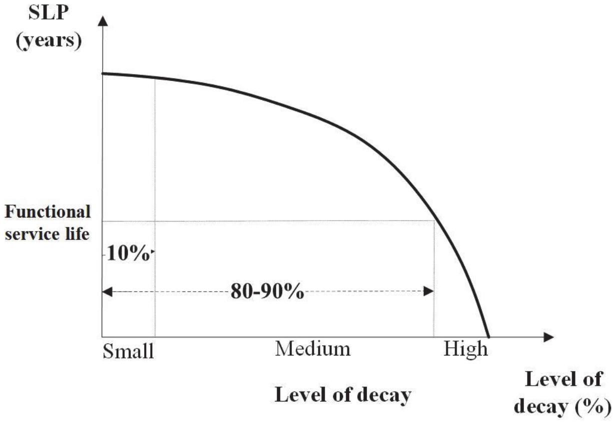

Figure 1. The link between the service life prediction (SLP) and the level of decay of the materials.

The prediction of the decay rate on building components is a necessary step to determine the time when a refurbishment process should be conducted before the end of technical/functional service life is reached i.e., before the component is rendered obsolete. The categorisation of decay results during the decay assessment (small, medium and high) would serve as the starting point in suggesting refurbishment interventions and their frequency of application.

For building components which are estimated to live for decades, the value of SLP needs to be corrected by introducing a new correction factor that considers the effects of the climate change in construction materials. Moreover, when the interventions are applied to historic buildings which hold in addition cultural and social values; the location, aspects of use, and the economic cost should be assessed in the final calculation.

2.2. Historic value assessment

Although a historic building does not necessarily have to be a heritage-designated building, its expected standard lifespan is considered at least twice longer than the lifespans of a building with no or low significance value. For this reason, they require high-quality interventions to ensure long term performance of the building, secure convey of their values and fulfilment of sustainability-driven criteria.

Based on the value that they represent, historic buildings have different protection statuses which can be of an international, national or local level. The international or national institutions (UNESCO, ICOMOS, Riksantikvaren in Norway, etc.) deal mainly with the conservation of the outstanding buildings (the so-called monuments) which have specific protection status and big restriction for change. The protection status of this group of buildings is regulated mainly from municipalities following the restrictions and requirements during the intervention processes.

In the city of Trondheim, apart from the listed buildings (Fredet), there is a large number of protected buildings (Vernet) which are categorised in three main groups (A, B and C) according to the value that they represent [11]. Further interdisciplinary developments (e.g. DIVE method [12]) have been applied in some case studies to these historic buildings in order to categorise them according to the value and giving instructions about the type of the intervention for building component [13]. The recommendations and limitations of the groups of historians, architects and others involved in cultural heritage preservation need to be included in the suggestion of the refurbishment scenarios that need to be applied in protected buildings.

2.3. Environmental assessment

The interventions in historic buildings need to follow the sustainability principles and to adopt the minimal technical interventions through principles of compatibility, reversibility and retreat-ability. The environmental impact of the intervention works can be assessed by applying the Life Cycle Assessment (LCA) analysis [14, 15] to the materials and processes used during the adaptation procedure. According to the EN 15978:2011 standard [16], the intervention works refer to the modules B2 until B5, respectively Maintenance (B2), Repair (B3), Replacement (B4), and Refurbishment (B5).

3. Results

The historic and cultural assessment of buildings indicates the issues to deal with regarding their protection class, rather than dealing with exact instructions on how these problems should be solved [12]. On the other hand, prediction of the materials durability for different building components tells when and where the refurbishment intervention should be done, but not what type of intervention is needed. For this reason, the results of these two independent assessments should be merged prior to deciding the type, the time and the location of the intervention. Both the results of the decay and historic assessments are obtained from classifications which are independent of each other and can be shown in a 2-D chart (Figure 2).

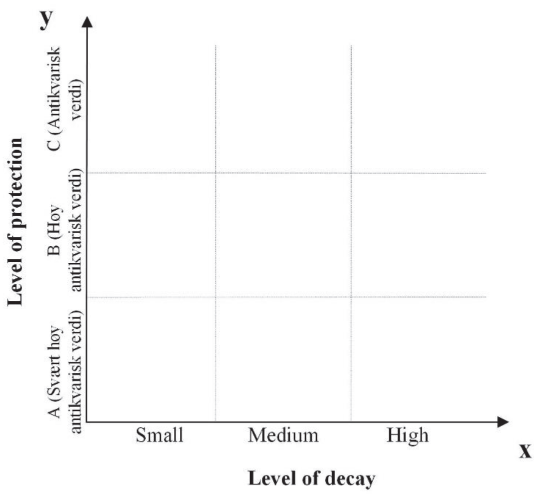

Figure 2. Regrouping of building components according to their decay status and protection level.

The service life is predicted for building components or assemblies' level while the categorisation according to the historic value is performed at building scale with different suggestions about interventions that are allowed to different components.

Each of the cells in Figure 2 contains information about the durability and performance of the constituting component/assembly (level of decay – x-axis) and the scale of allowed intervention in accordance to their protection status (y-axis). For each cell, a refurbishment intervention technique that fulfils both the requests of reducing the decay and keeping unchanged or enhancing the value is provided.

In most of the cases, especially in components with high capacity to change, different scenarios of interventions achieve this dual goal. Therefore, the most appropriate intervention scenario is selected in accordance with its environmental impact. Given the fact that the proposed refurbishment scenarios approach or even meet the actual technical standards [17] (e.g. thermal insulation), then the environmental impact of how it is achieved should be considered. Moreover, applying the environmental impact of the refurbishment works as a driver for scenario selection, would lead to the principles of maintenance, repair and reuse as much as possible from the original fabric over the replacing procedures, which is in the same line with the standard approach used by conservators. The new variable transforms the diagram of Figure 2 from a 2-D chart into a 3-D chart (Figure 3) with embodied emissions of the intervention works (modules B2-B5 regarding EN 15978:2011) as the third constituent of it.

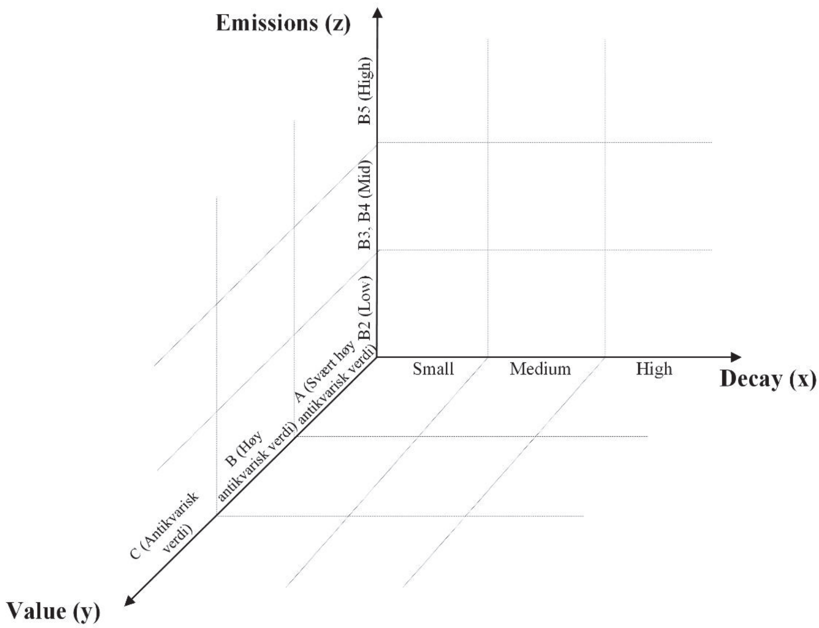

Figure 3. Inclusion of the environmental cost (embodied emissions) of the intervention works in the decision-making process.

However, in common practice, especially in public procurement works, the variable that mostly drives the decision of following a specific scenario rather than others, is the economic value of the work. In the new diagram, the monetary aspect is partially considered looking at the prediction of the level of decay and therefore the SLP (x-axis) and together with the law restrictions established to retain building historic, cultural and social values (y-axis) and the environmental impact in the z-axis, they compound the three pillars of the sustainability (environmental, social and economic) in the decision-making process.

Ideally, a good refurbishment would not only keep the same level of decay and protection class but would help to decrease the decay category and enhance the historical value of the building. Therefore, the next refurbishment rounds and the building itself would result in less environmental cost because the demand for the next interventions would be of a smaller scale and with an increased time of intervention intervals.

As our goal is the sustainable refurbishment of historic buildings, the main focus will be given to the components connected directly to the energy efficiency and GHG emissions, i.e. the external components such as outer walls, windows and roof. The environmental impact should be firstly estimated for the intervention processes itself (modules B2-B5 regarding EN 15978:2011) and later, the emissions during the operational phase B6 should be calculated in order to evaluate the payback energy to be generated by renewables. The emissions for each intervention scenario suggested for each cell of Figure 3 (for each component with a certain level of decay and historic value class), are calculated at the unit level which can be for $1m^2$ for walls and roofs or unit for windows.

The aim of the framework is to estimate the potential of the reduction of the emissions of buildings with similar typology and technique of constructions in the street, neighbourhood or city scale. Depending on the typology of constructions, this can be achieved in two ways:

- When the buildings are very similar to each other (e.g. surface and number of stories), the results of emissions from the refurbishment of an unit scale ($1m^2$) can be multiplied with surface of walls of a building to estimate the results at building scale and then multiplied per number of similar buildings to achieve the carbon footprint of the specific work at district scale. A sum of the emissions of each "winning" refurbishment work corresponding to each cell of Figure 2, would give the total impact of the entire refurbishment of the district.
- When the neighbourhood is heterogeneous regarding surface and height of buildings, the emissions' results from the refurbishment in unit scale can be multiplied directly with the surface of walls at district scale with similar shared criteria (the same value in x and y-axis) to estimate the environmental cost of the similar work and then, of the whole neighbourhood.

3.1. Example of application

The method described above has been applied to two buildings with different status of decay and level of protection. The application of the framework in an entire district is an ongoing process that will be published on a later stage of the study.

The buildings are located in Møllenberg area in Trondheim as it is shown in Figure 4. Because of the esthetical attributes that they carry, the municipality of Trondheim has classified Building 1 with the level of protection C and Building 2 with the level of protection B.

Figure 4. Photos of the Building 1 (left) and Building 2 (right) situated in Wessels Gate in Trondheim.

The service life prediction has been estimated for both wall sections using the factor method. The lifespan of the wood products in construction is over 30 years, but for some components, it reaches more than 100 years [18]. For typical timber log wall, the reference service life (RSL) has been assumed 50 years. Factor values for each component of the equation (1) have been selected according to the recommendations of ISO standards [19, 20] as given in Table 1.

Table 1. The factor values for the estimation of the service life.

Factor	Building 1		Building 2	
	Condition	**Factor**	**Condition**	**Factor**
A – Inherent performance level	Good quality	1.2	Good quality	1.2
B – Design level	Normal design	1.0	Good design	1.2
C – Work execution level	Normal	1.0	Normal	1.0
D – Indoor environment	Average risk	0.9	Average risk	0.9
E – Outdoor environment	Frequent risk	0.8	Frequent risk	0.8
F – Usage conditions	Residential use	1.0	Residential use	1.0
G – Maintenance level	Reduced maintenance	0.8	Good maintenance	1.2

The estimated service life ESL of the walls of the building 1 and 2 are:

$$ESL_1 = 50\times1.2\times1.0\times1.0\times0.9\times0.8\times1.0\times0.8 = 34.56\,years \quad (2)$$

$$ESL_2 = 50\times1.2\times1.2\times1.0\times0.9\times0.8\times1.0\times1.2 = 62.21\,years \quad (3)$$

The ESL of the external wall of Building 1 is approximately 70% of the RSL which corresponds to medium level of decay. In Building 2, the ESL is higher than the RSL due to good cyclic maintenance which makes the level of decay of a small scale.

The buildings have been constructed at the same time and their typical log sections (Figure 5) are similar for both buildings. Both the wall sections, after additional insulations works performed in the ’80s, have a thermal value U = 0.32 W/(m^{2}K) while according to the actual Norwegian TEK17 standard, this value for outer walls should be below 0.18 W/(m^{2}K) [17]. Walls have vapour barrier layers on both sides, recommended for cold climate, to avoid the risk of condensation. However, due to different levels of protection and levels of decay, different intervention scenarios will be suggested to them in order to reduce the decay and improve thermal performance.

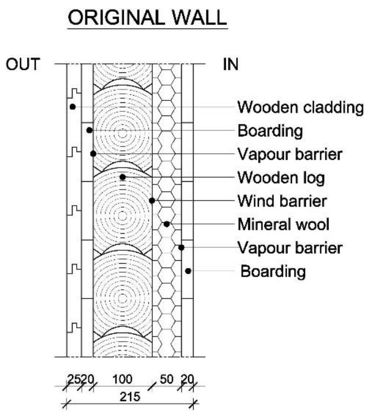

Figure 5. The original section of the wall sections

In Building 1, with C level of protection, it is allowable to have intervention works from outside. This type of intervention is also recommended as the thermal insulation is spread uniformly through the wall, minimizing cold bridges. To reach the desired U-value and reduce the decay, it is recommended to add 50 mm of insulation from outside and replace the original external cladding. This is the only scenario suggested for this type of wall (Figure 6). Another scenario would be the implementation of insulation works from inside, but this option is excluded because, as the external cladding needs to be replaced, it gives the possibility to work from the outer side.

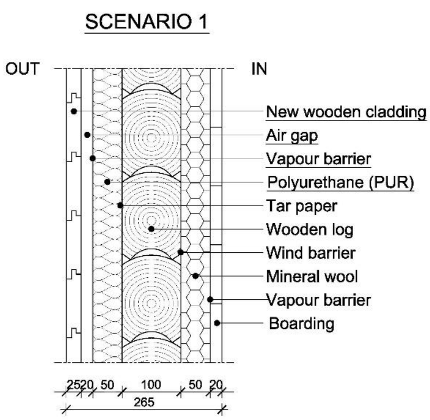

Figure 6. The proposed scenario for the outer walls of Building 1.

New paint of the façade is also included in the intervention works. The carbon footprint is calculated for middle change (Repair, Replacement) and it consists of the emissions for the production and transportation of new materials, the emissions during the installation works and the emissions of the end of live processes for the old materials:

$$E = E_{(p)} + E_{(t)} + E_{(i)} + E_{(eol)} = 19.17 + 0.64 + 0.23 + 2.45 = 22.49 kgCO_{2eq} / m^2 \quad (4)$$

For building 2, the intervention works will be executed from inside due to the protection status of the building. The wall is in generally in good conditions, but its thermal insulation needs to be improved. For this, two intervention scenarios are suggested: additional insulation from inside or replacement of the original insulation as shown in Figure 7.

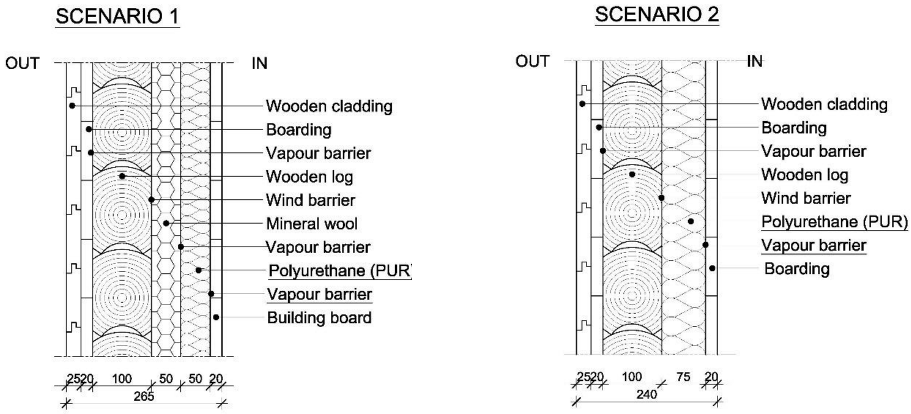

Figure 7. The proposed scenarios for the outer walls of Building 2.

Both scenarios reach the recommended U-value, therefore it will be the carbon footprint of the works which will be the driver for the selection. The environmental cost of the scenarios is calculated still for middle changes as follow:

$$E_1 = \left[E_{(p)} + E_{(t)} + E_{(i)} + \cancel{E_{(eol)}} \right]_1 = 5.70 + 0.14 + 0.08 = 5.92 kgCO_{2eq} / m^2 \quad (5)$$

$$E_2 = \left[E_{(p)} + E_{(t)} + E_{(i)} + E_{(eol)} \right]_2 = 8.65 + 0.14 + 0.12 + 3.55 = 12.46 kgCO_{2eq} / m^2 \quad (6)$$

From the comparison, the first scenario is the most environmentally friendly.
The 3-D chart that connects the level of decay, level of protection and level of embodied emissions of the interventions is given in Figure 8 for both buildings. The carbon footprint of the repair/replacement interventions for $1m^2$, multiplied with the total area of walls with similar features in the entire neighbourhood, generates the environmental cost of each work at the district level. The same procedure can be applied to different combinations in the 3-D chart, which encompasses all possible cases that can be met in the district.
The intervention works aim simultaneously the reduction of the level of decay, minimisation of the carbon footprint of the actual/ future interventions and whenever it is possible, the increase of the protection class of the building. Graphically speaking, the objective of the intervention works is to shift the entire set of dots in the 3-D chart as close as possible to the origin of the coordinates.

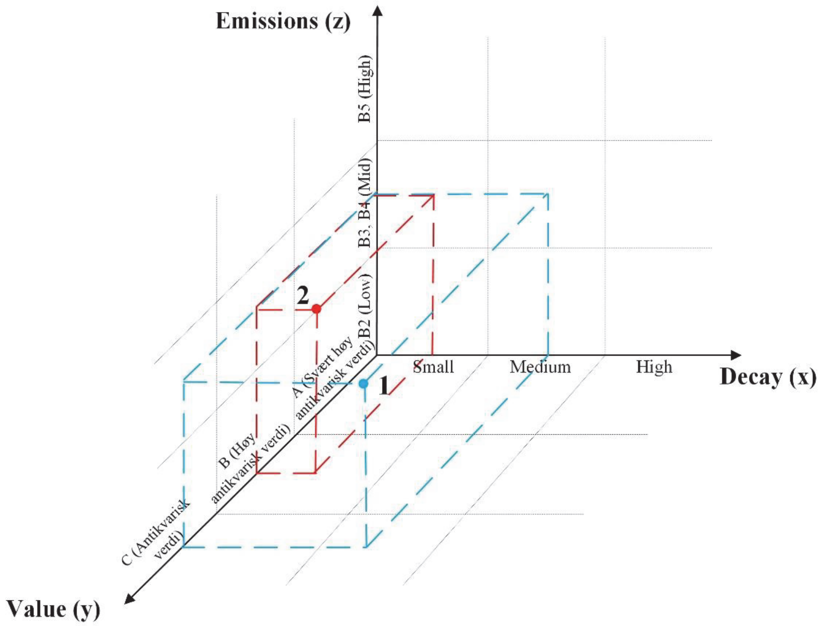

Figure 8. Position of the interventions in buildings in the 3-D chart (cyan dashed line for Building 1 and red dashed line for Building 2).

4. Discussions and Conclusions

The historic value of the building is the only non-renewable asset among the other assets and it should be preserved at any cost during the decision-making process. For this reason, it should be the primary driving factor during refurbishment works. Exceptions to this judgement can be done if the stability of the structure is compromised (due to hazardous events or long abandonment) and the proposed measurements may exceed the allowed level of intervention. After the historic and cultural values are ensured, their link with the level of decay of the material would suggest suitable refurbishment interventions. Considering the growing demands for minimizing the environmental impact, an intervention with satisfactory emission results during and after refurbishment can be preferred. By applying this framework, the results of each community remain independent and the conclusions of each component are taken into account.

The target of preserving the cultural heritage faces challenges in privately owned buildings, especially when the protection class is low. The proposed method does not treat the buildings individually, but it gives suggestions on a neighbourhood scale, thus enabling higher financing opportunities for private owners through collaboration with governmental institutions and involvement in larger projects.

The 3-D diagram presented in Figure 3 suggests a method to analyse, at once, the existing constrains and guidelines when planning an intervention to historical buildings, e.g. for improving the energy performance [21]. The technical compatibility, economic viability, use of the building and the indoor/outdoor environments are considered during the assessment of the level of decay strictly linked to the SLP; the heritage significance is ensured from the historic value assessment and law regulations; while the energy performance is the driver considered during the environmental assessment in a life-cycle approach.

The enlargement of the historic buildings' concept to a street, district or urban level reflects the refurbishment needs for specific categories of buildings, usually private residential houses, which were neglected in the previous interventions as they were not holding memorable historic values. The proposed method makes the path for sorting and assessing the limitations and possibilities of these buildings regarding their historic values, physical characteristics or decay rate, easier and more flexible. Moreover, the assessment and then, the choice of a sustainable solution for groups of buildings that hold the same significance, preservation status and condition of the decay, would result in time and money-saving rather than treating each building separately. These results, incorporated with the energy efficiency reduction due to refurbishment works, help to estimate the operational energy needed from the neighbourhood which serves as a base for the calculation of energy produced from the renewables, thus facilitating the move towards Zero Emission Neighbourhoods in historic urban areas.

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Article 6

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Application of Zero Emission Refurbishment method at a district scale

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Abstract: The refurbishment of historic buildings, if planned and implemented correctly, provides enormous benefits. The proposed Zero Emission Refurbishment (ZER) method, applied as an example to a historic block in the city of Trondheim, links together the building's capacity to change with the decay level of the materials to find low-carbon interventions that satisfy the requests of the involved stakeholders. It aims to give solutions in a district scale; thus the interventions can be implemented through large-scale projects that ensure the uniformity of work, enhancement of cultural value and reduction of time and cost of the action. The overall carbon footprint of the intervention measures, linked with the energy improvement of the buildings after, will serve as an indicator for the estimation of renewable energy generated from the district and therefore, for the shift towards Zero Emission Neighbourhoods in historic urban cities.

Keywords: Historic buildings, refurbishment, district scale, zero-emission.

1. Introduction

The refurbishment strategies related to historic buildings are mainly focused on energy performance (Smith, 2014, Pisello et al., 2016, Berg et al., 2017). As all the refurbishment actions aim to reduce the thermal transmittance of the building envelope, the way how this is achieved becomes the issue to be solved when dealing with historic buildings. The historic value adds complexity to the problem, but, as the only non-renewable asset, it should be the main driving factor to be guaranteed through the interdisciplinary process.

The presented article shows an example of the application of the Zero Emission Refurbishment (ZER) method in a historic block in the city of Trondheim in Norway. The method connects two independent grading systems (level of protection and level of decay) to find suitable refurbishment scenarios with low carbon emissions. The framework of the method gives strong emphasis to the climate change mitigation by proposing solutions that reduce the operational energy consumption, as well as to climate change adaptation by adjusting the future intervention works (maintenance and adaptation) to the new predicted climate normals.

The emissions from the upgrade works of external components summed up with the emissions from the operational phase indicate the total amount of renewable energy that needs to be produced from the district (Bertolin and Loli, 2018) to achieve zero-emission targets. The first component, although with a smaller arithmetic value, plays the most important role in the preservation of the original material and the energy consumption of the district itself.

2. Materials and methods

2.1 Zero Emission Refurbishment method

The ZER method merges the results of two grading systems that are needed to decide the intervention works. The starting point of the method utilises the historic value categorisation according to the attributes that the buildings hold. On the other side, the service life prediction for building components or assemblies suggests the time of the intervention to avoid irreversible decay status. A re-categorisation of the above independent outcomes can lead to the selection of refurbishment scenario works that satisfy both the requirements of conservators and material science communities. The re-categorisation is done by placing the unit sections of building envelope components (e.g. walls) of all the buildings in the district into a 2-D diagram with axes scaling the decay status and level of protection. For each different section group, one or more intervention scenarios are proposed that fulfil both the requests of reducing the decay and keeping unchanged or enhancing their value. When more than one scenario is suggested, the selection of the most appropriate intervention is done considering the environmental impact of the work, thus turning the initial 2-D diagram into a 3-D decision-making system (Loli et al., 2019).

The total environmental cost of interventions in the walls $E_{ZER,w}$ is calculated with the following equation:

$$E_{ZER,w} = \sum_{i=1}^{n} (A_i \times E_i) \quad (1)$$

where: A_i is the total wall area of the specific group i in the entire district (in m^2), and E_i is the environmental cost of the refurbishment of 1m^2 wall of the specific group i (in kgCO_{2eq}/m^2).

The same formula can be applied for the refurbishment works of other building envelope components. The total emissions from the measures performed at district level E_{ZER} are then calculated by the formula:

$$E_{ZER} = E_{ZER,w} + E_{ZER,o} + E_{ZER,r} \quad (2)$$

where: $E_{ZER,o}$ are the emissions from the refurbishment of the entire openings (windows and doors) and $E_{ZER,r}$ from the refurbishment of the entire roofs of the district.

2.2 Description of the block

The above method has been applied to a historic block in the city of Trondheim, which is composed of buildings with different status of decay and level of protection (Figure 1). The data for the labelled buildings are taken from the Trondheim Municipality for 28 buildings in the block. In Figure 2, it is given the typical wall section of these wooden buildings. They were subjected to refurbishment interventions in the '80s by adding a layer of mineral wool from the inside. However, the section does not reach the requirements for energy-efficiency (U_{min} = 0.18 W/m^{2}K) according to the actual Norwegian standard TEK17 (Ministry of Local Government and Regional Development, 2017); therefore, it needs further upgrade nowadays.

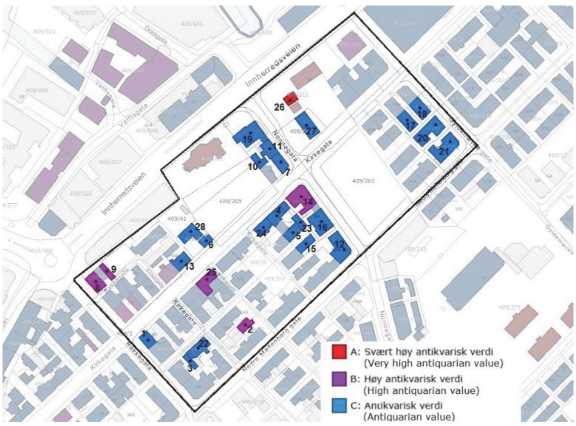

Figure 1 – The buildings block situated in Møllenberg

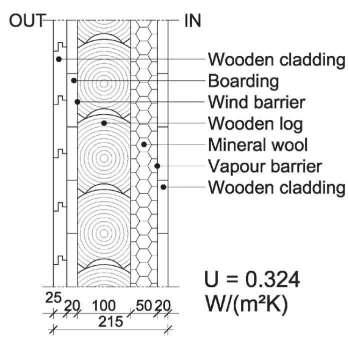

Figure 2 – The wall section of the buildings

3. Results

The service life has been estimated for the wall sections of every building by applying the modified factor method. For the timber log wall, the reference service life (RSL) has been assumed 50 years. The estimated service life (ESL) values are divided into three categories which correspond to medium-high decay (33-50 years), medium decay (50-67 years) and low decay (67-135 years). The ESL values have been calculated using the climatic conditions of the Recent Past (1960-1990) scenario (Climate for Culture, 2020).

3.1 Selection of the intervention

The sections of all buildings are grouped into a 2-D diagram according to their level of decay (low, medium and medium-high decay) and level of protection (A, B and C), as shown in Figure 3. For each of the section groups in Figure 3, the specialists can suggest one or more intervention scenarios that fulfil the recommendations. For some wall sections, more than one intervention scenario that improves the wall thermal transmittance is possible. The criteria for the selection of the most appropriate intervention is the one with the lowest carbon footprint. The selected scenario and the carbon footprint of the intervention work for 1m^2 of wall section are reported in Figure 4.

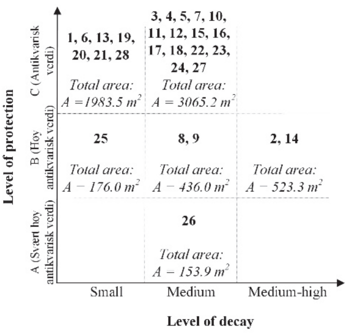

Figure 3 – The grouping of buildings into a 2-D diagram

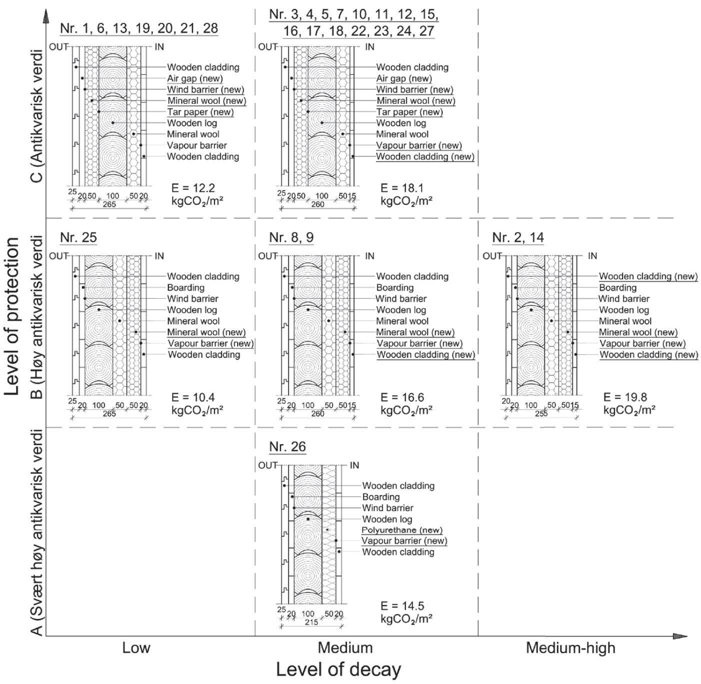

Figure 4 – The refurbished wall unit for each group and the environmental cost of it

The buildings within the class of protection C show higher flexibility of change, so the intervention can be applied from the outside for better insulation of the wall. For buildings within the class of protection B, the intervention will be applied from inside by adding 50mm of insulation. In such cases, special attention will be given to avoid the creation of thermal bridges. This type of intervention gets very close to the minimum technical value for thermal transmittance. Regarding the building with the level of protection A, the only suggested intervention is the replacement of the old insulation with a new one. The old insulation is not judged in good conditions to be applied to other buildings, so it can be disposed to landfill for the end-of-life stage, which increases the emissions cost. The new U-value of the wall does not meet the TEK17 standard value requirement, but notwithstanding it has a significant improvement in respect to the original section.

3.2 Calculation of emissions and service life improvement

The next step of the method is the calculation of emissions of the entire intervention works in the walls of the selected block. The result is achieved by using the formula in equation (1) as follows:

$$E_{ZER,w} = \sum_{i=1}^{6} A_i \times E_i = 1983.5\times 12.2 + 3065.2\times 18.1 + 176.0\times 10.4 + 436.0\times 16.6 + 523.3\times 19.8 + 153.9\times 14.5 = 101\ 340 kgCO_{2eq} \qquad (3)$$

This result needs to be added to interventions in windows and roofs, and then to the emissions emitted from the buildings during the operation phase (corresponding to the annual energy use in kWh/m^2/year estimated through computer modelling software or direct measurements). The sum of the emissions from the intervention works in the walls and windows (vertical plan) with those corresponding to the operational energy consumption after the refurbishment (horizontal plan) will serve as a basis for knowing the emissions that should be compensated from the on-site renewable energy production from the block.

Finally, the service life prediction of the improved wall section is calculated to forecast the time of the new intervention actions over the future. For this, the Far Future scenario, which projects the environmental-related variables in the timeframe 2070-2100, is used. By doing so, the suggested time of future actions considers the effect of climate change but also the new improvements in the quality and the thermal transmittance of walls, windows and roofs.

4. Discussions and Conclusions

The Zero Emission Refurbishment framework tends to link together the results of three independent communities in a methodologic approach where the output of one community serves as the input for the other. It enlarges the scale of the application to district-scale to ensure intervention works uniformity throughout the district, resulting in enhancement of value and time- and cost-efficiency. This approach considers many residential houses that are nowadays at risk due to lack of or bad maintenance. The overall carbon footprint of the refurbishment works, linked with the energy improvement of the buildings, serve as a basis for the shift towards Zero Emission Neighbourhoods in historic urban cities.

The method has been applied to a small block in the city of Trondheim in Norway, but it has the flexibility to be applied to districts with various scale and attributes of buildings. As a simplifying assumption, the original wall section has been considered the same for all the buildings. The method can be further improved by making a more specific grouping of the wall sections where each grid in the 2-D diagram can contain more than one section.

The framework gives strong emphasis to the reduction of carbon emissions and therefore, to climate change mitigation. Besides, the future interventions incorporate the expected climatic conditions; thus, the method integrates climate change adaptation measures.

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