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 term 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.

Keywords: zero emission, historic buildings, maintenance, conservation, refurbishment

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 overexploitation 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 interdisciplinary research to decision-making that integrates perspectives of the cultural heritage safeguarding 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 safeguarding 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 (max 200 words)

The core objective of the paper is to combine the perspective on preservation of historic buildings with that on Green House 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 safeguarding, is based on the following five steps:

1) A comprehensive survey of the definitions of the most used interventions, 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].

2) Identification and characterization of the allowed interventions in a historic building. 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].
3) Identification of terms and definitions adopted in the field of professionals and energy – and emissions specialists (e.g. building life cycle stage, Zero Emission Building architecture, and low carbon solutions) to understand the applicability to interventions in historic buildings. 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].
4) Classification of the level of interventions, based on effects on heritage value of historic buildings. 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].
5) Use of the LCA framework [28, 32-34] in the proposed method to reach a Zero Emission Refurbishment (ZER) balance. 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: (1) 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]); (2) 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 [39]; and (3) the research needs described in the scientific literature [11, 14].

3.1 – Definitions of interventions for existing and 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 decrease in 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.

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 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 [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 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, 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 sustaining the historic building in an appropriate condition to retain its significance slowing the deterioration and increasing a bit its 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 its functionality and/or its appearance (original condition). Minor repairs of damaged or deteriorated materials can be part of maintenance.	Y/N – In historic buildings, repair is generally viewed as a remedial conservation intervention to recover functionality and/or the appearance of deteriorated materials. It has to be preferable to replacements and based on evidence to respect heritage significance. In case of use of new materials, they have to match the old 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 alteration and intervention i.e. facelift or refit (i.e. superficial or cosmetic) to the envelope to enhance its appearance/ function, and/or extensive maintenance and repairs to reach modern standard (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.
REPLACEMENT	Construction operations that replace an entire character-defining feature with new material because the level of deterioration or damage of existing materials precludes repair or as action in connection with a change of use, or 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. Replacement becomes a conservation action if the material that is replaced is reused.
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 keep unchanged the use or to propose a contemporary use compatible with its heritage value. It has to interpret the property value with minimal change to its distinctive materials, features, and spaces.
RENOVATION	Action/s, driven by law/regulations requirements, to upgrade of components, elements and systems (including energy efficiency) to the today\`s level. It can includes 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 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. While protecting its heritage value, 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.

The whole classification system for interventions that can be applied to existing buildings during their performance management process [41] is reported in Figure 1 . These interventions can be 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 Figure 1) are admitted, while, concerning adaptation, only those labelled in red if preserve the significance and respect the conservation requirements (see section 3).

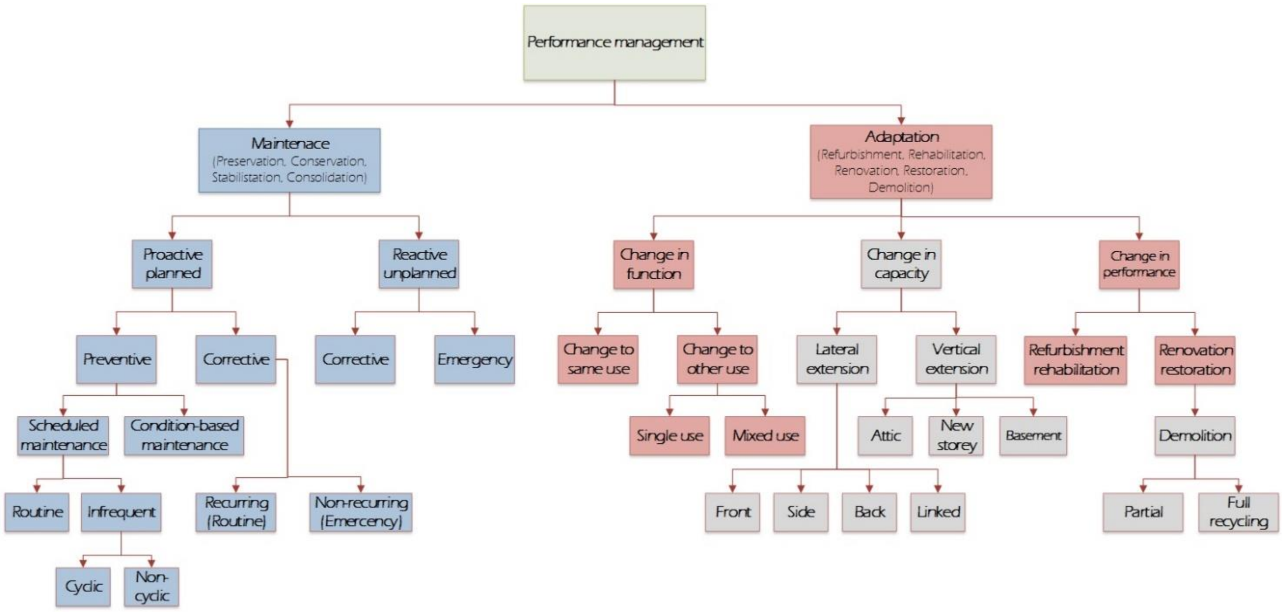


Figure 1 – Interventions that can be applied to an existing building [41]. All types of maintenance interventions can be applied to historical buildings (blue) while only interventions in red can be applied during adaptation process of them.

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 (ref) [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.
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 and reported in Figure 1a of the online material. 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 CO2 balance was proposed by the ZEB centre for a ZEB pilot building (Figure 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 CO2 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 CO2 eq/ m^2 per year]

CO_{2mo} annualized Material emissions during Operation (mo) stage, i.e. product stage replacement only [kg CO2 eq/ m^2 per year]

CO_{2e} averaged CO2 equivalent emission factor for Electricity (e) [kg CO2 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 (equation 2), which refers to the Zero Emission Refurbishment (ZER) balance, shifts the emphasis away from intervention costs towards CO2 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 Figure 1a and 1b – 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 during 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 in order to calculate the overall impact of the building and therefore, the payback amount.

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 has 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 work-force 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 CO2 emissions for each level of a building management intervention (i.e. low, middle and major) 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:

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

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_{2p} emissions from the Product (p) stage of new 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 CO2 equivalent emission factor for electricity [kg CO_2 eq/kWh]

Q_{el} total electricity delivered to the building for maintaining the functional and technical performance of the building fabric and building-integrated technical systems [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 Figure 2, 3 and 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 figures 2, 3, 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 (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]).

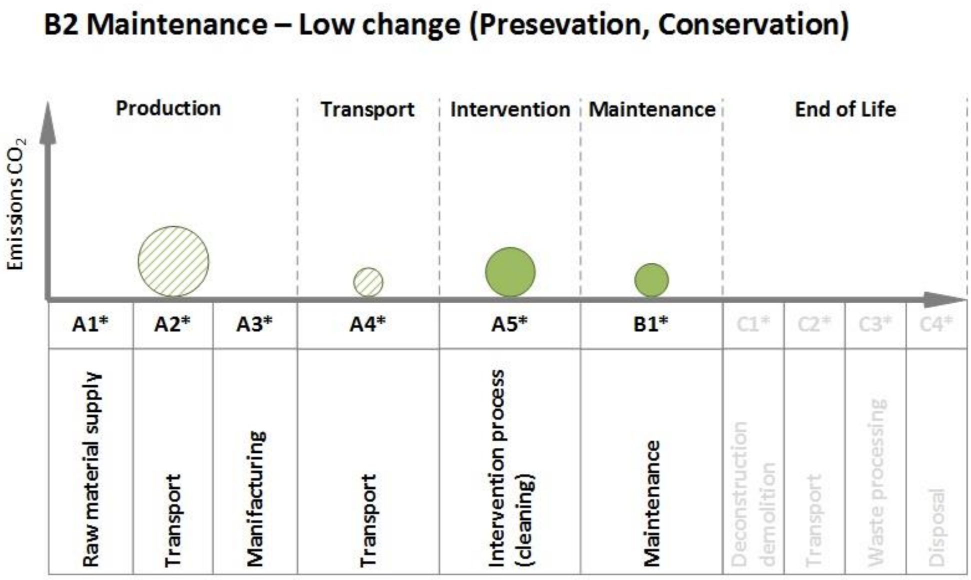


Figure 2 – CO2 emitted (green) during low change interventions. Emissions during preventive conservation derive from the periodical cleaning and maintenance phase (solid green circle) while

emissions from remedial conservation derive from the use of new materials (green striped circles). Adapted for existing and historic buildings from [14].

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

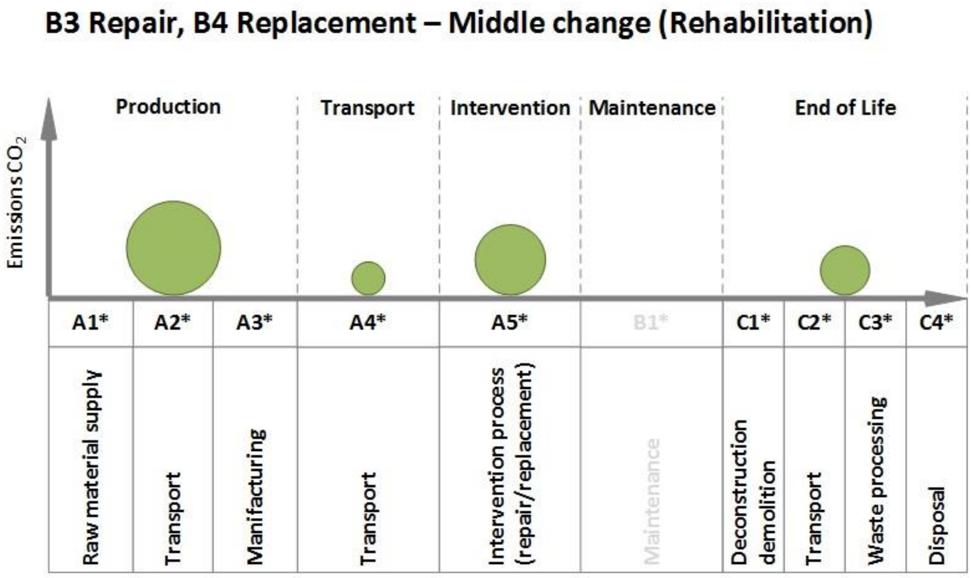


Figure 3 – CO2 emitted (green) during middle change interventions. Generated emissions derive from the use of new materials in higher amounts than during low change interventions. Adapted for existing and historic buildings from [14].

Middle change level (Figure 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*).

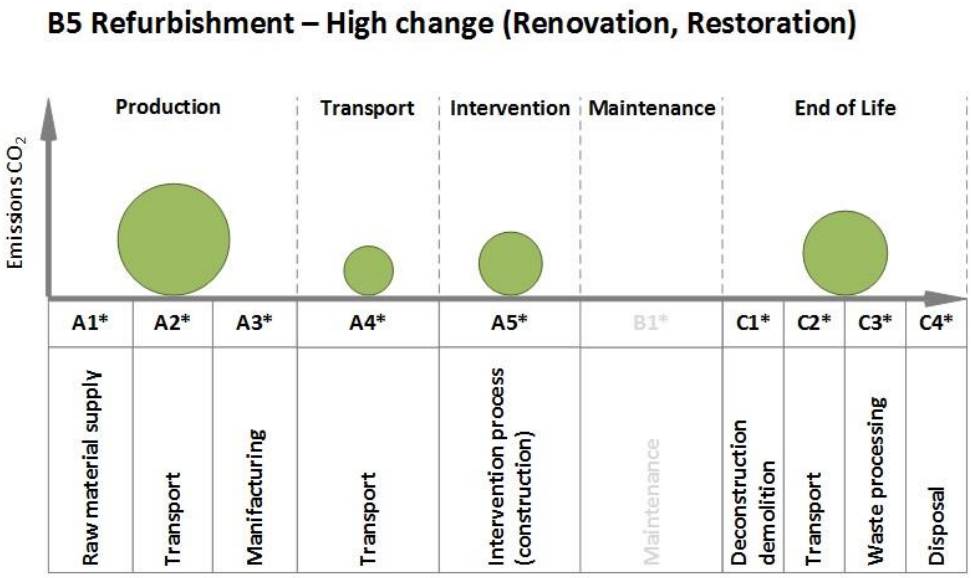


Figure 4 - CO2 emissions (green) during high change interventions. Adapted for existing and historic buildings from [14].

The highest level of interventions (Figure 4) (the refurbishment (B5) module in the standard definition [14]) includes deeper actions than the possible repair and replacement of damaged materials (middle 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, higher emissions are expected than for the same level of intervention in existing building with low significance (e.g. higher embodied and/or transportation emissions). The total emissions should be compensated with on-site renewable energy generation in order to reach a Zero Emission Refurbishment (ZER) balance (Figure 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.

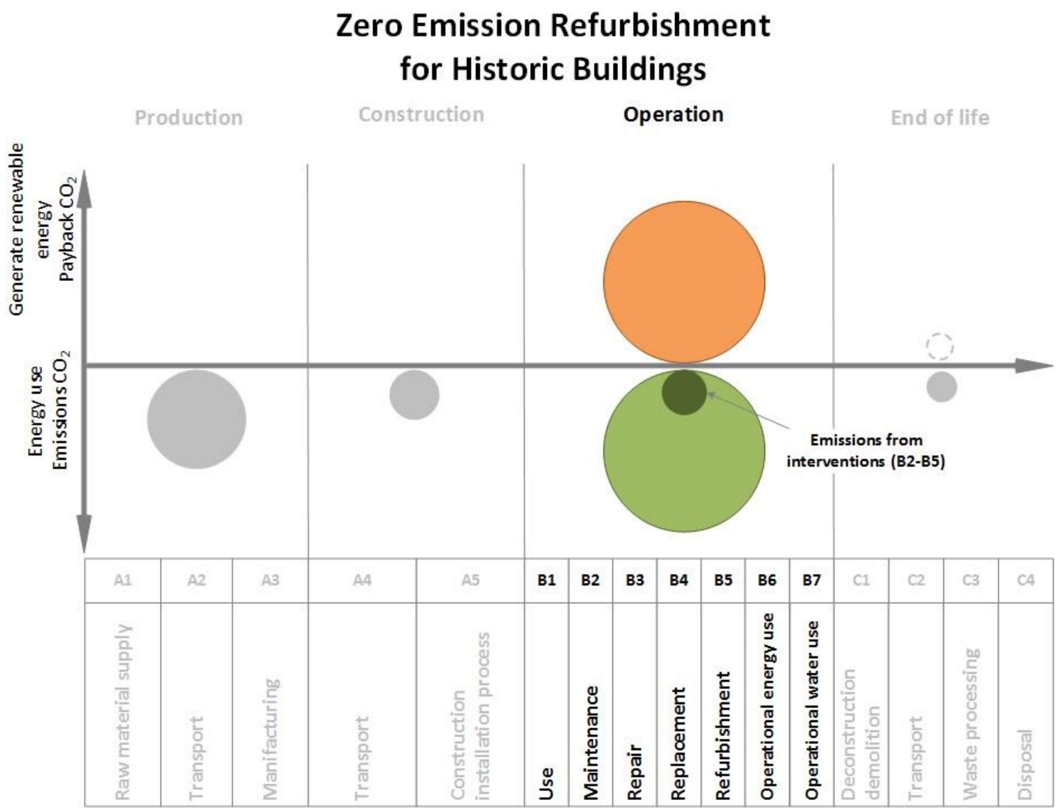


Figure 5 – Zero Emission Refurbishment balance for historic buildings. The emissions during the interventions are included in the emissions from the normal operation of the building in order to calculate the payback.

As seen in figure 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 CO2 equivalent emission factor for Electricity (e) [kg CO2 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 CO2 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 the building after the intervention process to the demand before the intervention (i-1):

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

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:

a) $k_i = 1$ for low change (maintenance) interventions that do not reduce the energy demand of the building,
b) $k_i < 1$ for middle 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 (Figure 6). Figure 6.a shows the emissions after a low change (maintenance) periodic intervention ($at\ time\ t_i$) that does not reduce energy demand; Figures 6.b, 6.c express respectively the reduction of the energy demand after a middle change (repair, replacement) or a high change intervention (refurbishment).

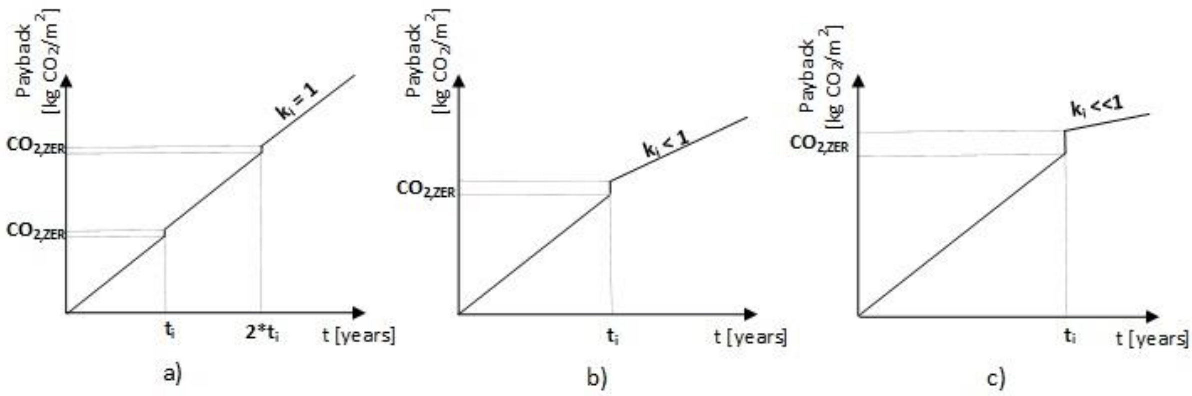


Figure 6 – Total emissions to be generated from renewables for each type of intervention: a) maintenance, b) repair, replacement and c) refurbishment.

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

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

where:

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

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

CO_{2e_i} averaged CO2 equivalent emission factor for Electricity [kg CO2 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 CO2 eq/m^2].

4.2 Relationship between level of decay and levels of interventions

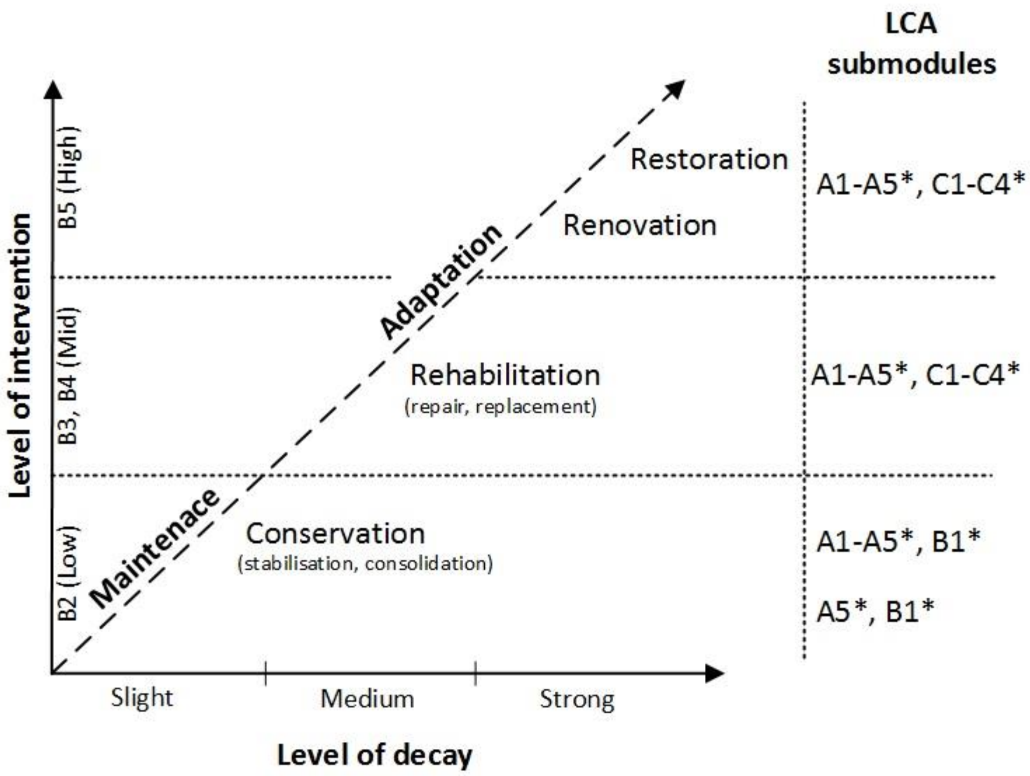


Figure 7 – Relationship between level of decay (LoD) and levels of interventions that can be applied to historic buildings. LCA stages to take into account during low, middle and high levels of interventions (column on the right).

The relation expressed in figure 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 formula to two simplified scenarios of intervention

The proposed decision-making tool (i.e. equation 2) 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 Figure 8.

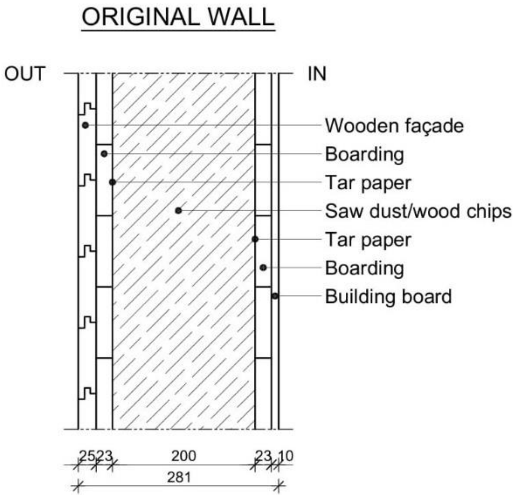
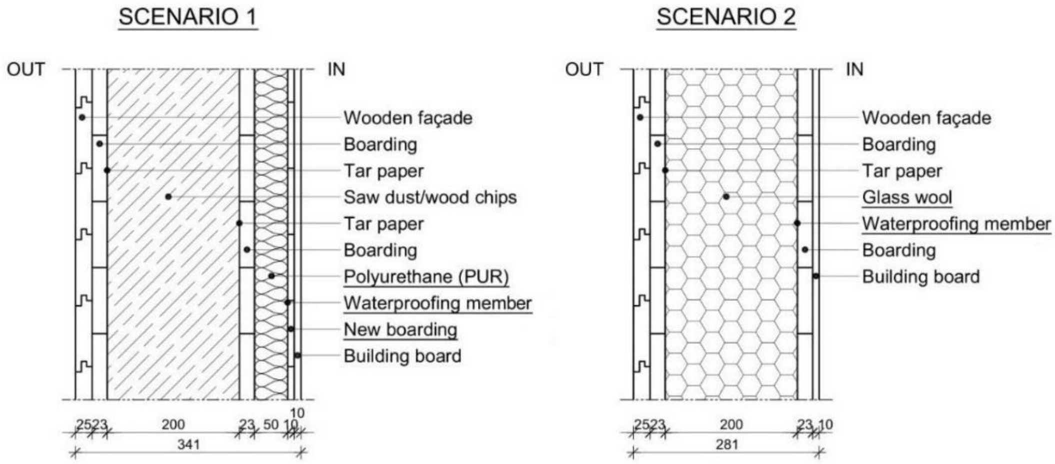


Figure 8 – The section of the original wall with the description and the dimension of its components in millimetres. The outdoor and indoor wall exposition is also highlighted.

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^2K), while according to the Norwegian standard TEK17 [55], it should be below 0.18 W/(m^2K). Therefore, two refurbishment scenarios were proposed to improve the thermal transmittance of the original wall in value 0.171 W/(m^2K) 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 Figure 9. The interventions are done from the internal part of the wall in order to keep unchanged the original external facade.



Scenario 1: Additional insulation:

1. Remove building board
2. **Add thermal insulation (PUR)**
3. **Add waterproof member**
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 waterproof member**
7. Reinstall boarding
8. Reinstall building board

Figure 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.

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.

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:

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

while for the scenario 2 is:

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

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:

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

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:

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

and for the whole surface:

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

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 kWh/m^2 (corresponding to emissions factor 132 gCO2eq/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 payback 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.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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