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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]:

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

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].

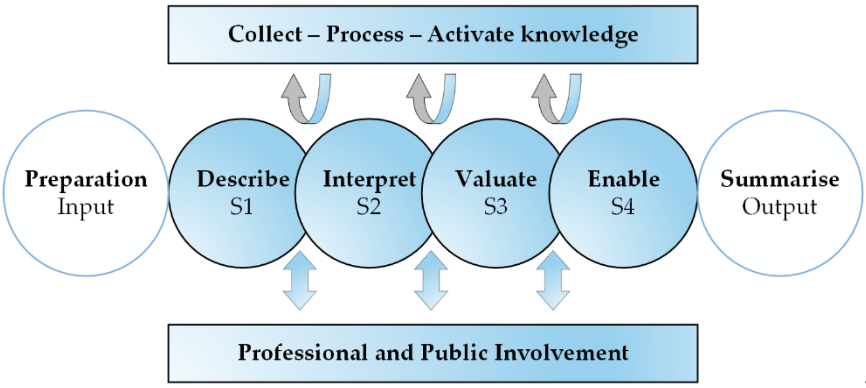


Figure 1. Structure of the DIVE approach.

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.

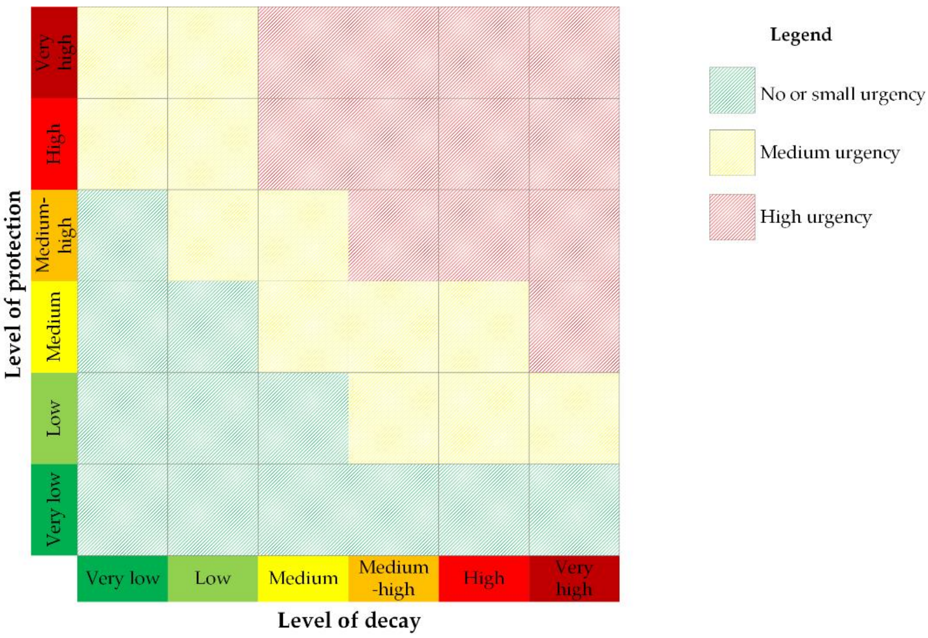


Figure 2. The link between the levels of decay and the levels of protection in historic buildings. The colour code highlights the urgency need for adaptation interventions.

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

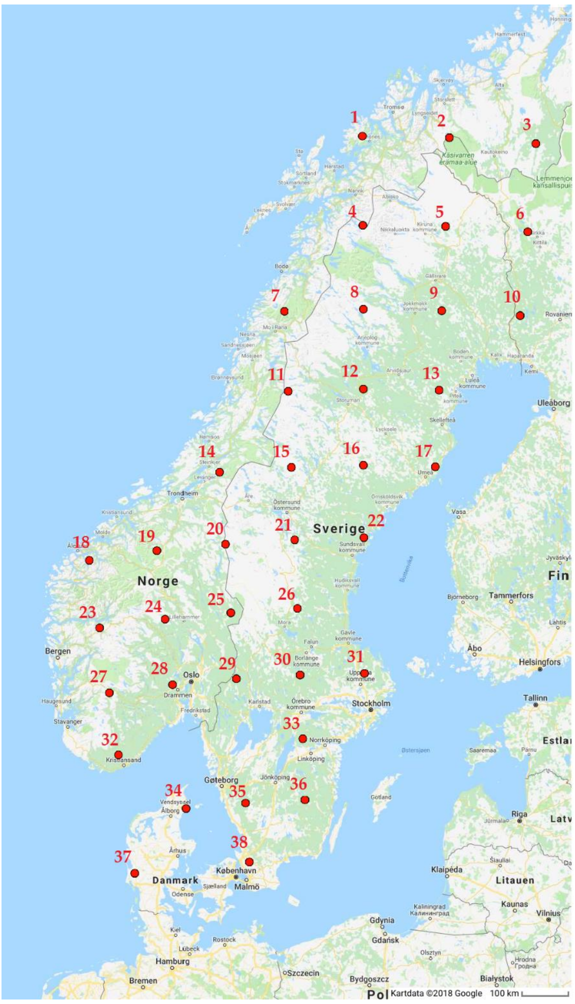
The climate change effect will affect the deterioration level in historic buildings depending on the geographic location and type of constructive material [31]. For this reason, cultural heritage managers have to plan and implement adaptation actions that can work effectively for the years to come [47]. 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).

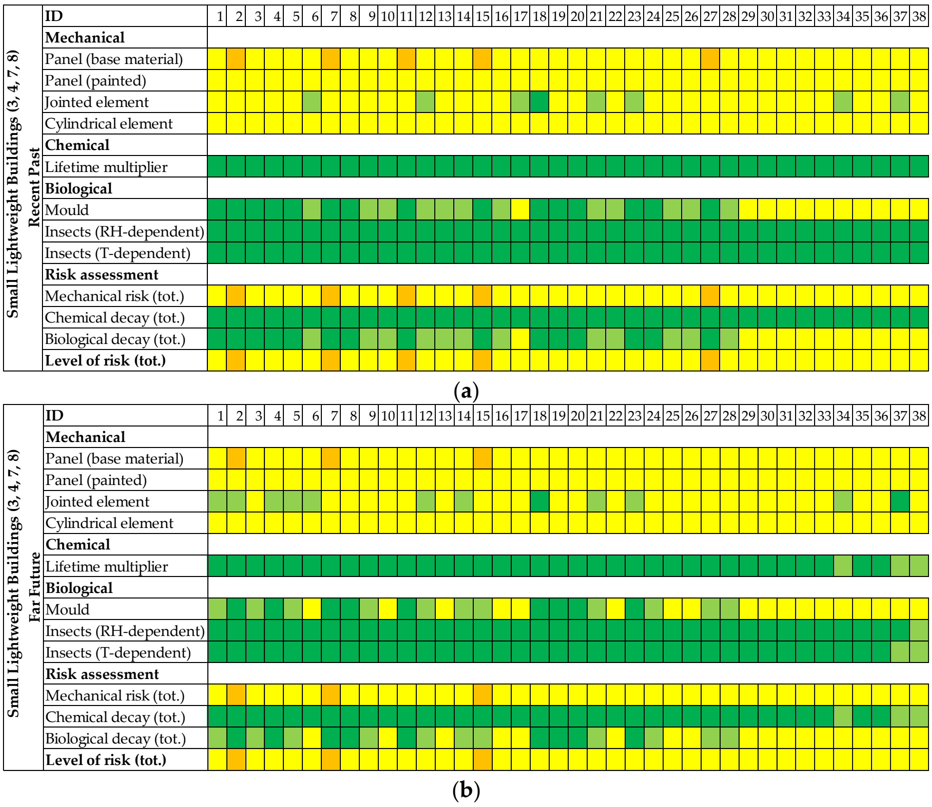


Figure 3. Risk assessment matrix of the deterioration of small lightweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

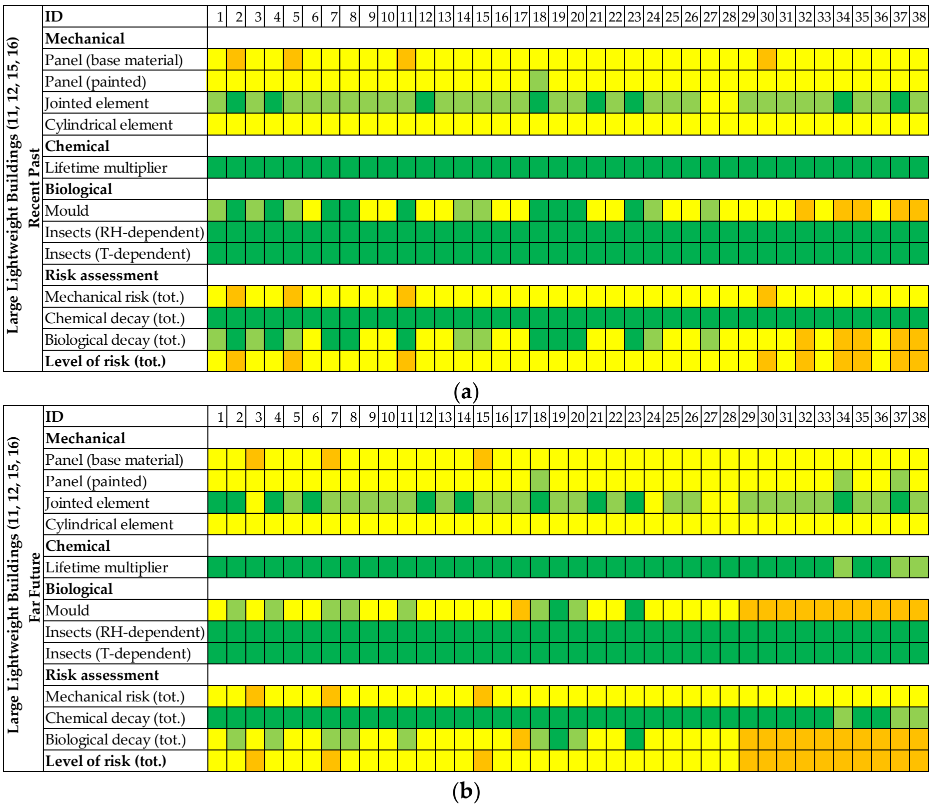


Figure 4. Risk assessment matrix of the deterioration of large lightweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

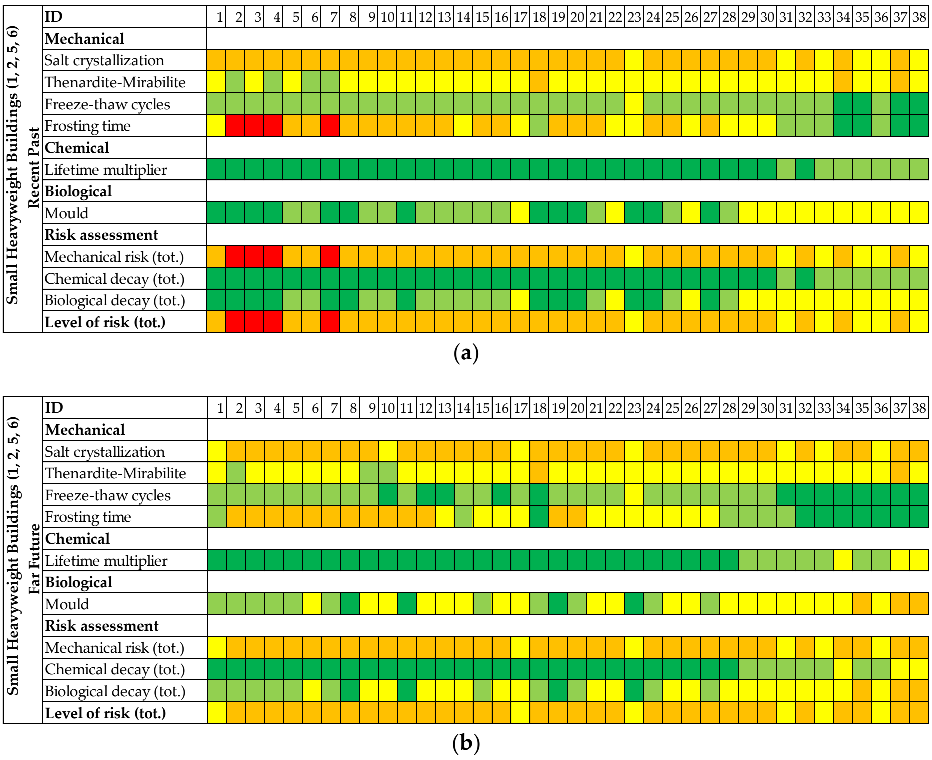


Figure 5. Risk assessment matrix of the deterioration of small heavyweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

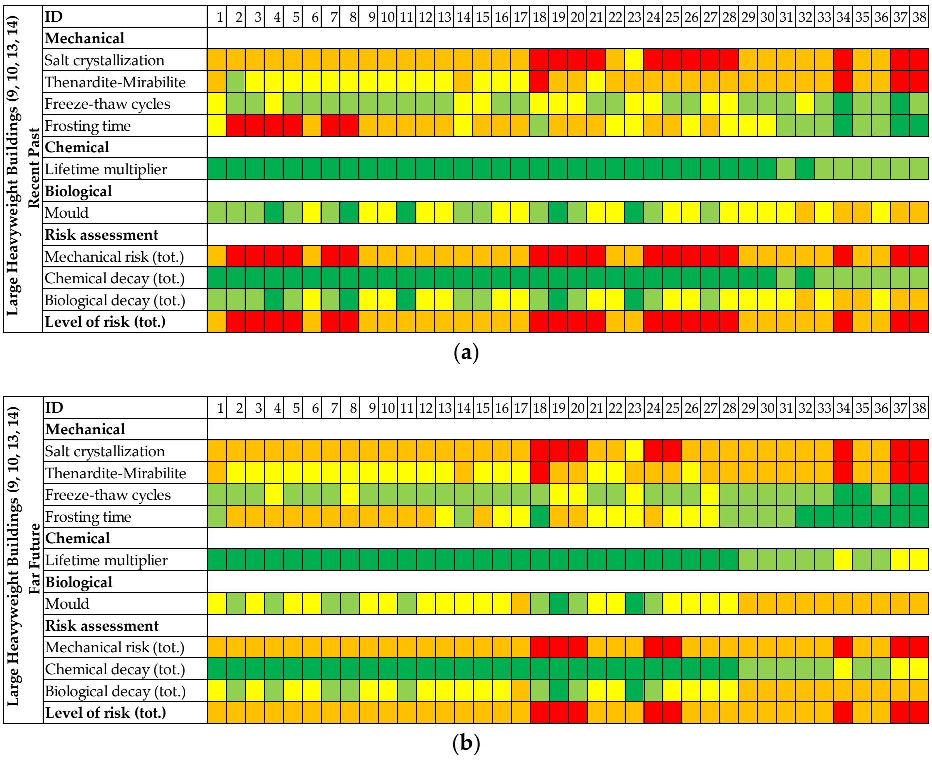


Figure 6. Risk assessment matrix of the deterioration of large heavyweight buildings in: (**a**) Recent Past (1961–1990); (**b**) Far Future (2071–2100).

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:

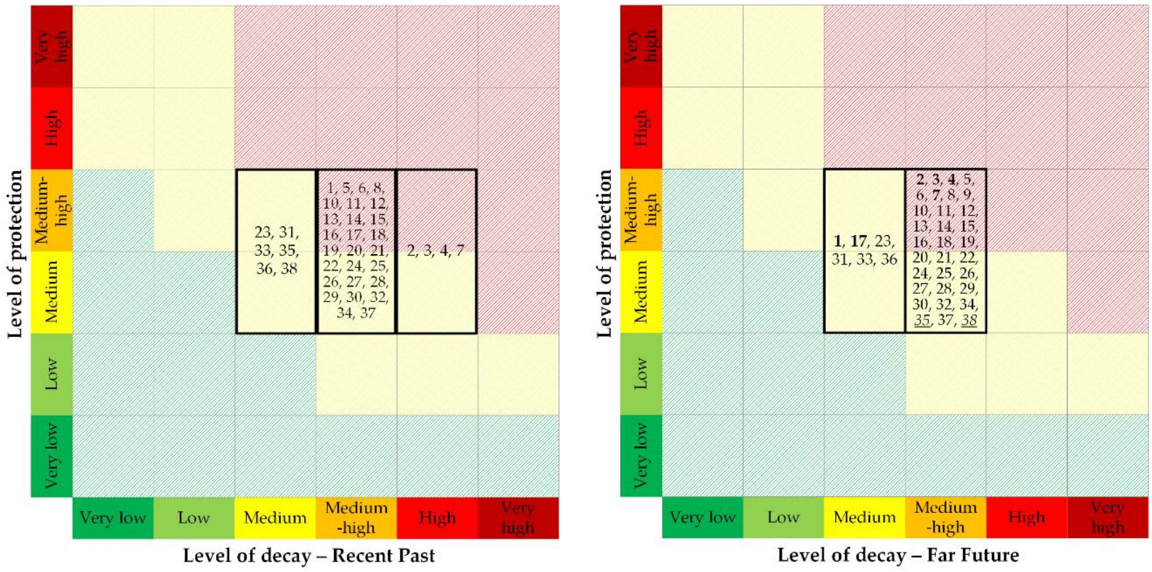
- In Scandinavian countries, the mechanical deterioration indoor in all types of buildings has a general decrease in the Far Future, although the decay remains in the ranges of medium to high risk.
- The chemical and biological risks increase. The former, exemplified by the lifetime multiplier indicator, 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.

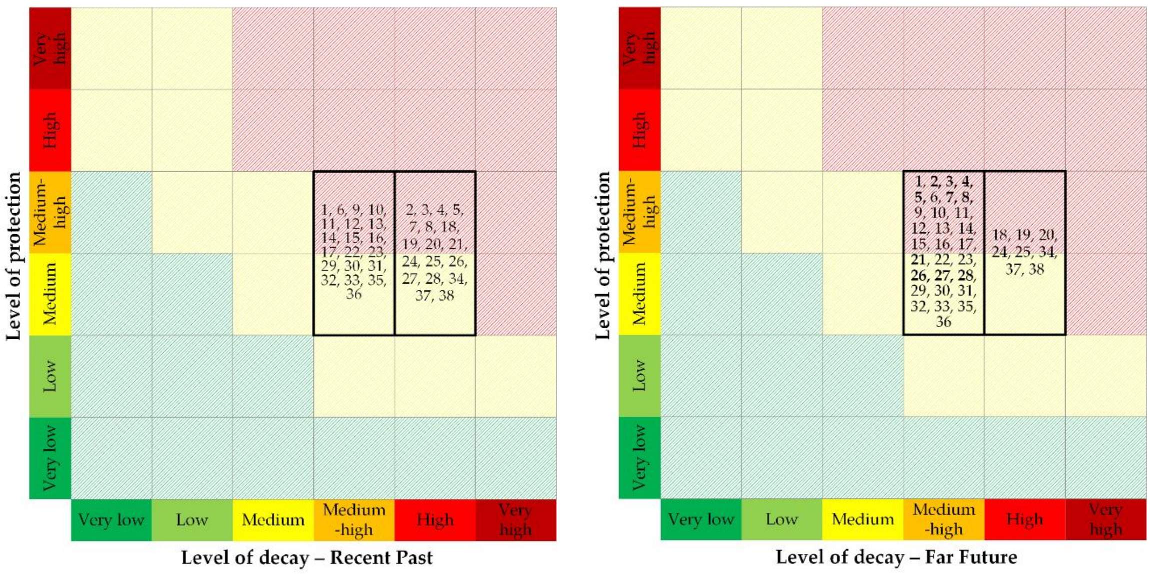
The locations in the Scandinavian countries, where interventions are required to minimize the risk of losing CDEs in historic heavyweight buildings, are inserted in the matrices in the Figures 7 and 8. The level of protection of the buildings according to the legislation is considered medium and medium-high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