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Painted Wood Climate Risk Analysis by the HERIe Model of Building Protection and Conservation Heating Scenarios in Norwegian Medieval Stone Churches

Terje Grøntoft [1,*] and Lena P. Stoveland [2]

[1] NILU-Norwegian Institute for Air Research, Instituttvn 18, Box 100, 2027 Kjeller, Norway
[2] NIKU-Norwegian Institute for Cultural Heritage Research, Storgata 2, 0155 Oslo, Norway
* Correspondence: teg@nilu.no

Abstract: HERIe was used to model the effect of changes to indoor climate on the risk of humidity-induced mechanical damage (cracking and plastic deformation) to wooden panels painted with stiff gesso in two Norwegian medieval stone churches: Kinn (mean relative humidity (RH, %) = 79%) on the humid west coast, and Ringsaker (mean RH = 49%) in the drier eastern part of the country. The risk involved in moving cultural heritage objects (paint on wood) between the churches and a conservation studio with more "ideal", stable conditions was also modeled. A hypothetical reduction in RH to ~65% and, proportionally, of the climate fluctuations in Kinn, and an increase in the RH in Ringsaker to a more stable value of ~63% via conservation heating, were found to improve (Kinn) and uphold (Ringsaker) the conformity to relevant standards and significantly reduce the risk of damage, except in the scenario of moving objects from Ringsaker to a conservation studio, when the risk would increase. The use of conservation heating could save ~50% of the heating cost. The estimated risk reductions may be less relevant for objects kept in situ, where cracks in the original paint and gesso have developed historically. They may be more relevant when moving original objects away from their proofed climate into a conservation studio for treatment.

Keywords: Norwegian medieval stone churches; cultural heritage degradation; polychrome painted wood; conservation treatment; HERIe climate risk modeling; humidity-induced mechanical damage; climate standard; conservation heating; energy saving

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1. Introduction

As in the more famous wooden stave churches, Norway has several medieval stone churches that house religious objects of great cultural significance. Their indoor climates are characterized by large seasonal fluctuations and, often, extremely dry or moist conditions that are governed by the outdoor conditions or the heating regimes in the buildings [1]. Incorrect indoor relative humidity (RH, %) and temperature (T, °C) values and fluctuations, also termed the indoor climate in this work, can cause plastic deformation and cracking in polychrome painted wooden objects [2–4], followed by different and potentially accelerating damage processes such as cupping and the flaking of paint and ground layers. Changes to the historical climate, to which the objects are acclimatized [5], may thus result in reduced material value and increased conservation costs.

Energy saving is a requirement to mitigate greenhouse gas emissions. Heritage buildings, such as churches, often have high energy consumption and energy cost, and adopting energy-saving measures can help reduce the carbon footprint [6]. Recent international crises, with the accompanying dramatically increasing energy prices, are an additional concern. As the outdoor climate in Norway changes to become more humid, tempered, and fluctuating [7], the chances for change in the indoor climate in churches beyond the range of that experienced in historically proofed climates [5] may also increase. Significant increases in rainfall, leading to the occurrence of wood rot, have also been predicted [8] and were recorded in the recent past [9] in western Norway. However, only small changes to the humidity content of walls have been predicted [10]. It is essential that energy-saving measures in the churches should help reduce, or at the least not increase, the climate risks and conservation costs regarding building interiors and objects.

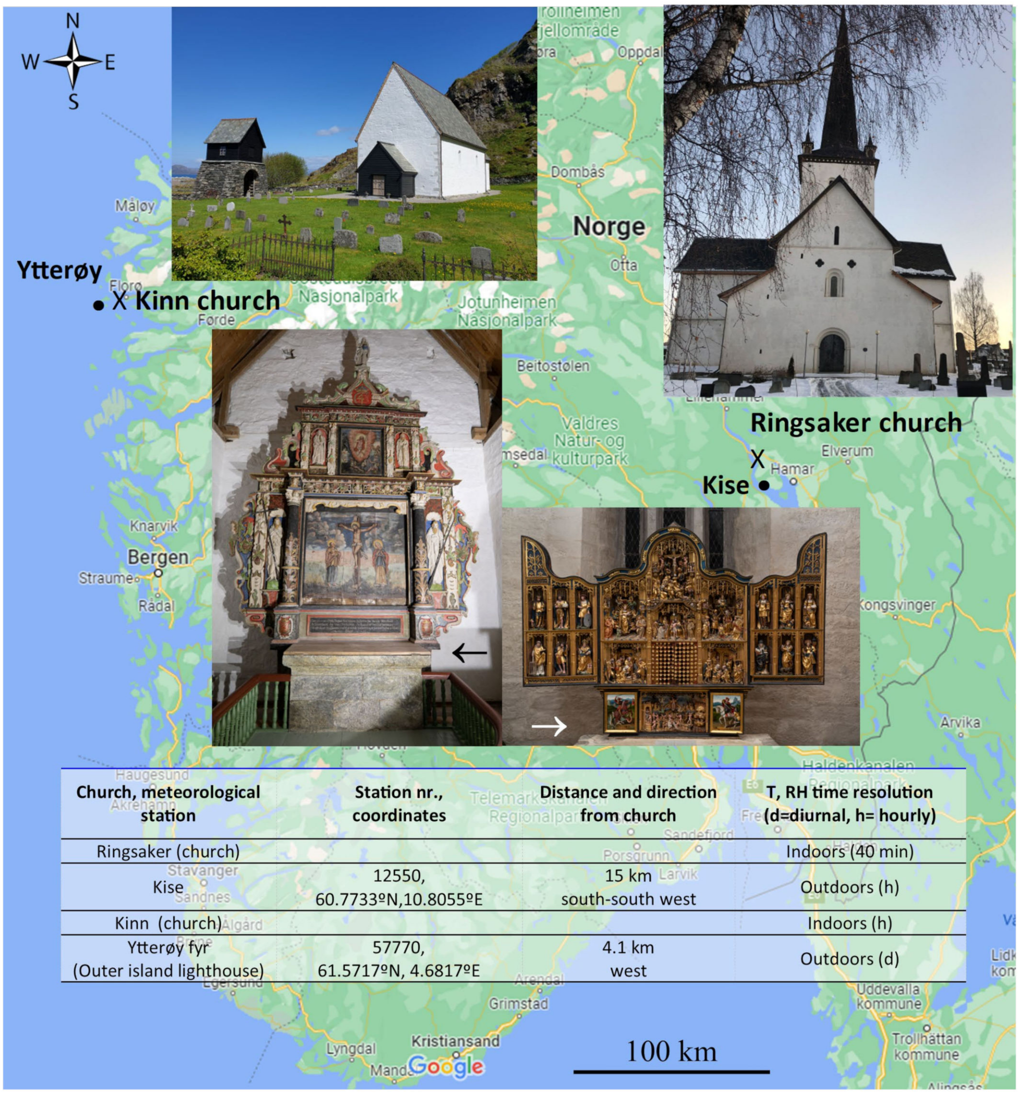
The aim of this work was to improve our understanding of the climate sensitivity of polychrome painted wooden objects in Norwegian stone churches by analyzing and modeling how changes in indoor RH and T might affect their preservation. The effect of measures to improve preservation climates and/or save energy on the risks of mechanical damage, plastic deformation, and cracking to painted wooden objects was assessed. Two churches, Kinn and Ringsaker (both dating from around 1150), which are located in very different climates and have different heating regimes, were selected for the study. Both house valuable polychrome wooden objects with past and/or present condition issues that can be related to unfavorable indoor climates [11–15]. The indoor climate data from the two churches were compared to the CEN 15757 standard and ASHREA guidelines (the term "guideline" is also used in this work as a generic term describing both formal "standards" (CEN EN 15757:2010) and other specific "guidelines" (ASHRAE)), and the HERIe [16] (https://HERIE.pl/, accessed on 12 January 2023) modeling tool was used to assess the risk of mechanical damage. To our knowledge, only a few exemplifying studies recording the application of HERIe have been published by others than the model developers [17].

The limitations of simplified modeling are well known. Accurate and precise modeling can only be performed if the model represents the phenomena of interest and possess good input data. HERIe simulates the worst-case scenarios of humidity-induced mechanical damage risks to paint and gesso on wooden panels, which may not represent the actual risk to historically acclimatized and naturally aged (and already cracked) objects [18]. HERIe is, however, a powerful tool in aiding the decision-making processes by estimating the risks involved when changing the indoor climate or moving objects between locations, for example, for treatment in a conservation studio [17]. It could be expected that the trend in the risk of damage to different geometries, depending on changes in the environment, resembles that of panels, but it was outside the scope of this work to assess such variations.

The HERIe model is briefly described herein to understand its use in this work. For a more detailed description, readers are referred to the published literature. Derivations that are particular to this work are described in detail. The current modeling did not consider the multitude of possible local objects and microclimate variations, combinations, and synergies. The evaluations were based on measurements of the local climate near the altarpieces in the Kinn and Ringsaker churches and, thus, do not represent the indoor climate of these buildings as a whole. The practical means and possibilities [19] of changing the buildings' indoor climates and of realizing the indoor climate scenarios were not evaluated. It has been noted that engagement with modeling in heritage science and practice has been limited [20]. The model application below is a contribution intended to redress this situation.

2. Locations and Objects

The Kinn and Ringsaker churches are located in the southern part of Norway. Kinn church is a (mainly) unheated stone building on a small island on the west coast. It is located north of a rising cliff and is directly exposed to the harsh weather conditions of the open North Sea in the west and north. Ringsaker church is a heated stone building, located inland east of the main Scandinavian mountain range (Figure 1). In the Köppen system, Kinn is in an oceanic climate and Ringsaker is in a subarctic climate [21,22]. In the following sections, the churches will mostly be referred to simply as "Kinn" and "Ringsaker".



Church, meteorological station	Station nr., coordinates	Distance and direction from church	T, RH time resolution (d=diurnal, h= hourly)
Ringsaker (church)			Indoors (40 min)
Kise	12550, 60.7733ºN,10.8055ºE	15 km south-south west	Outdoors (h)
Kinn (church)			Indoors (h)
Ytterøy fyr (Outer island lighthouse)	57770, 61.5717ºN, 4.6817ºE	4.1 km west	Outdoors (d)

Figure 1. The Kinn and Ringsaker churches (X) and locations of the climate loggers (arrows) near their altars. The meteorological stations at Ytterøy, near Kinn, and Kise, near Ringsaker, are also marked. Photos: Kinn (left): Smestad, T.R., NIKU, 2020. Ringsaker (right): church: Jernæs, N.K., NIKU, 2019. Altar: Lindstad, B., 2020.

Kinn houses religious objects from the 16th century and later, including a painted wooden altarpiece carved in 1644, with an integrated central section from a late medieval triptych and painted elements from 1703 (Figure 1) [23]. The altarpiece's material composition, condition, and conservation treatments in 1971 and in 2004–2005 have been described elsewhere [14,15]. The sculptures and sculpted scenes in the altarpiece are made from oak, while lime and pine were used in other parts of the construction, such as the panel paintings. The altarpiece is probably painted with a thin oil-based paint on a relatively thick and porous chalk-glue ground. The objects have a long history of wear, cracking, flaking paint, and paint loss, undergoing restoration treatments before 1971 about which there exists relatively little information. Loose and flaking paint was consolidated with polyvinyl acetate (PVA) in 1971, with sturgeon glue in 2004, and with Lascaux medium for consolidation (MFK) in 2005. Newly flaking paint, paint loss, and possible activity from wood borers were observed on the altarpiece during a condition re-assessment in 2020 [15].

Although Kinn remains mainly unheated, it has ~15 electrical tube ovens of 1000 W output efficiency each, located below the seats. These are turned on during the occasional gatherings and events in the church, such as during a confirmation ceremony in May 2012 when all the ovens were turned to maximum, which gave a temperature varying between 8 and 12 °C [11]. In 2012, it was reported that a portable oil-filled electrical radiator was used for shorter periods for local heating behind the altar, in an attempt to reduce the observed moisture in this location. However, due to the very humid outdoor and indoor conditions in Kinn, it was found that any advantages to using heating to reduce the RH or surface moisture were very slight or non-existent. Heating a church that has remained largely unheated until this day is generally not recommended from a conservation perspective [24]. Heating could also affect the moisture content and moisture transport in the walls, which could potentially cause evaporation and increased RH [11]. Continuous heating would necessitate unwanted energy use and increased electrical bills. It seemed better that a reduction in the indoor humidity (RH and condensation) should, as far as possible, be via measures that reduce the moisture infiltration into the church through openings, for example, by doors and windows, and in the church fabric from the rain and the ground [25,26]. Occasional local heating might be more efficient if this moisture infiltration could be reduced. It has, however, been suggested that improved insulation, resulting in less infiltration, could reduce indoor air circulation and air movement and increase the risk of mold growth [11].

Ringsaker has a richly ornamented interior, with one of the most important and well-preserved altarpieces in Norway [27]. It was produced from oak wood in Antwerp in the early 16th century and consists of polychrome sculptures and sculpted elements and doors, with beautifully painted scenes [12]. It was painted with oil-based paint and has large areas of gilding, metal foils, and decorative punch marks. Detailed reports of its materials, construction, past treatment history before 1982 (including varnish removal, consolidation with wax, and revarnishing), its condition, and the indoor climate in the church have been provided [12,13]. Observations during the last investigations and a condition assessment in 2019 reported the shrinking of painted panels, craquelures on the paintings, some new loose and flaking paint on the sculptures, pieces of the sculptures that had fallen off, and signs of overcleaning, as well as layers of soil and dust. The need for structural repairs and the stabilization of mechanical elements such as doors, due to loads and movements, were also noted. The 2020 treatment included surface cleaning, the consolidation of loose paint on the sculptures (using Lascaux medium for consolidation), gluing the loose parts of the construction, retouching, and re-varnishing the paintings.

Ringsaker was unheated until wood stoves were installed in 1865 [12]. Electric tube stoves with two heating settings were in place along the north and south walls and beneath the seats before floor heating was installed in the 1960s. The sacristy has electrical panel stoves. The heating control is manually operated, with the aim of keeping a stable temperature of 18 °C. The few RH measurements reported from before 2019 were of a "variation in the RH of between 42 and 58%" in the winter of 1968, and of "a similar variation as in 1968" in the winter of 1982. Dry air due to the electric heating and RH fluctuations were reported to cause cracking and flaking paint.

Figure 2 shows damage to the painted wood of the altarpieces in Kinn and Ringsaker before the conservation treatments.

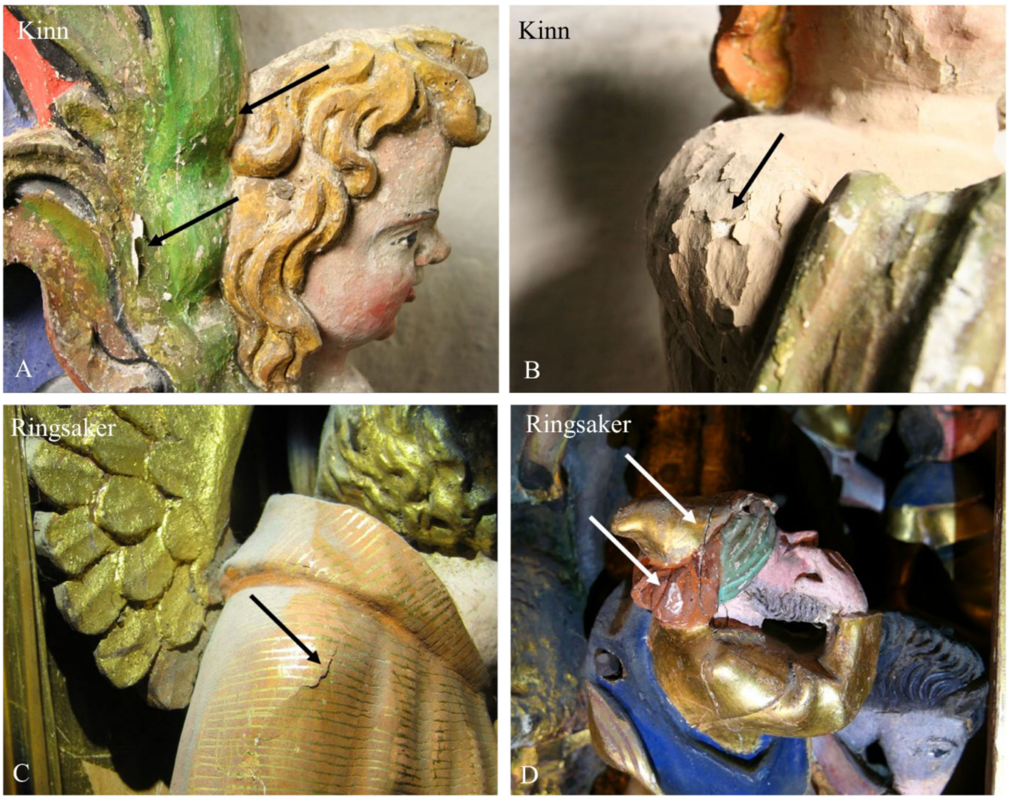


Figure 2. Details of loose, flaking paint and paint loss (**A**,**B**) of carved figures on the Kinn altarpiece before treatment in 2005. Details of cracked paint in the cape of a sculpture (**C**) and of cracks and small paint loss on the head and shoulders of a figure (**D**) of the Ringsaker altarpiece, before treatment in 2020. Photos: (**A**,**B**): Solstad, J., NIKU, 2005. (**C**,**D**): Olstad, T.M., NIKU, 2019.

3. Methods

3.1. Climate Measurements

The indoor climate conditions (RH and T) in the churches were measured during annual monitoring campaigns, using pre-calibrated Testo 177-H1 loggers with hourly resolution in Kinn in 2011–2012 [28], and Tinytag ultra2 loggers with 40-min resolution in Ringsaker in 2019–2020 [12,13]. The logger of the climate data for this work, in Kinn, was mounted on the front of the base of the altarpiece, between 0.1 and 1 m above the floor. The logger in Ringsaker was mounted on the side of the base of the altarpiece, ~1.5 m above the floor (Figure 1). The logger in Ringsaker was moved from the measurement location from 29 April to 25 May 2020. The RH and T values over this period were simply linearly interpolated, from the last value measured in the church at the end of April to the first value again measured in the church at the end of May. The interpolation was not expected to change the overall results of the study, although any variations of concern in this period will have been omitted (see Section 4, Results). The outdoor values of RH and T were collected from the nearest meteorological stations found to best represent the ambient conditions of the churches [29] (Figure 1).

3.2. Evaluation of Indoor Climate Adjustments in the Churches Using Conservation Guidelines

A description of the indoor climate guidelines is provided in Appendix A. The general climate risk in the churches was assessed by calculating the conformity to the CEN15757 standard [30] and ASHRAE guidelines [31] (in Excel). It was considered that the comparison of the climates in the churches with the CEN standard, which specifically address the risk of mechanical damage in organic hygroscopic materials, and the ASHRAE B class, which addresses temperature reduction in the winter, were of particular interest. The evaluation was made using a combination of the short-term, seasonal, and fixed limits of the guidelines/classes, calculated to always present the most stringent of the three limits via the RH and T time series, resulting in the least conformity. The conformity of the RH and T values with the limits was then calculated as the "percentage of time when the guideline limits were met", alternatively interpreted as the "percentage outside of limits" [32,33]. The guidelines provide, by their very definition, the limits of critical risk regarding damage at transgression. It is therefore important to avoid any transgression, and high conformity (near 100%) will still indicate a risk. However, the conformity, besides noting the risk at values of <100%, is also a measure that is usually expected to correlate with the frequency of critical transgressions, signifying the probable rate of the development of the resulting damage and, thus, condition at any future point in time (until "total damage" is assessed). The conformity comparison of time outside of different (guideline) limits is, in our view, a useful and simple additional measure to compare the variations (fluctuation amplitudes and durations) in RH and T time series.

HERIe modeling maps the risk of mechanical damage in terms of painted wooden panels in situ in the churches, after hypothesized changes in indoor climates, and when hypothetically moving a painted panel to a conservation studio. The indoor climate scenarios (see Section 3.4) used lower RH values in Kinn than might be obtained by building measures [26] in a situation with some, but probably still sparse, heating, and of a higher but more stable RH (<65%) in Ringsaker that could be obtained via conservation heating with a reduced temperature, and that could still be considered acceptable for preservation. Conservation heating, or humidistat-controlled heating, refers to the concept of heating a building to keep the relative humidity below given limits [34–38]. The energy consumption calculations were finally made as monthly heating degree days for comfort [39] and conservation heating.

3.3. Mold and the High RH Limit

The climate scenarios were of RH changes in the churches moving toward an (upper) RH limit of 65%, considering the mold risk, which has been a matter of major concern when suggesting limits. An RH limit (of 65%) has been adopted by the National Trust for its properties in England, Wales, and Northern Ireland, "considering primarily the risk of mould growth, with this threshold allowing for the difference between measurement of a bulk room environment and cooler microclimates close to external walls, as well as providing for sensor inaccuracies" [35]. The intention was to keep the coolest parts of a room below the more widely recognized 70 to 80% RH mold threshold. In Norwegian winters, which are colder than British winters, high RH levels close to, and condensation on, external walls would be more likely. In the recorded high humidity in Kinn (see Section 3.4), mold occurrence could reasonably be expected. However, no mold was reported on objects, room surfaces, or the external walls. It was reported in 2013 that this might be due to the building's natural ventilation [11]. Rot was later observed in 2016 in the building's structure, and some mold was recorded in the cellar [26]. The sea salt exposure of the church from the north Atlantic westerly winds [40,41], which would, in some amounts, be ventilated to the indoor air, may inhibit mold growth [42]. Salt exposure can, however, also damage wooden materials [43–45]. The amount of salt on the wood and painted surfaces in the church has not, as far as we know, been measured. No mold occurrence has been reported in Ringsaker [12,13]. A scenario change in Ringsaker to a more stable RH of <~65%

was not expected to increase the mold risk. Zero (mm) expected mycelium growth was calculated in Ringsaker over the period of the 2019–2020 in situ recorded and scenario (see Section 3.4) climate data, according to the method described in earlier publications [33,46].

3.4. Climate and Object Scenarios

In Kinn, a situation was hypothesized wherein building construction measures were possible and were effective in reducing the indoor humidity to RH scenario values, RH_{adj}, in steps of ~5% and below the set scenario RH maximum limits of $RH_{max,lim}$ = 85%, 80%, 75%, 70%, and 65%, assessed proportionally to the measured values over the whole measurement range, according to Equation (1):

$$RH_{adj} = RH_{measured} \cdot \frac{RH_{max,lim}/0.95}{RH_{max,measured}}. \quad (1)$$

It was assumed that it was inconvenient, or improbable, to adjust the highest peaks of the measured RH values throughout the year to below the limit values. The absolute maximum adjusted RH value was, therefore, set to a 5% higher value than the RH scenario maximum limit value. In that case, $RH_{measured}$ = $RH_{max,measured}$, and the absolute maximum RH_{adj} = $RH_{max.lim}/0.95$. For example, the 65% scenario for the highest RH (peak), adjusted from the measured values in 2011–2012, would thus be $RH_{adj.max}$ = 65/0.95 = 68.4%.

In Ringsaker, a modified temperature should approach, as near as possible, a constant RH = 65% through the year, and be between a minimum temperature of 10 °C and a maximum of 25 °C, and was expected to result in conservation-heating saving. This modified temperature was calculated from the recorded RH and T values (in 2019–2020) and the calculated absolute humidity (AH, g/m^3) from the equation given by the authors of [47] (p. 51). The estimations were made by first calculating the absolute humidity in each time step (of 40 min) of the measurements. The RH was then fitted, again using the equation from [47] (p. 51) to be as close as possible to the set limit (of 65%) at that absolute humidity via a sequential numerical adjustment of the temperature from that measured. The fitting involved a changing of the temperature in each time step, proportionally to the respectively calculated distance of the adjusted RH (via Equation (2)) from the RH limit (= 65%), until the least possible sum of the estimated RH differences, from the RH limit throughout all the time steps of the annual measurement series, was obtained. In time steps wherein the maximum or minimum set temperature limits (25 °C and 10 °C) were reached, no further RH changes were allowed. A graphic representation of the scenarios is provided in Section 4.2.

The HERIe modeling process (Section 3.5) was performed for the measured and adjusted climates, and, in addition, for a scenario with the hypothetical removal of painted wooden panels from the churches in the winter (1 January) and summer (1 July) to a conservation studio with a stable indoor climate (RH = 50% and T = 20 °C), for a duration of one year. It must still be taken into consideration that maintaining a stable indoor climate (±5% RH) is not achievable in most conservation studios. The modeling was performed regarding mechanical damage under the scenarios and conditions listed in Table 1, which were found to represent possible climate modifications and resemble important painted wooden objects (Section 2) in the churches most closely. The only differences between the model characterization of the objects in the two churches were the thicker wooden panel and the additional modeling of lime and pine wood, compared with that of oak, in Kinn.

Table 1. Climate scenarios and modeling relevance for original wooden objects with gesso and paint (see Section 5, Discussion), along with modeling conditions in both Kinn and Ringsaker. RH_{av} and T_{av} are the average relative humidity and temperature of the data series.

Scenario	Kinn	Ringsaker	HERIe Risk Relevance
Recorded RH and T	RH_{max} = 96%, T_{max}= 20 °C RH_{av} = 79%, T_{av} = 9 °C	RH_{max} = 77%, T_{max}= 21 °C RH_{av} = 49%, T_{av} = 17 °C	Low relevance for original objects with proofed fluctuations Unknown relevance as a proxy for original objects that have recently undergone conservation treatments
Modified RH and T	RH reduction by building measures, $RH_{max\ limit}$(%)–RH_{av}(%): 85–74; 80–69; 75–65; 70–61 and 65–56, T_{av} = 9 °C	Conservation heating to RH_{max}–RH_{av}: ~65–63% and T_{min} = 10 °C (T_{av} = 13 °C)	Kinn: Low relevance for original objects if reductions in RH stay within proofed fluctuations Ringsaker: High relevance for original objects as the change in RH from proofed fluctuations Unknown relevance as a proxy for original objects that have recently undergone conservation treatments
Removal to conservation studio (RH = 50%, T = 20 °C)	From recorded and reduced RH (scenarios 1 and 2) in January and July	From recorded and adjusted RH (scenarios 1 and 2: T_{av} = 13 °C) in January and July	High relevance for original objects when moved outside proofed RH fluctuations to a conservation studio Moderate relevance for original objects when returning to the proofed climate from a conservation studio Unknown relevance as a proxy for original objects that have recently undergone conservation treatments
HERIe modeling conditions			
	Damage		Mechanical
	Paint Material		Painting on wood
	Wood species		Oak. Kinn: also lime and pine
	Direction of cut		Tangential, radial
	Panel thickness (mm)		40 (Kinn), 20 (Ringsaker)
	Gesso		Stiff
	Water vapor transport		Through one side
	Long-term mean RH and T values		Scenario 2: From uploaded data Scenario 3: Set to the recorded or adjusted annual average scenario values, but set up to the available modeling RH maximum = 70%

In Kinn, the wooden panels and other wooden elements are probably both tangentially and radially cut (pers. comm with T.M. Olstad on 2 June 2022). In Ringsaker, they seem to be mostly radially cut. Modeling was conducted for both tangential and radial cuts. The tangential cut then represents a "worst case" scenario. Due to the slow humidity response of the oak and thick panels (40 mm), two years of data are required for modeling. As this was not available, data were obtained by duplicating the available annual measurements series to two years, which would then still represent the measured annual variation but not any real two-year period. The annual data series of seasonal (ASHRAE) and monthly (CEN15757) moving averages needed for the calculation of the ASHRAE guideline limits were also obtained from these extended data series, as recommended by the authors of [48]. The data series for modeling the move to a conservation studio (Scenario 3) was obtained by simply extending the two-year series to a three-year series by adding an annual data set of constant RH = 50% and T = 20 °C, from 1 January and 1 July in the second year. In these model climate data series, the dates of the approximate first year represent the measured values (see Section 3.1). Later dates that will still be used below to describe the data sets represent the simulated values.

3.5. The HERIe Modeling of Mechanical Damage Risk to Painted Wooden Panels

The HERIe model [14] of mechanical damage to the painted wooden panels provides a linear risk indication between 0 and 1, representing the change in the relative strains from values of ±0.002 to ±0.004, at the interface between the gesso and wood support of the painted panels. The positive values represent the per-mill elongation in tension and the negative values the per-mill compression. When the strain reaches ±0.002, plastic deformation of the modeled gesso begins. When the strain reaches ±0.004, it cracks. The maximum strain (tension or compression) calculated over the time series of the climate data input [17] determines the damage risk indices, RIs, reported in HERIe. The HERIe model can evaluate the risk of the deformation and cracking of an initially undamaged paint layer on soft or stiff gesso on 5- to 40-mm-thick oak, lime, poplar, or pine wood panels, with water vapor transport into the panel from one or two sides. The long-term climate variables (RH and T) that determine the zero strain, from which the fluctuation strains of the input climate are calculated in the model, are calculated as the average of the input data or are set by the user from a selection of values. It should be noted that the model overestimates the strain on changes from or especially toward very high humidity, but that this is of little significance below an RH = 70% (pers. comm. with an HERIe developer).mm

The "long-term mean RH and T values", applied as input to scenario 2 (Table 1) in the HERIe modeling process were "from uploaded data". The maximum strain and risk in the churches would then be established by fluctuations from the measured averages, due to either tension in the paint at high RH or compression at low RH. The scenario 3 HERIe modeling process was performed for the risk of the mechanical compression damage of gesso (and paint) when moving panels to the conservation studio (at RH = 50% and T = 20 °C), and the risk of tension damage when moving them back to the church. The model input for "the long-term mean RH and T values" when moving the panels to the studio was selected as the closest annual average scenario RH values of the data sets at intervals of 5% from RH = 50%, up to the available maximum model RH value for this input of 70%, and to the annual mean scenario temperature (excluding the time in the studio). The model input for "the long-term mean RH and T values" when moving the panel back from a conservation studio to the churches was set at the scenario values of the studio, although using T = 21 °C instead of 20 °C since the modeling input options were 19 °C and 21 °C. Thus, the annual change to the stable condition in the studio was assessed in the modeling to be a "long-duration change" from the climate in the church and not an annual period in a cycle.

The accessible modeling maximum for "the long-term mean RH and T values" of 70% RH was significantly lower than the recorded RH and high RH scenarios in Kinn. In nearly all these instances with an RH > 70%, the compression risks (RI) in the conservation studio predicted by HERIe were ~1 (the RI of the radial oak panels was 0.96). In scenarios of moving radial oak and pine wood panels back to the church from the studio, the RI was, however, modeled to be significantly lower than 1 at an RH between 70% and 80%. The model input of the "the long-term mean RH and T values" = 70% RH in these cases may have resulted in an underestimation of the risk, although, in such instances of changes to high humidity, it was also reported that the model overestimated the risk (as per the pers. comm. with one of the HERIe developers, https://herie.pl/, accessed on 12 January 2023). It seemed that this modeling analysis, with a comparison of the RH in the conservation studio (=50%) to a lower value than the mean recorded RH of the dataset (70% rather than the 70–80% of the dataset) was of little consequence for the overall risk assessment.

3.6. Energy Consumption Calculation by Heating Degree Days

The degree days for comfort heating, representing the heating needs in this respect, were calculated by subtracting the outdoor temperature from an indoor set point of 17 °C, as is customary in Norway [40]. The subtraction was made for each point in the time series of the data and was summarized over the months and year. The comfort heating was compared with the indoor measured situation by subtracting the indoor temperature from the outdoor measured temperature and then aggregating the degree days over the months and year. A comparison with the conservation heating scenario of reducing the temperature to a minimum of 10 °C, to approach an RH of 65%, was then made by subtracting this indoor (conservation heating) scenario temperature from the outdoor temperature and again summarizing the degree days over the months and year. The method of calculation of the conservation heating temperature modifications is described in Section 3.4.

4. Results

4.1. Conformity to Guidelines

The CEN 15757 standard and ASHRAE B class, which include seasonal relaxation, were thought to be the most interesting criteria to apply in the churches for this risk modelling. Figure 3 shows the measured data compared with the ASHRAE B class's combined fluctuating and fixed limits. The CEN 15757 variable limits are (not exactly) similar, but that standard does not include a combination with outer fixed limits, as illustrated in Figure 3.

The period of linear interpolation in May 2020 is seen in Figure 3B. The temperature in the church was relatively stable throughout the year, and a regular RH increase and regular fluctuations were observed in the spring. The reduced level of total recorded variability through the year due to the missing data will have reduced, somewhat, the 7th to 93rd percentile variable limit band width of the CEN 15757 standard. The 7th to 93rd percentile band of the data was estimated to be ~±5%, which is much lower than the bandwidth of ±10% that should, in this case (due to low variability), be used according to the standard (see Appendix A). The interpolation will thus not have affected the comparison with this standard. Table 2 reports the percentage conformity to the CEN 15757 standard and ASHRAE classes (see Appendix A, Table A1) of the measured data in the churches and the scenario 2 situation, with modifications to about 65% RH.

Table 2. Conformity (%) to the temperature and RH limits of the CEN 15757 standard and ASHRAE classes of measured data; scenario 2 data were modified to RH_{lim} = 65%.

CEN Standard and ASHRAE Classes	Kinn		Ringsaker	
	Temp [1]	RH	Temp [2]	RH
CEN 15757 [3]	**n.a.**	**98; 100**	**n.a.**	**98; 100**
AA	44	0; 52	100	32; 56
A1	44	0; 79	100	75; 61
A2	44	0; 90	100	70; 65
B [3]	**100**	**14; 99**	**100**	**96; 100**
C	100	36; 100	100	100; 100
D	100	36; 100	100	100; 100

[1] In Kinn there were no scenarios for changes in the temperature. [2] The temperature in the heated Ringsaker church conformed fully to all standard classes in both scenarios. [3] The CEN standard and ASHRAE B class thought most appropriate/interesting for application to the churches are in bold script. n.a. = not available.

Table 2 shows a near-full conformity of the recorded climates in the churches to the CEN15757 standard but a zero to low RH conformity to the ASHRAE classes, which all include fixed outer RH limits (see Appendix A) for Kinn, and a reduction in RH conformity regarding the more stringent ASHRAE classes (AA to B) for Ringsaker. This situation is illustrated in Figure 3 with the ASHREA B combination of fluctuating and fixed outer limits. The RH conformity in Kinn increased with the scenario reduction to RH ~65% and to near 100% for the ASHRAE B to D classes. For Ringsaker, an increase in the RH to a stable value of ~63% (RH_{lim} = 65%) increased the RH conformity to the most stringent ASHRAE AA class but decreased the conformity somewhat to the A1 and A2 classes. The reason for this is the fixed upper limit of RH_{lim} = 65% in these classes (see Appendix A). With the RH modification to ~63%, more of the data points come above this outer fixed limit. With the stringent constant limits of the AA class (±5%) the original variable situation through the year was, however, worse (32% fit) than if all the data through the year were closer to RH = 65%.

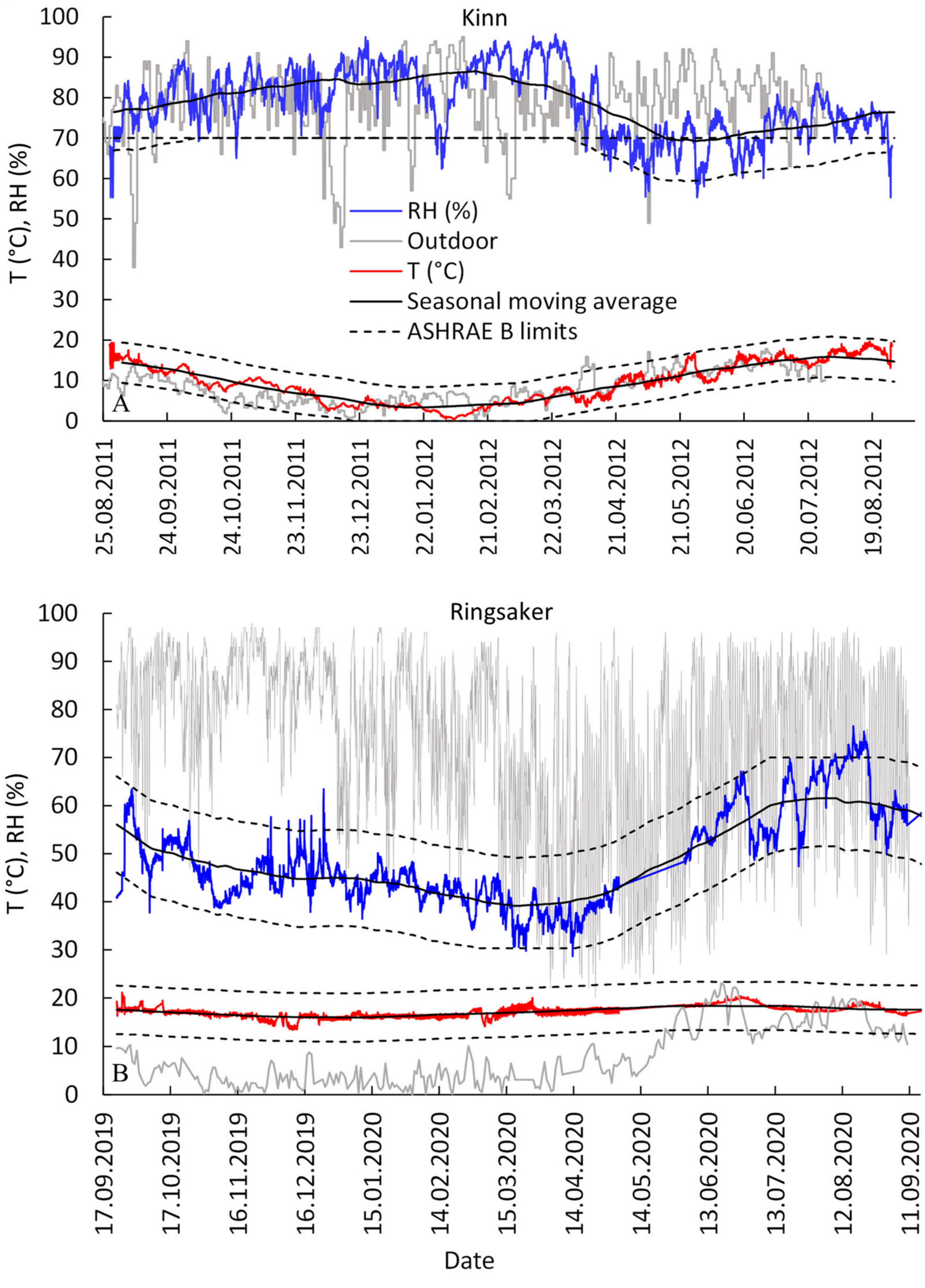


Figure 3. Comparison of the climate conditions in Kinn (**A**) and Ringsaker (**B**), with the ASHRAE B class's combined fluctuating and fixed outer limits. The outdoor RH and T are also shown.

4.2. Mechanical Damage Risk to Painted Wooden Panels

Figures 4 and 5 show the HERIe modeling results for the strain levels and risk of mechanical damage to the different and most relevant painted wood from various species, with the duplicated, bi-annual, RH and T values in Kinn and Ringsaker, in the measured situation (scenario 1), and in the scenario 2 situation, with the maximum modified indoor climate obtained by building modifications, in Kinn, to $RH_{max}(\%) - RH_{av}(\%)$ = 65–56, and by conservation heating in Ringsaker to RH_{max} ~65% and T_{min} = 10 °C (Table 1).

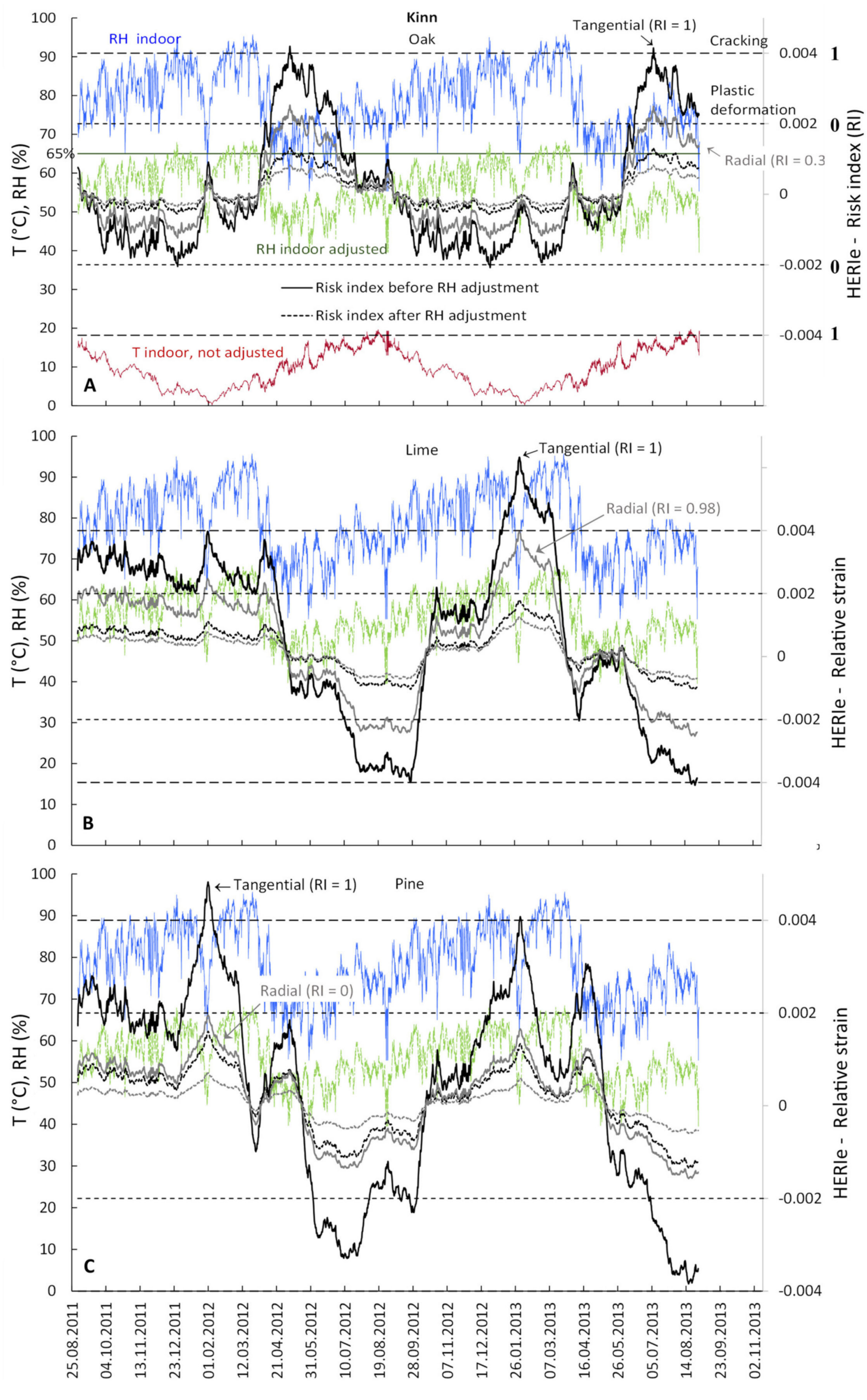


Figure 4. HERIe modeling results for the strain levels and the risk of mechanical damage to painted wood of various species of oak (**A**), lime (**B**), and pine (**C**), in Kinn at the recorded annual (duplicated to bi-annual) RH and T, and for the scenario of reduced RH (to < ~65%) according to building measures. The scenario temperature was not adjusted from that recorded. The descriptions of the curves are mainly given in the upper diagram (**A**).

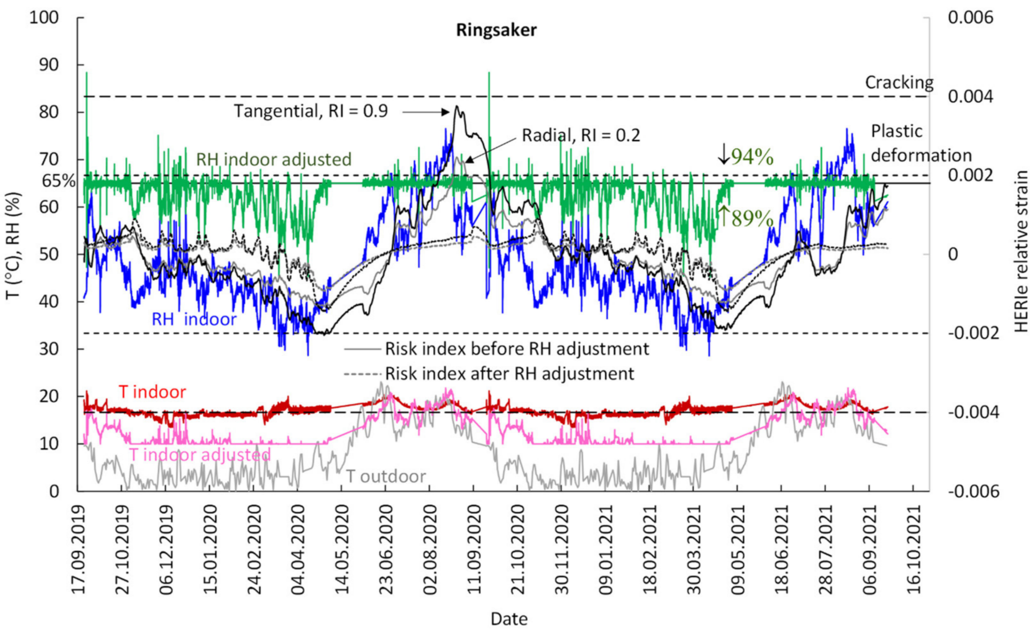


Figure 5. The HERIe modeling results of strain levels and the risk of mechanical damage to painted wooden panels in the Ringsaker church for the recorded annual (duplicated to bi-annual) RH and T measurements and for the hypothetical conservation heating scenario with an adjustment of the RH (to < ~65%) by reducing the temperature. The outdoor RH and T values are shown. The percentage of annual integrated fit of the RH values (to 65%) from the original measured RH values above (↓) and below (↑) the set conservation heating RH limit of ~65% are given.

It can be seen in Figure 5 that all the sharp RH peaks could not be fitted exactly using the sequential integration minimizing method. The percentage best fit, as shown in Figure 5 (as it would be for most data sets), was, therefore, somewhat less than 100%. During much of the autumn and winter in Ringsaker, the conservation heating would lower the temperature to the limit of 10 °C, resulting in an adjusted RH of lower than 65% and a somewhat lower percentage fit (89%) to the limit of RH = 65% from the lower (than 65%) measured RH values than from the higher (than 65%) measured RH values (that had a percentage fit of 94%, although also of much fewer data points). It should be taken into consideration that the adjusted RH curve in Figure 5 was obtained from modeling to investigate the energy-saving and object damage risks. The peaks are due to a lack of model fit and do not represent any real-world maxima and minima. This may, however, also reflect the practical difficulty in making precise RH modifications to limits via temperature adjustment.

Figures 6 and 7 show the HERIe modeling diagrams of the relative strains and risk indices of mechanical damage to painted oak wood panels in the tangential directions if the object was moved to a conservation studio in January (scenario 3, Table 1) from the recorded RH, and from the scenario when adjusted to below ~65% RH for Kinn and Ringsaker. The risk assessments for the recorded climate in the churches (i.e., from the recorded "long-term mean RH and T values") before moving a panel to a conservation studio are presented in Figures 3 and 4. It seems incorrect to present a risk assessment for this period, compared to the recorded "long-term mean RH and T values" (of T = 20 °C and RH = 50%) for the scenario 3 climate of the conservation studio; this period of the modeled risk assessment was removed in Figures 5 and 6. For paint on wooden panels that were cut in the radial direction, the shapes of the strain curves were similar but the risk was lower. Removal of the panel to a studio in July yielded different strain curves but a similar maximum high and low strain and risk.

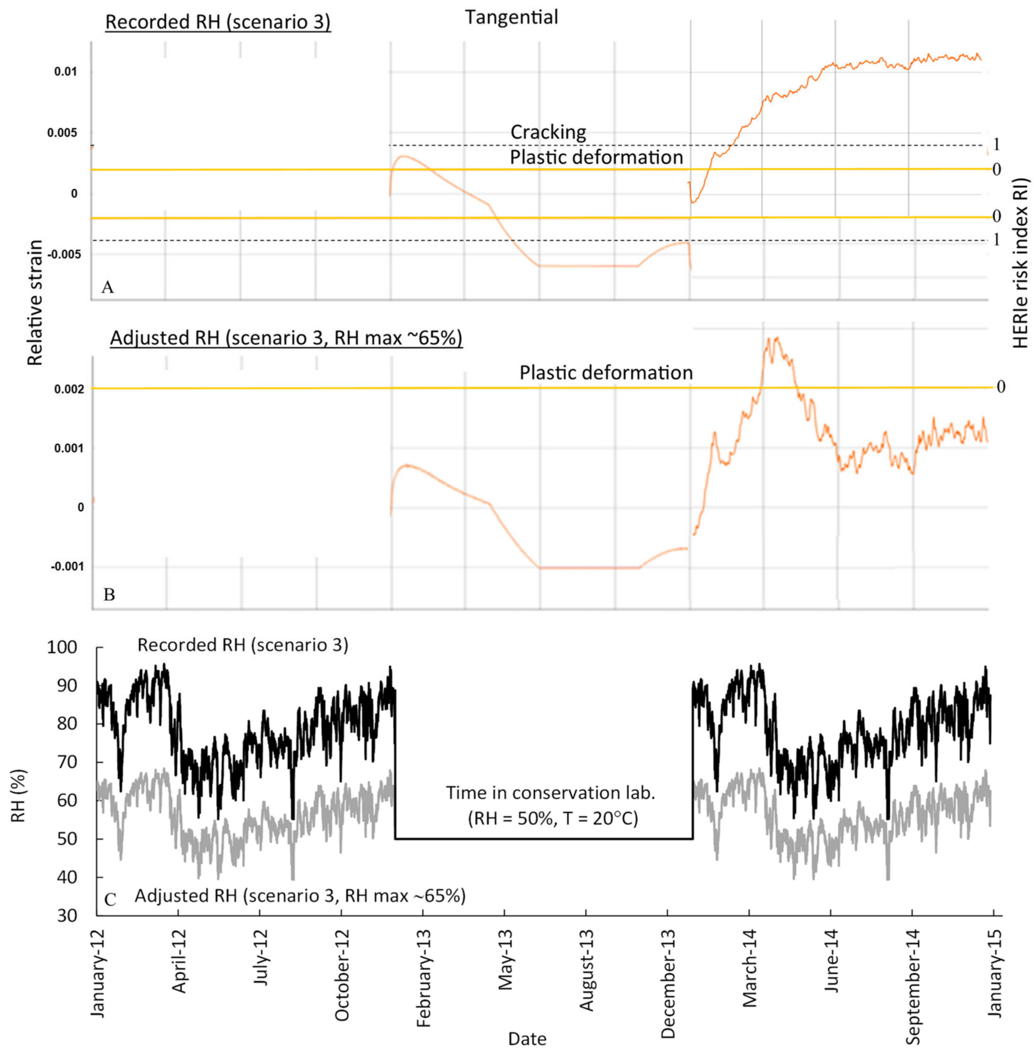


Figure 6. The HERIe modeling results of the strain levels and the risk of mechanical damage to painted oak cut in the tangential direction when it was moved to a conservation studio in January, from the recorded RH (**A**,**C**) and from an adjusted RH_{max} ~65% by the (hypothetical) building measures (**B**,**C**) for Kinn (scenario 3). An incongruity is seen at its removal back to a conservation studio (in January 2014), which was due to the combination of HERIe graphs for the Scenario 3 removal to and from the studio (for which the different input values for the "long-term mean relative humidity" were used).

It can be seen that the risk follows the RH fluctuations with some delay for the 40-mm-thick oak panel at Kinn (Figure 6), presumably due to the longer time needed for RH equilibration with the thicker oak panel at Kinn than at Ringsaker (Figure 7). With the panels from both Kinn and Ringsaker, the negative strain and, thus, the compression risk, developed to a constant level during their annual stays in a conservation studio. When the transport was from the adjusted low RH scenario for Kinn (RH_{av} = 56%, RH_{max} ~65%), or the recorded RH for Ringsaker (RH_{av} = 49%), HERIe predicted no risks in the studio (Figures 6B and 7A). When the transport was from the high RH situations in the churches (the recorded RH for Kinn was RH_{av} = 79%) and adjusted the RH for Ringsaker (RH_{av} = 63%), the constant compression strain of the paint layer in the studio represents a significant risk of cracking for Kinn and of plastic deformation close to cracking for Ringsaker (Figures 6A and 7B).

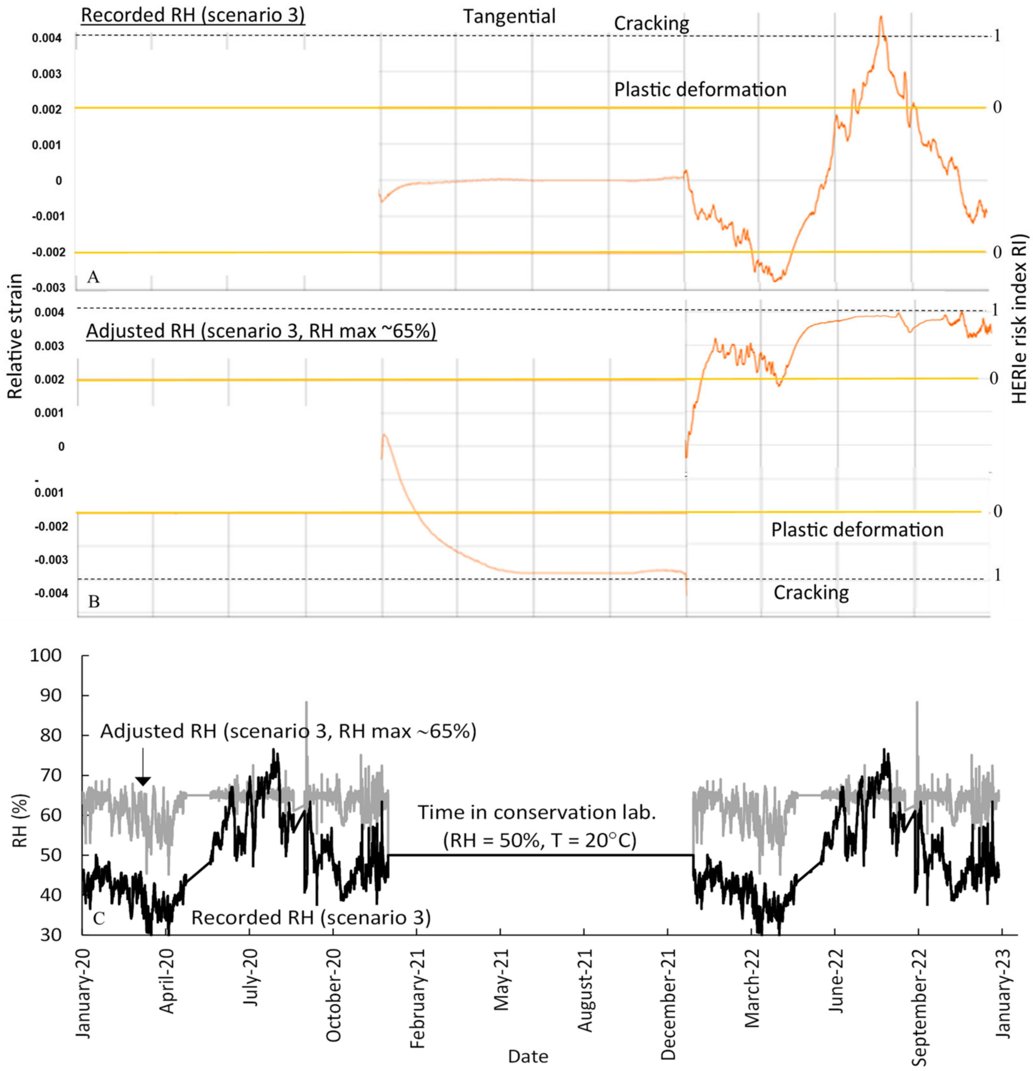


Figure 7. The HERIe modeling results of the strain levels and the risk of mechanical damage to painted oak cut in the tangential direction of the wood when moved to a conservation studio in January from the recorded RH (**A**,**C**) and an adjusted RH_{max} ~65% by conservation heating (**B**,**C**) at Ringsaker (scenario 3). An incongruity is seen at its return to the studio (in January 2022) due to the combination of HERIe graphs for the scenario 3 removal to and from the studio (for which different input values for the "long-term mean relative humidity" were used).

Some other variations in the curves in Figures 6 and 7 should be commented upon. On moving a painted panel from the higher humidity in the church to the dryer and warmer studio, HERIe predicted an instant increase in tension in the Kinn panel (Figure 6) that is much smaller in the Ringsaker panel when moving from the high RH scenario of ~65% (Figure 7B), before the slow drying and development of compression strain occur. This prediction of an initial increase in tension may be due to the instant effect of the higher temperature in the studio than in the churches. Due to the larger T increase in the studio from the higher RH in Kinn (ΔT = 11 °C, RH_{av} = 79%) than in Ringsaker (ΔT = 7 °C, RH_{av} = 63%), the duration of the period of constant compression strain in the studio is then shorter in Kinn than in Ringsaker.

The compression or tension risks in the scenario 2 and scenario 3 climate scenarios (Table 1, Figures 4 and 5), were assessed from the HERIe risk curves (as seen in the minimum and maximum RH scenarios in Figure 4 to Figure 7) and are shown in Figures 8 and 9.

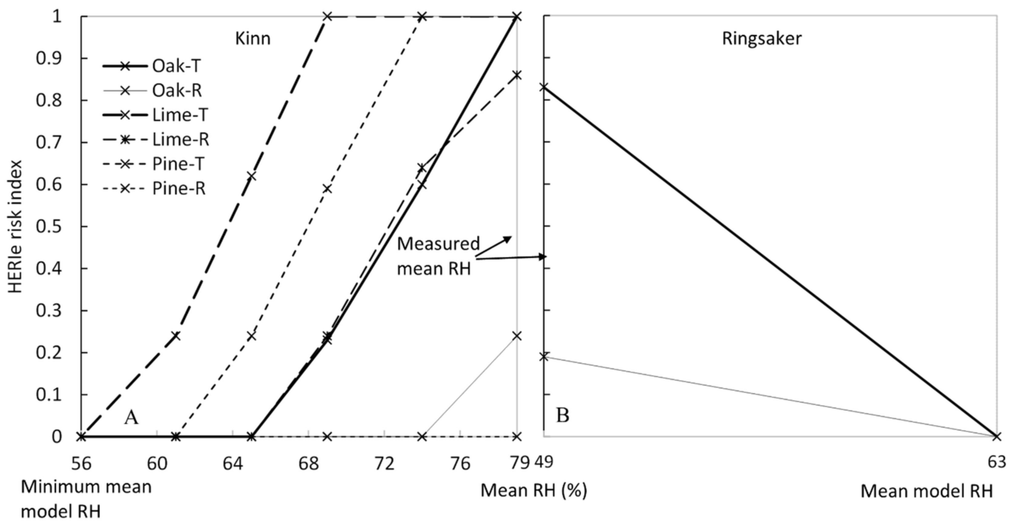


Figure 8. HERIe risk indices for the Scenario 2 (Table 1) reduction of RH to lower values for Kinn (**A**) and to a higher conservation heating value for Ringsaker (**B**). The crosses represent the modeling situations. All the curves reach from the lowest to the highest RH value in the diagrams and are partly overlapping.

Figure 8A shows that, according to HERIe, paint and stiff gesso on 40-mm-thick tangentially cut oak, pine, and lime panels in the very humid indoor climate of Kinn would probably crack within two years. If it was possible to reduce the mean RH to ~56%, along with, proportionally, the climate fluctuations, no deformations would probably happen. Between the 79% and 56% RH, there would be a near-linear reduction in the cracking and plastic deformation risk (from 1 to 0) over a 15% RH interval, with the reduction in risk starting for the oak panels already at ~79% RH, for pine at ~74%, and for lime at ~69% RH. The risk of damage to radially cut panels in the recorded climates in the churches was found to be less, at ~0.86 for lime, ~0.24 for oak, and zero for pine, implying some risk of plastic deformation, and decreased to zero with a similar near-linear rate to the tangential cut wood. Less (or no) new cracking might, however, be expected on old and already cracked panels. Figure 8B shows that the potential conservation heating in the Ringsaker church, with an increasing RH from an annual mean of 49% to a more stable mean of 63%, was found to reduce the risk of paint deformation on tangentially and radially cut 20-mm-thick painted oak panels in the church from risk indices of 0.83 and 0.19 (indicating a risk of plastic deformation) to zero risk.

The reductions in the RH for one year in Kinn, before moving the painted wooden panels to a conservation studio with a stable RH of 50% and T of 20 °C (scenario 3), were found to provide a similar reduction in risk in the studio (Figure 9A) and when moving the panels back to the church (Figure 9B) as when in situ (Figure 8). However, these figures include variations in the RH reductions needed in the church for an initial decrease in the risk and then in the rate of decrease, depending on wood species, the wood cutting direction, and the month of the year when reinstalling the panels in the church. The displacement of the July risk curves toward a lower RH and, thus, a higher risk compared to the January risk curves when moving the panels back to Kinn from the studio (Figure 9B) seemed to be due to a longer period of gradual increase in RH in July than in January, which resulted in the buildup of more tension strain before this was released by a sharp drop in RH (see the curves in Figure 6). In Ringsaker, the damage risk (RI) of moving a panel to a conservation studio after one year in the modified and more stable climate, with a higher (than recorded) mean RH = 63%, was found to increase when compared to moving it from the recorded mean RH = 49%, from 0.25 to 1 (with certain cracking) of the tangentially cut wood and from zero to 0.49 (with plastic deformation) for the radially cut wood (Figure 9C). The risk of moving the painted panel back to the conservation-heated church (RH_{av} = 63%) was found to be high (>1) but was slightly less than when moving it back to the recorded fluctuating climate situation (RH_{av} = 49%) (Figure 9D). As with the situation in situ (Figure 8), these indications of damage should be considered in the context of the historical condition (cracks) and proofed climates (see Section 5, Discussion).

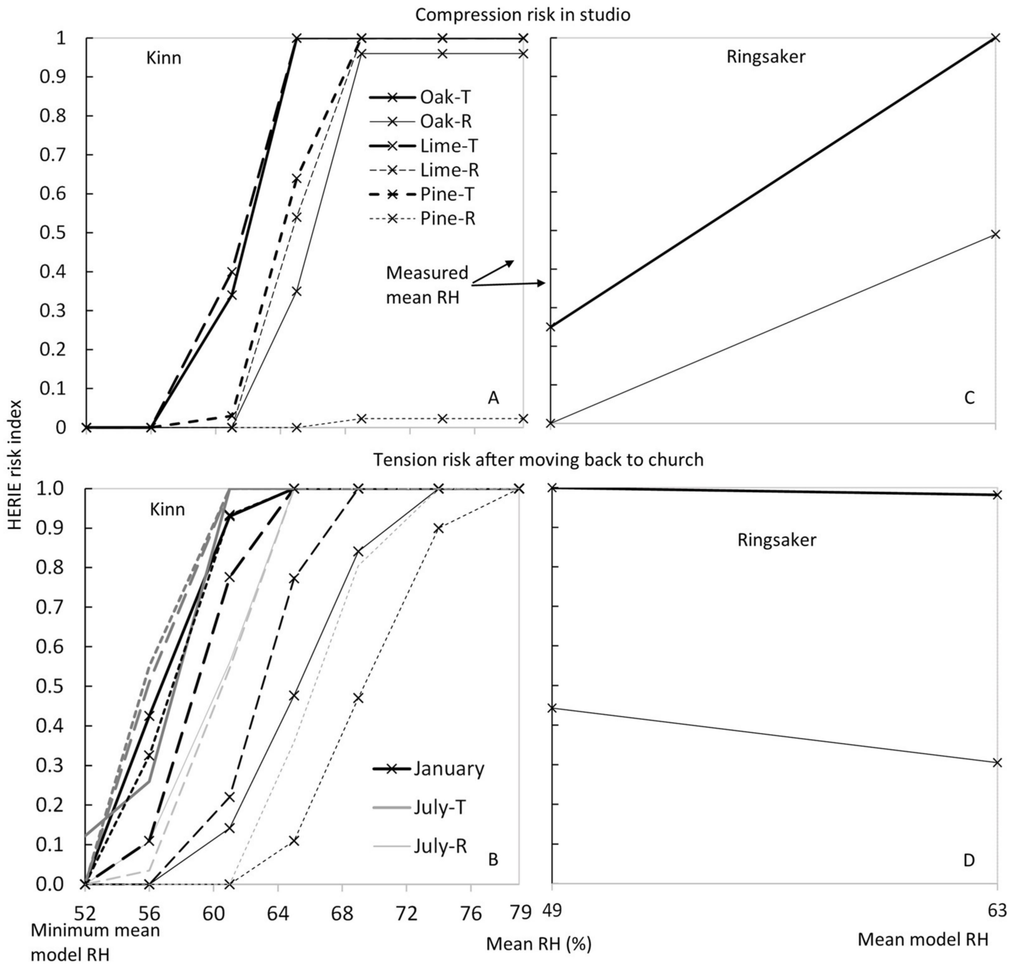


Figure 9. The HERIe compression risk indices when moving a painted panel to a conservation studio (RH = 50% at T = 20 °C) in January (**A**,**C**), and the tension risk on moving the panel back to the churches after one year (**B**,**D**), from the recorded and reduced scenario values of RH for Kinn and from the increased conservation heating RH scenario value for Ringsaker (scenario 3, Table 1). A difference in the risk in January and July was only found for the time when moving the panel back to Kinn (**B**). The crosses represent the modeling situations that were at the same RH in July as in January but, for clarity, are only given in January. T = gesso on tangentially cut wood. R = gesso on radially cut wood. All the curves (except for the tangentially cut oak in July) reach from the lowest to the highest RH value in the diagrams and are partly overlapping. The legend in (**A**) is applicable to all the diagrams.

4.3. Conservation Heating

Figure 10 shows the calculated heating degree days for Ringsaker in the recorded situation and for different heating scenarios.

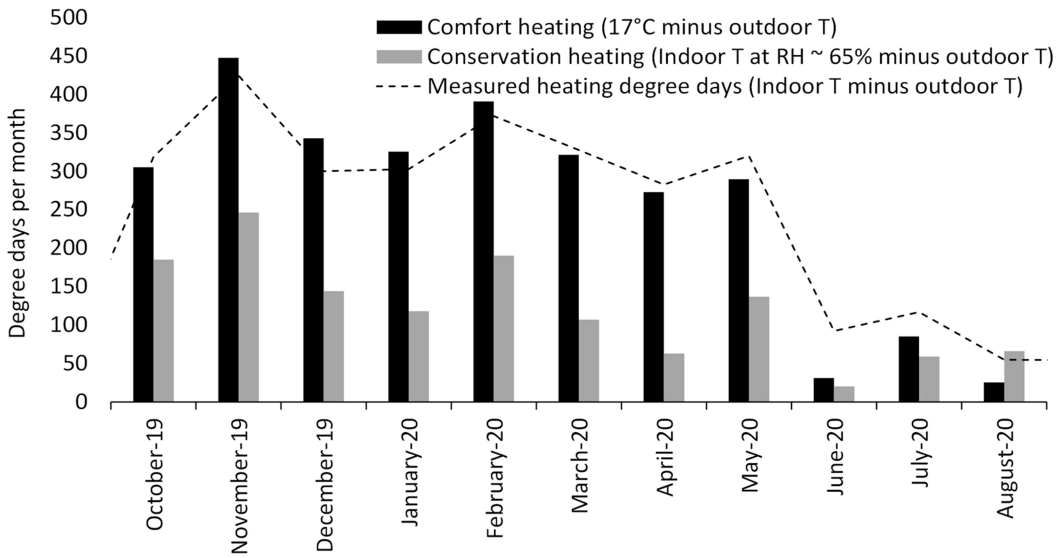


Figure 10. Monthly heating degree days for the different scenarios for Ringsaker.

The larger number of degree days for conservation heating than for comfort heating in August reflects the high humidity measured in this month (Figure 5) and, thus, a need to increase the temperature to a level above that needed for comfort heating, and above that of the measured situation, to reduce the RH to below 65%. In all the other months of the year, it would be possible to reduce the heating, if the scenario 2 conservation heating regime was accepted. If needed, the degree days of a regime with different set points (than RH_{max} ~65% and T_{min} = 10 °C) could, of course, be calculated. About 1400 annual heating degree days would be needed in this conservation heating regime. About 1600 heating degree days, or ~50% of the energy costs, would then be saved, compared to the approximately similar 3000 annual degree days of both the comfort heating scenario and the measured situation. This saving should be added to the saving in terms of conservation costs obtained by an expected reduction in the deformation and deterioration rate of conserved painted wooden objects.

5. Discussion

The near-full conformity of the recorded climates in the churches and of the scenarios of changed climates to RH ~65% to the variable limits of the CEN15757 standard and ASHRAE B class indicated that the measured fluctuations in the churches may not cause new critical mechanical damage. As, however, one critical fluctuation event can be sufficient to cause non-reversible mechanical deformations [33], this 98% conformity may still indicate a risk. The very high recorded RH for Kinn resulted in low conformity to all standard classes that include a maximum RH limit, raising concerns, especially about possible mold and rot, little of which was, however, observed in the church (see Section 3.3). The comparison with the standards was made to a single year with the available data. The variation in the historical fluctuations has certainly been larger and the damage and deterioration that was noted in the conservation reports may have occurred in worse situations or for reasons that were related, for example, to the specific properties of original painting materials and methods or to past conservation treatments.

In situations with intermittent heating, it may be an issue for conservation if significantly more fluctuations would be recorded with a higher resolution in terms of the measurements than one hour, and a different evaluation would then be obtained by the guidelines. However, most materials do not respond to fluctuations immediately. It has been found that fluctuations of a duration of less than one hour do not affect most museum objects [49] (p. 626). In a museum with a controlled indoor environment (~22.5% < RH < ~42.5%), RH measurements along with hourly resolution were reported to give the same evaluation via guidelines (CEN

15757 and ASHRAE) for measurements with a higher time resolution than one hour [50]. Based on the situation in the churches, with heating aiming to keep a stable temperature for Ringsaker, and the observed nominal effect of the infrequent intermittent heating on the high RH in Kinn, a higher measurements resolution than was used in this study would probably not significantly affect the results. This possibility, however, cannot be excluded.

The HERIe modeling process represents well-defined situations that are explored experimentally in the laboratory. The modeling is more applicable to "worst case" scenarios [17] involving original undamaged gesso layers, in situations where a climate-induced mechanical damage mechanism is dominating. This highlights the fact that the cumulative deterioration process of an aged painted object is influenced by its condition and environmental history. Most objects with a gesso/wood interface that are subjected to fluctuating climates are likely to have developed multiple small cracks (known as craquelure). The cracks release the tension and reduce the chance of further deformation and cracking [16]. The development of cracking is a complex matter involving the different dimensions of the cracking patterns and paint layer(s) [51]. The damage mechanisms and risks to a painting with a fully developed craquelure pattern are very different from that of a recently painted object. Cracking is not expected to happen in the future if the climate (RH and T) fluctuations (periods, amplitudes, and frequency) are within those of the proofed historical climate [5]. The risks to original or old painted wooden objects in the churches would thus appear if there were climate variations in situ, or, in the case of moving objects to a different location, changed beyond the historical variations. There may have been periodic changes in the historical climates that affected the condition of the objects, due, for example, to the introduction of changing heating regimes. This could, however, not be determined from the historical records. It has also been stated that a "conservation treatment erases proofed fluctuations" [5], and thus irreversible changes could occur to a newly treated object located in the "proofed climate" due to processes that will, however, be more or less different than those for the original paint and gesso in the HERIe model [14].

There was, thus, considerable uncertainty in how well the modeling of the risk of damage represented the risk of the original conserved painted wooden objects in Kinn and Ringsaker, and, thus, the model's relevance. The mechanical damage risks indicated by the analysis from the HERIe modeling in situ in both churches, and in the scenario where RH values were over about 70% in Kinn, may be of less concern for the original/old paint and gesso or previous conservation treatments that have been acclimatized to the churches' environments. This could be interpreted as a reason for the apparent lower risk assessment by the CEN 15757 standard and ASHRAE B class than for the modeling analysis. It is not always possible to identify the exact causes of observed damage to aged cultural heritage objects that are subject to concomitant deterioration processes and need treatment. New cracking and flaking paint and ground layers after conservation treatments might relate not only to movement in the paint-gesso-wood interfaces due to climate fluctuations but also to such factors as the initial adherence of the paint and ground, the curing of the paint, and the influence of the surrounding atmosphere and environment. Due to these uncertainties, the HERIe modeling results are presented only as an indication of the risk to newly treated objects.

The high risks, which are probably more directly relevant, indicated whether moving a panel/object, from the high humidity recorded in Kinn (RH_{av} = 79%, T_{av} = 9 °C) and the conservation heating regime in Ringsaker (RH_{av} = 63%, T_{av} = 13 °C) to a (yet unrealistically stable) conservation studio (RH = 50%, T = 20 °C) and then back to the churches, could perhaps imply that the compression of the gesso and paint due to the drying and shrinking of the wood in the studio would produce additional cracking to that already present in the proofed climate, and that moving the item back to the church could worsen its condition. The modeling analysis indicated that a reduction to below 60–65% RH in Kinn would significantly reduce these risks, with a decreasing risk also for plastic deformations, along with the further lowering of the RH (toward 50–55%). The modelling indicated that to reduce the tension risk of cracking a reduction to below 60% of RH would only be necessary in the situation of moving painted panels back to Kinn from a studio in July. These modelling assessments do not evaluate the appropriateness of such changes or consider the effect of a lower RH on the building. Although, in the case of Ringsaker, it was found that the conservation heating regime (at a stable RH of ~63%) would reduce the risk of cracking and plastic deformation, the risk of moving a panel/object from the conservation heating regime to a conservation studio (and back to the church after one year) could be significant and higher than if moving the panel/object from the recorded climate in the church, due to an increased compression risk in the studio (Figure 9C). The high indicated risk when moving a panel/object back to Ringsaker seems of less concern for the original paint and gesso since the scenario RH and T values in the conservation studio were near to the average of the recorded and proofed climate in the church; this risk was indicated to be slightly less when moving back to the conservation heating scenario than to the recorded climate (Figure 9D). The risk of new damage may be higher, although uncertain, when moving an object that has been treated in a conservation studio back to either the recorded fluctuating climate or to a more stable conservation heating scenario.

Thus, the HERIe risk indications seem mainly to be the drying-out of the wood and the compression of the original paint and gesso in a studio, with the possible strains in objects newly treated in situ, and tensions put a strain on objects treated in a conservation studio when they are returned to the churches. Lastly, it could be noted as a general observation about heritage model applications that it can be challenging for non-developers (users) to understand all the conditions of modeling. The clear explanations on the HERIe web pages were helpful but, still, the HERIe model is based on the application of complex physics and time dependencies in the data, which can be difficult to fully understand.

6. Conclusions

The conformity to relevant climate guidelines (CEN 15757 and ASHRAE B) was improved in several scenarios of reduced indoor RH in the church at Kinn (from RH_{av} = 79%) on the west coast of Norway, and was upheld in a conservation heating scenario (RH_{av} = 63%) that was found to save about 50% of the heating cost in the drier Ringsaker church (RH_{av} = 49%), which was east of the southern Norwegian mountains. Analysis via HERIe (https://HERIE.pl/, accessed on 12 January 2023) modeling indicated a significant reduction in the risk of mechanical damage (the cracking and plastic deformation) of painted wooden panels with stiff gesso in Kinn, in the context of a scenario with a mean RH of ~70% and no risk below a mean RH of ~56%, and also with no risk in the scenario of stabilized conservation heating climate in Ringsaker (as would also be expected if stabilizing the humidity in the church around the recorded mean RH of 49%). A lowering of the RH in Kinn to below 60–65% would significantly reduce the risk of damage when moving panels out of the church to drier and warmer indoor climates and then back to the church. The risk of damage when moving panels from the scenario of conservation heating climate in Ringsaker was, however, found to increase, compared to the recorded climate. Although there were considerable uncertainties related to the representation in the modeling of the complex historical deterioration of objects in the churches, the damage mechanisms, and the environmental influences, the results offer clear indications that modification of the RH in the churches could have substantial benefits in reducing the risk of mechanical damage to the painted wooden objects. This reduction in risk would be most significant for those objects with original paint and gesso that might be moved from (and back to) the churches, for example, because of conservation treatment.

The analysis shows the usefulness not only of the HERIe modeling tool but also that its representation of old, painted, and often conserved, wood objects is not straightforward. HERIe provides important warnings about the worst-case critical risks to case panels with original paint and gesso, in the current case, which may, however, not represent the situation of many objects in situ. To predict the deterioration that commonly leads to the conservation of painted wooden heritage objects it seems that other descriptive methods, possibly more specific models of different paint deterioration mechanisms and, probably, more general models of environmental doses and the effects on object changes are also needed.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The CEN15757 standard recommends RH limits that are equal to the 93rd and 7th percentile of the measured fluctuations from the monthly moving average, but of ±10% RH from the monthly moving average if these percentile values are less than 10%. The ASHRAE guideline classes, AA, A, B, C, and D, are briefly explained as follows [5]: A1 (formerly A) allows for the seasonal relaxation of RH ±10% and T of up 5 °C and down 10°C, compared to the customary strict AA controls of ±5% RH and ±2 °C variation from the annual average and only a seasonal T adjustment of ±5 °C. A2 allows the double extent of short-term RH fluctuations, compared to A1 (10% vs. 5%), but there is then no seasonal adjustment, which should provide the same protection against mechanical damage as under A1. Conformity to the A classes signifies a "small risk of mechanical damage to high vulnerability artifacts, no mechanical risk to most artifacts, paintings, photographs, and books". The A (A1 and A2) relaxation of the limits was not meant to be seen as a larger change from the "no mechanical risk" situation of the AA class, similar to that of B–D, which are assigned to provide guidance for smaller museums or more vulnerable buildings. B addresses those situations where very low winter temperatures are preferable to very low RH. C addresses the need to control just the RH between 25% and 75%, to avoid the rapidly increasing risks at lower and higher values.

Table A1. Climate parameters and allowed fluctuations and limits in standards [31].

CEN Standard and ASHRAE Classes	Short Term (Hour, Day)		Seasonal		Outer Fixed Limits, Low–High	
	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)
CEN 15757	7th and 93rd percentile of annual fluctuations from the monthly moving mean but maximum ± 10%	n.a.	n.a.	n.a.	n.a.	n.a.
AA	±5	±2	no	±5	35–65	10–25
A1	±5	±2	±10	−10–+5	35–65	10–25
A2	±10	±2	no	−10–+5	35–65	10–25
B	±10	±5	±=10	−20–+10	30–70	n.a.–30
C	n.a.	n.a.	n.a.	n.a.	25–75 *	n.a.–40
D	n.a.	n.a.	n.a.	n.a.	−75 *	n.a.

* Not continually above 65% RH for longer than number of days needed for visible mould growth, given from reported Table [31].

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