https://doi.org/10.1051/e3sconf/202236211003

Climate change impact on the degradation of historically significant wooden furniture in a cultural heritage building in Vestfold, Norway

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Abstract

Climate change is expected to significantly affect the interior climate of old, leaky buildings without HVAC systems. As a result, the items of cultural significance that are hosted indoors will experience new ambient conditions, which will affect their degradation. In the current research, the impact of climate change on the biological, mechanical, and chemical degradation of a cabinet and a storage trunk which are made of wood and have paintings on their outer surface is investigated. These two items are found in two different rooms of a historic timber building in Vestfold, Norway. Data from the REMO2015 driven by the global model MPI-ESM-LR are used in order to account for past, present, and future climate conditions. In addition, climate data from ERA5 reanalysis are used in order to assess the accuracy of the MPI-ES-LR_REMO2015 model results. Whole building hygrothermal simulations are employed to calculate the temperature and the relative humidity inside the rooms that host the items of interest. The transient hygrothermal condition and certain characteristics of the timber surfaces are used as inputs in models that describe their degradation. The biological degradation is examined by using i) the updated VTT mould model and ii) the *Growing Degree Days* (*GDD*) for temperature and humidity dependant insects. The mechanical deterioration is assessed by the method proposed by Mecklenburg et al. (1998). The concept of the *Lifetime Multiplier* (*LM*) is used in order to assess the chemical deterioration of the furniture. Results reveal a significant mechanical degradation risk and a very high chemical deterioration risk. The biodeterioration risk remains at acceptable levels. Moreover, it could be possible that the storage trunk would be damaged by certain insects in the future. It is then suggested that both items should be moved to a room with proper conditions in order to minimize their chemical and mechanical deterioration risk and extend their life span. Finally, the significance of implementing bias correction in the data from climate models is underlined.

Introduction

The climate in Norway is expected to be warmer and wetter in the future (Christensen et al., 2001; Benestad, 2002; Hanssen-Bauer et al., 2003; Hanssen-Bauer et al., 2009). The indoor climate of old leaky houses will also be affected by these climatic changes (Choidis et al., 2021). As a result, the artifacts hosted in such buildings will experience new ambient conditions with further implications on their deterioration.

Martens (2012), Silva and Henriques (2015), Rajčić et al. (2018) and Huerto-Cardenas et al. (2021) investigated the impact of climate change on the mechanical, chemical and biological deterioration of wooden artifacts that are hosted inside museums. The methodologies that they implemented can be applied to any case study and provide a good indication of the threats of climate change on the artifacts. Proper preventive measures can be then suggested to avoid the deterioration of the tangible cultural heritage.

In the current research, the focus was placed on two wooden pieces of furniture hosted inside a historic building in Vestfold, Norway (Figure 1). The historic building dates back to 1407, it has openings without transparent components, leaky log walls and it doesn't have any Heating, Ventilation, and Air Conditioning (HVAC) systems. The furniture of interest is of historical significance. More specifically, they are i) a wooden storage trunk that is hosted in the northeast-oriented room of the upper floor of the building and ii) a wooden cabinet that is located on the ground floor (Figure 1). The two pieces of furniture have oil paintings on their surface (Figure 1).

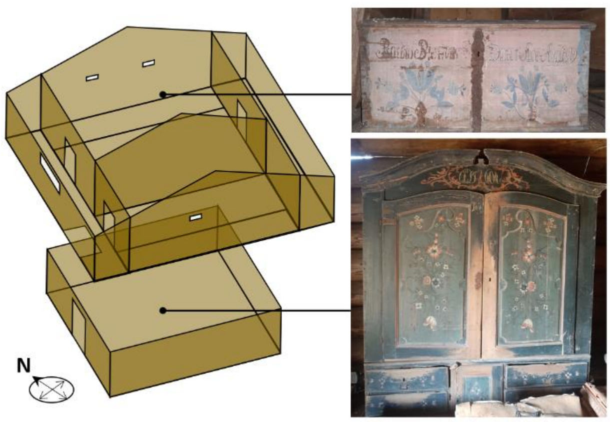

Figure 1: Wooden storage trunk and cabinet hosted on the upper and the ground floor, respectively, of the historic building.

Discoloration, embrittlement, cracking and delamination of the paint layer on the surface of the furniture were observed (Figure 1). Moreover, a significant presence of fungi was documented for the historic building under investigation by Choidis et al. (2021). The impact assessment of climate change on the biological, mechanical, and chemical deterioration of the items of interest is important in order to define whether it is needed to relocate them or take any preventive measures to minimize their degradation in the coming years.

Methods

The methodological approach followed in this paper can be discretised in three main stages, i) the outdoor climate data, ii) the indoor climate, calculated by using whole-building hygrothermal simulations and iii) the implementation of proper models in order to assess quantifiably the deterioration of the items of interest given the indoor climate. The first two steps have been implemented and described in detail by Choidis *et al.* (2021). Thus, in the current research focus was placed on the third part.

Outdoor and indoor climate

In the current research data from the REgional MOdel REMO (version REMO2015), driven by the global model MPI-ESM-LR were used in order to account for climate change. Specifically, three ten-year periods were used, 1960–1969 (past), 2010–2019 (present) under Representative Concentration Pathway (RCP) 8.5, and 2060–2069 (future) under RCP8.5. In addition, climate data from ERA5 reanalysis were used in order to assess the accuracy of the MPI-ES-LR_REMO2015 model results. The climate data were used as an input in a whole-building hygrothermal model of the historic building under investigation (Figure 2). For that scope, the software WUFI®Plus V.3.2.0.1. was used. More information about the synthesis of the climate data and the employed hygrothermal model can be found at Choidis et al. (2021).

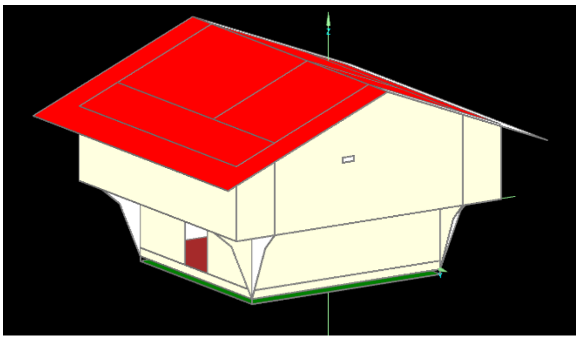

Figure 2: Whole-building hygrothermal model of the case study using the software WUFI®Plus V.3.2.0.1. (Choidis et al., 2021).

For the aims of the current study, the hygrothermal model was run under all four described climate excitations in order to calculate the indoor air temperature and relative humidity on the ground floor and in the northeast-oriented room of the upper floor, where the cabinet and the storage trunk are kept (Figure 1). These two parameters were later used as an input in proper models in order to calculate the biological deterioration due to mould and insects, the mechanical and the chemical deterioration of the two pieces of wooden furniture.

Biological deterioration by mould

Biological deterioration caused by mould growth constitutes a risk to both the preservation of the artifacts and the health of the visitors. The updated VTT mould model (Ojanen et al., 2010) is one of the most widely used methods in the literature to evaluate mould risks (Vereecken and Roles, 2012). The updated VTT model is an empirical mould growth prediction model, which is based on regression analysis of a set of measured data (Hukka and Viitanen, 1999; Viitanen and Ojanen, 2007). It takes into account the surface temperature, the surface relative humidity, the type and the quality of the substrate wood. Instead of the surface temperature and relative humidity, the air temperature and the air relative humidity near the surface can be used as inputs. The mould growth development is expressed by the mould index (*M*), which can range between 0 and 6 (Table 1).

Table 1: Description of the mould growth index (Viitanen and Ojanen, 2007).

Index	Growth Rate	Description
0	No growth	Spores not activated
1	Small amounts of mould on surface (microscope)	Initial stages of growth
2	<10% coverage of mould on surface (microscope)	-
3	10–30% coverage of mould on surface (visual)	New spores produced
4	30–70% coverage of mould on surface (visual)	Moderate growth
5	>70% coverage of mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

The open-source software WUFI Mould Index VTT 2.1 was used to calculate the mould growth on the wooden furniture according to the updated VTT mould model. The untreated components of the furniture and the parts where the surface treatment was degraded and removed are the most vulnerable to mould growth. Thus, the material 'untreated pine or spruce' was selected from the drop-down menu of the software in order to parametrize the model accordingly. Finally, three main levels of risk associated with mould growth are shown in Table 1.

Table 2: Risk levels associated with the mould index, according to Viitanen et al. (2015).

Risk Level	Range
Low risk	$0 \leq M < 1$
Medium risk	$1 \leq M < 2$
High risk	$2 \leq M \leq 6$

Biological deterioration by insects

Damage to heritage items can be caused by the larvae of certain moths and beetles and the juvenile and adult forms of insects such as silverfish and booklice. The risk of insect damage depends on relative humidity for some species and temperature for most insect types. The risk also depends on the availability of the right sort of food. Some insects are fed with proteins, while others with cellulosic materials (Ashley-Smith, 2013).

In this study, deterioration risks caused by insects was assessed by using the approach of the *Growing Degrees Days* (*GDD*) (Brimblecombe and Lankester, 2013). *Degree days* constitute a measurement of heat units over time, equivalent to the number of degrees that the average temperature is above a baseline value. *GDD* are appropriate for the assessment of insect growth because insects have a predictable development pattern based on heat accumulation. Insects are exothermic and their body temperature and growth are affected by their surrounding temperature. Every insect requires a consistent amount of heat accumulation to reach certain life stages, such as egg hatch or adult flight. *GDD* values interpret that heat accumulation (Ashley-Smith, 2013). The calculation of *GDD* gives a rough indication of the likelihood of insect activity. Within this study two indices were considered:

- Annual *GDD* above 15 ºC, with 15 ºC < T < 30 ºC, for insects such as the drugstore beetle and the clothes moth;
- Annual *GDD* above 15 ºC, with 15 ºC < T < 30 ºC and RH > 75%, for insects such as silverfish, psocoptera, and woodworms.

With,

$$GDD = \frac{365 \times \sum_{i=1}^{n}(T_i - 15)}{n} \quad (1)$$

Where,

- T_i is the air temperature at the hour i [ºC];
- n is the number of total data [-].

There is a correlation between the *GDD* and the insect lifecycle. Brimblecombe and Lankester (2013), showed a linear equation for this relationship for one species (*Stegobium Paniceum*) which equates one growth cycle - period between episodes of egg laying- to 490 *GDD* (Ashley-Smith, 2013). Therefore, the number of the insect growth cycles can be approximated by the following division:

$$Insect\ growth\ cycles = \frac{GDD}{490} \quad (2)$$

Table 3: Risk levels associated with the insect growth cycles.

Risk Level	Range
Low risk	Insect growth cycles < 1
High risk	Insect growth cycles ≥ 1

Mechanical deterioration

The furniture under investigation is made of wooden panels. The outer surface of the furniture is covered with hide glue, a gesso layer, and a paint layer (Huijbregts et al., 2012). Wood is a hygroscopic material and the fluctuations of the air relative humidity affect its moisture content and dimensional changes, i.e., swelling and shrinkage. The response of the painted surface of the furniture is different from the response of the bulk material due to different absorption and desorption characteristics (Mecklenburg et al., 1998; Vici et al., 2006; Martens, 2012). The differential deformation between the surface and the whole object is restricted by glue layers and joints and therefore high mechanical stresses may occur due to the air relative humidity fluctuations (Martens, 2012). When the material stresses exceed the yield strain of wood, it deforms plastically.

A methodology defined by Mecklenburg et al. (1998) and more recently used by Martens (2012) was implemented to assess the mechanical deterioration of the furniture with the decorative paintings on their surface. The different response time that is needed for i) the surface layer and ii) the bulk material to reach an equilibrium with their ambient environment after a step change in air relative humidity is presented in Table 4.

Table 4: Relevant responses and corresponding response times for the painted panels of the two pieces of furniture (Martens 2012).

Relevant responses	Response time
Surface response just under oil paint	4.3 days
The full response of the entire panel	26 days

The criteria to assess the risk of mechanical degradation of the painted furniture is based on the relative humidity response ($RH_{response}$), which is defined as the relative humidity of the object assuming that at the end of the response time, the object reaches an equilibrium with the environment. The $RH_{response}$ of objects at a generic instant i can be calculated through the following equation (Martens, 2012):

$$RH_{response,i} = \frac{RH_{response,i-1} + \frac{RH_i}{n/3}}{1 + \frac{1}{n/3}} \quad (3)$$

Where,

- $RH_{respnse,\,i}$ is the relative humidity response at time i [%];
- RH is the relative humidity of the environment [%];
- i is the current time within the data set [-];
- RH_i is the relative humidity at the instant i [%].
- n is the number of data points within the response time [-].

Through the calculation of the $RH_{response}$, the risk of mechanical damage on painted wooden furniture can be assessed. In detail, for painted wooden panels, the diagram proposed by Mecklenburg et al. (1998) based on the yield deformation criteria, which combines the surface and full material response to relative humidity variation in the environment, was adopted (Figure 3). For each time step, the calculated $RH_{response}$ for the surface layer was plotted on the vertical axis and the $RH_{response}$ of the entire wooden panel was plotted on the horizontal axis.

Figure 3 shows areas where the response of the surface and the whole wooden panel causes elastic and reversible dimensional deformations (area indicated as "elastic behaviour" in Figure 3). When fluctuations exceed the "elastic behaviour" area, deformations become irreversible, increasing in magnitude as the relative humidity fluctuations distribute deeper in the area indicated as "plastic behaviour compression response" or "tension response". Finally, when the environment becomes too dry, the $RH_{response}$ can reach the "failure" area in Figure 3, causing visible cracks in the material (Camuffo, 1998; Huerto-Cardenas et al., 2021).

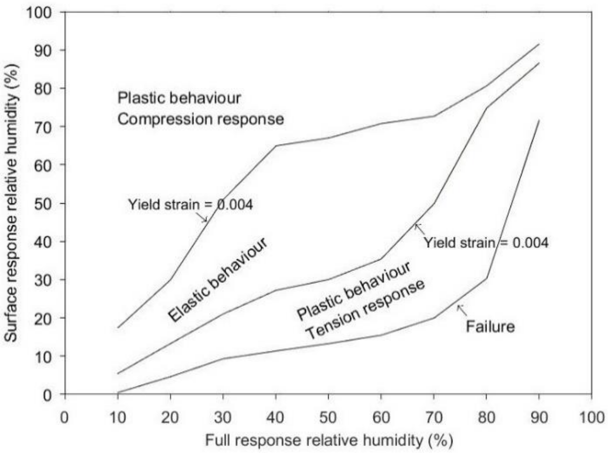

Figure 3: Mechanical risk assessment for the wooden furniture with the decorative paintings on its surface (Mecklenburg et al, 1998).

Chemical deterioration

The chemical degradation is mostly related to the deterioration of the cellulose of wood-made materials and the yellowing of the protective varnish on paintings (Michalski, 2002; Silva and Henriques, 2015). The *Lifetime Multiplier* (*LM*) concept defined by Michalski (2002) is a well-accepted method to calculate the chemical deterioration of the artifacts of interest, given the air temperature and the air relative humidity in the rooms in which they are kept. This parameter estimates the life expectancy of the material, compared to the case of maintaining the object in an environment with temperature and relative humidity fixed at 20 ºC and 50%, respectively. The *LM* was calculated by the following equation:

$$LM_i = \left(\frac{0.5}{RH_i}\right)^{1.3} \times e^{\frac{E_a}{R}\times\left(\frac{1}{T_i+273.15}-\frac{1}{293.15}\right)} \quad (4)$$

Where,

- LM_i is the *Lifetime Multiplier* at instant *i* [-];
- E_a is the activation energy [J/mol];
- *R* is the universal gas constant [8.314 J/molK];
- T_i is the air temperature at instant *i* [ºC];
- RH_i is the relative humidity at the instant *i* [%].

The activation energy is the energy required for a chemical reaction to take place. For the yellowing of varnishes, it is 70 kJ/mol (Michalski, 2002). A global value of the *LM*, representative of the risk condition for the entire 10-year periods examined in the current research, was calculated by using the *equivalent Lifetime Multiplier* (*eLM*). The *eLM* represents an average of the reciprocal values of the individual *LM* calculated for each interval. The *eLM* was calculated according to the equation provided by Silva and Henriques (2015):

$$eLM = \frac{1}{\frac{1}{n}\times\sum_{i=1}^{n}\frac{1}{LM_i}} \quad (5)$$

Where,

- eLM_i indicates the *equivalent Lifetime Multiplier* [-];
- *n* is the number of total data [-].

Finally, in Table 5, the three main classes of risk associated with the *eLM* values are presented.

Table 5: Risk levels associated with eLM values, according to Silva et al. (2016) and Verticchio et al. (2019).

Risk Level	Range
Low risk	*eLM* > 1
Medium risk	0.75 < *eLM* ≤ 1
High risk	*eLM* ≤ 0.75

Results and Discussion

Outdoor and indoor climate

Climate data for three different decades, i.e., 1960–1969 (referred to as past), 2010–2019 (referred to as present), and 2060–2069 (referred to as future), derived from the MPI-ES-LR_REMO2015 model were used for the examination of the climatic changes occurring throughout the years. A fourth climate file with data derived from the ERA5 reanalysis for the period 2010–2019 (current) was used in order to examine the accuracy of the climate model data.

The signal of climate change in terms of the outdoor air temperature (Figure 4a) is an average increase of 1.6 ˚C from past to present conditions, and 1.2 ºC from present to potential future conditions. The air temperatures are slightly underestimated in the model data, showing an average difference of 0.3 ºC compared to the ERA5 reanalysis. According to the climate model data, the outdoor air relative humidity remains at the same levels under past, current, and potential future conditions, with an average value of approximately 85% (Figure 4b). The air relative humidity is overestimated significantly by the climate model data since, according to the ERA5 reanalysis dataset, its average value is 78%.

The historic building under investigation has exterior log walls with significant air leakages, openings in the building envelope without transparent components, and it doesn't have any HVAC systems. Thus, the indoor climate of both the ground and the upper floor is very similar to the outdoor one. The ground floor doesn't have any openings, while the room of interest on the upper floor has two openings (Figure 1). This explains the wider range of the air temperature and the air relative humidity values on the upper floor compared to the ground floor (Figures 4a and b).

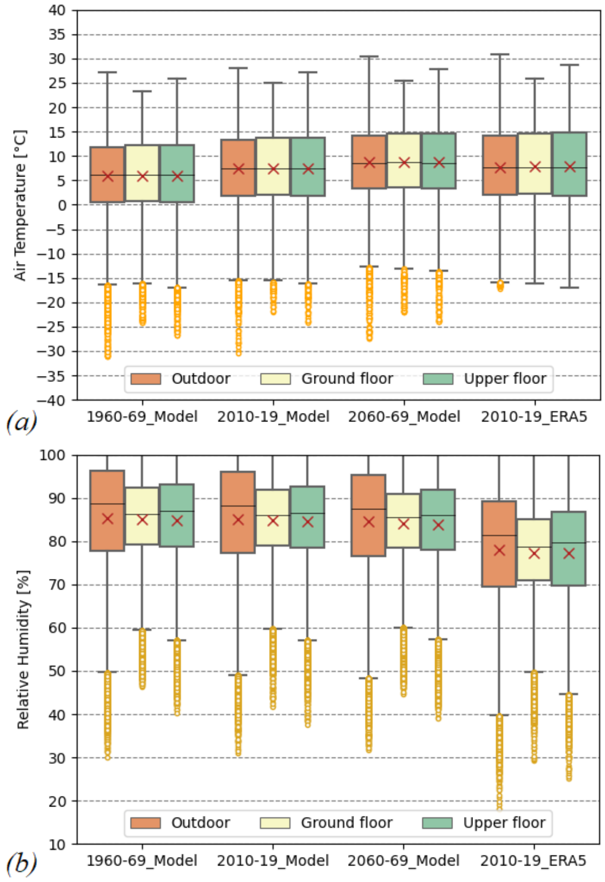

Figure 4: Boxplots of (a) the air temperature and (b) the air relative humidity for all examined climate excitations. In the boxplots, the box shows 50% of the data, with median represented as a horizontal bar and the average value highlighted with the 'x' symbol. The whisker extends to two standard deviations of the data and the circles represent the outliers.

Biological deterioration by mould

In Figure 5, the results of the mould index calculated for the wooden cabinet on the ground floor and for the wooden storage trunk on the upper floor of the historic building are presented. In all examined cases the values of the mould index are lower than 1 and thus remain at acceptable levels. Given the data from the climate model there is an increase in the mould risk from the past to the current conditions and a slight decrease from the current to the future ones. This observation contradicts other research in which an increasing trend of the mould risk is attributed to climate change. The selection of three arbitrary 10-year periods to represent the past, current and future conditions is a limitation of the current study. Thus, the consideration of 30-year periods, or even better continuous data series would provide a better overview of the signal of climate change. In most cases, the mould risk is slightly higher on the upper floor. The mould risk of the wooden furniture is significantly overestimated by the climate model, compared to ERA5. This is linked to the overestimation of the air relative humidity by the climate model compared to ERA5. Given the current mould risk, as calculated by the data from ERA5, and the signal of climate change as described above, the items of interest will not be threatened by mould in the future.

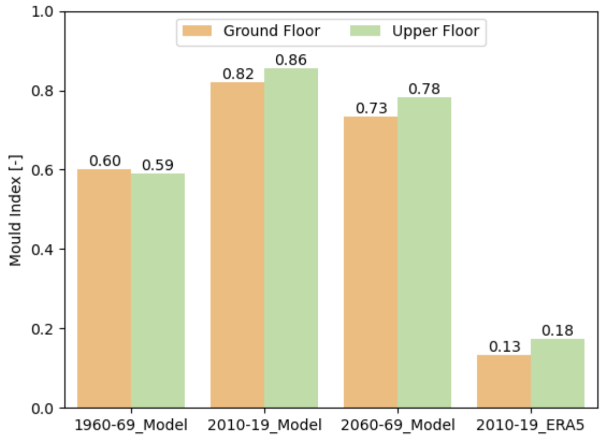

Figure 5: Average of maximum annual mould index.

Biological deterioration by insects

In Figure 6a the insect risk due to temperature-dependent insects is depicted. In all examined cases the risk is not significant and corresponds to less than 1 cycle on an annual basis. There is an increasing trend of this type of damage due to climate change, which is linked to the increasing trend of the air temperatures. The risk of the upper floor of the building is higher in all examined cases. The deterioration risk due to drugstore beetle and clothes moth is underestimated by the climate model, compared to the ERA5. This is linked to the underestimation of the air temperature by the climate model compared to the ERA5. Given the increasing trend of the risk it is possible that in the future there could be almost 1 growth cycle at the upper level of the building and thus the wooden cabinet would be at risk.

In Figure 6b the risk due to insects that demand both proper temperatures and high humidity levels for their growth is presented. In all cases the insect attack risk remains at acceptable levels. Again, there is an increasing trend due to climate change. The risk for this type of insects is higher on the ground floor, given that is more air tight than the upper floor and it is more difficult to be discharged from the moisture loads. The deterioration risk by woodworm, silverfish, and psocoptera is slightly overestimated by the climate model compared to the ERA5. This is linked to the overestimation of the air relative humidity by the climate model compared to the ERA5.

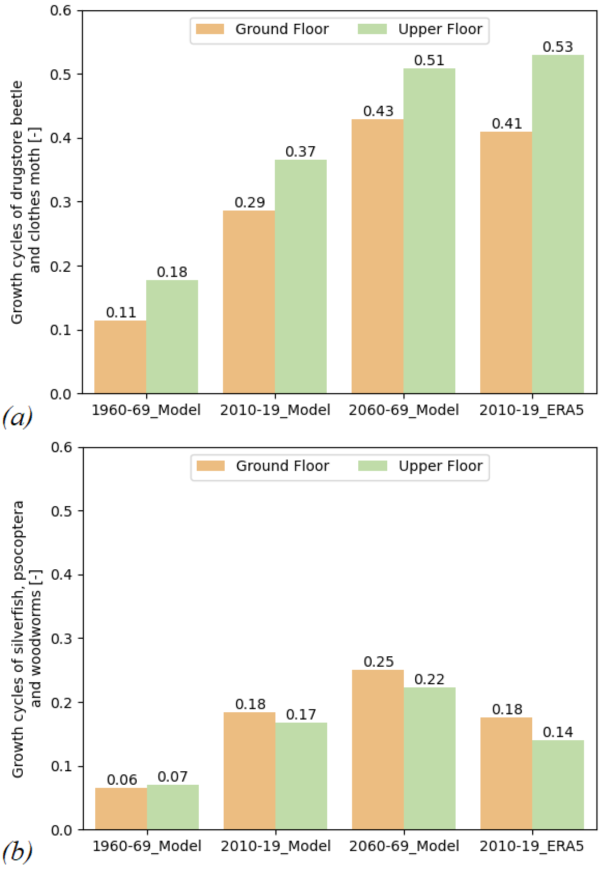

Figure 6: Average annual growth cycles for (a) drugstore beetle and clothes moth, (b) silverfish, psocoptera and woodworms.

Mechanical deterioration

In Figure 7a and b the risks associated with the mechanical deterioration of the wooden furniture on the upper and the ground floor, respectively, are depicted. As already described in the methodology section, the safety area to avoid mechanical damage to the material is the one in which the response of the surface and the whole wooden panel causes elastic and reversible dimensional deformations. The rest areas in Figure 7a and b represent irreversible deformation. Moreover, in Table 6 the percentage of the datapoints in the "plastic behaviour" area is presented.

In none of the examined cases there are datapoints in the failure area (Figure 7a and b). However, in all cases the response relative humidity remains at high levels and approximately half of the datapoints are in the "plastic behaviour" area, in which the deformation of the objects of interest is irreversible (Figure 7a and b, Table 6). There is a decreasing trend in the mechanical deterioration risk due to climate change (Table 6). However, the overall decrease in the risk is small. The mechanical deterioration risk is higher on the upper floor, given that it has openings without transparent components and, thus, it is more exposed to the outdoor environment. The climate model overestimates the mechanical deterioration risk compared to the ERA5 reanalysis. This is linked to the overestimation of the relative humidity by the climate model data, which results in higher response relative humidities. In the area of high response relative humidities of the diagram proposed by Mecklenburg et al. (1998), even small changes in the response relative humidity result in surpassing of the yield strain.

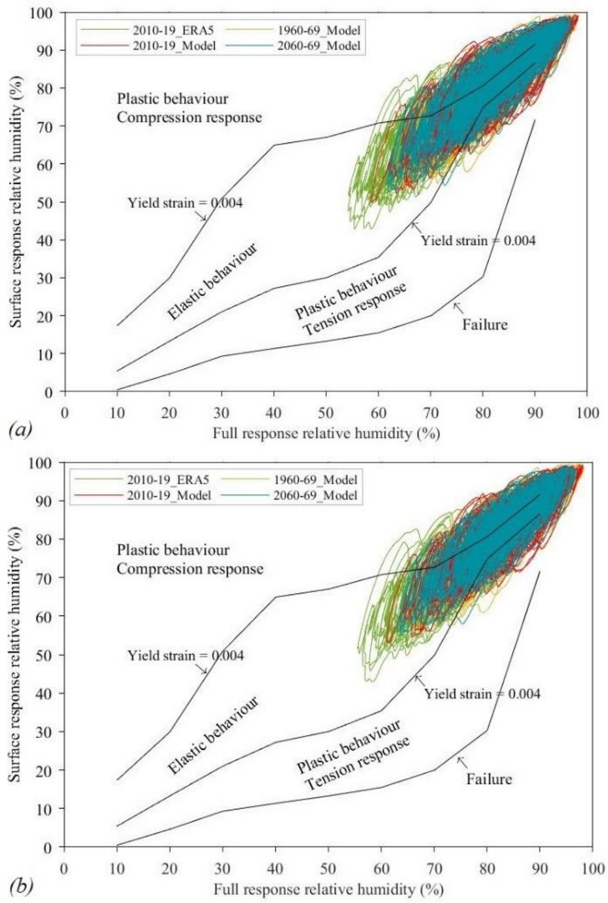

Figure 7: Risks associated with mechanical deterioration of the wooden furniture with the decorative paintings on their surface, located at (a) the upper floor and (b) the ground floor of the building.

Table 6: Percentage of the datapoints in the "plastic behaviour" area.

Floor	1960-69 Model	2010-19 Model	2060-69 Model	2010-19 ERA5
Upper	66%	64%	62%	46%
Ground	65%	61%	59%	45%

Chemical deterioration

The chemical deterioration risk is depicted in Figure 8, considering the *equivalent Lifetime Multiplier*. In all examined cases the values of the *eLM* are lower than 0.75 which is considered as the upper limit of the high-risk area. There is a very slight increase in the *eLM* due to climate change, meaning that the chemical deterioration risk decreases. However, in all cases the values remain too low, at unaccepted levels. The chemical deterioration risk is overestimated by the climate model compared to ERA5.

This is attributed to the overestimation of the air relative humidity by the climate model compared to ERA5. The low values of the *eLM* indicate that proper measures should be taken for the preservation of the items of interest.

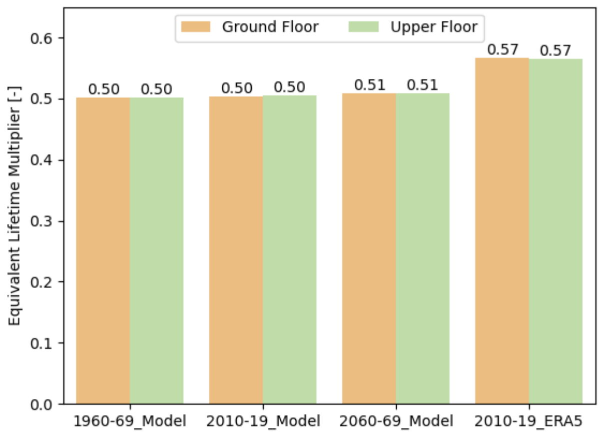

Figure 8: Chemical deterioration assessed by the equivalent Lifetime Multiplier.

Conclusion

The focus of the current research is the impact assessment of climate change on the biological, mechanical and chemical deterioration of two wooden furniture hosted inside a historic building. The building is located in the county of Vestfold, Norway. Climate data from REMO2015 driven by the global model MPI-ESM-LR were used in order to take into account the climate change. The climate data refer to the past, present, and potential future climate conditions. In addition, climate data from ERA5 were used in order to assess the accuracy of the climate model data. Whole-building hygrothermal simulations were employed in order to calculate the indoor environmental conditions, i.e., air temperature and the air relative humidity, in the rooms that host the furniture of interest. The computed air temperature and air relative humidity were then used to calculate i) the mould growth on the two items, using the updated VTT mould model, ii) the insect growth cycles by using the *GDD* approach and iii) the mechanical deterioration risk by using the diagram introduced by Mecklenburg et al. (1998) based on the yield deformation criteria and iv) the chemical deterioration risk by considering the *eLM*.

The findings reveal no risk for mould or insects for the two items of interest. It is possible, however, that in the future there would be a minor risk by drugstore beetles and clothes moths, especially on the upper floor of the historic building. The mechanical deterioration risk of the two pieces of furniture remains in high levels under past, present, and potential future conditions. Moreover, the protective varnish layer of the paintings of the two pieces of furniture has a significant risk of chemical deterioration as it was calculated by the use of the *eLM*. It is, thus, suggested that the items should be moved to a room with proper climate in order to minimize their mechanical and chemical deterioration risk and extend their lifespan.

It was observed that the data from the climate model slightly underestimate the air temperature and overestimate the air relative humidity compared to the ERA5 reanalysis. This has further implications for the calculations of the deterioration mechanisms. Specifically, the climate model:

- overestimates significantly the mould risk,
- underestimates the risk by drugstore beetle and clothes moth,
- overestimates the mechanical deterioration risk,
- slightly overestimates the chemical deterioration risk as calculated by the *eLM*.

It is suggested that in a future study the data from the climate models should be bias corrected.

A limitation of the current research is that arbitrary 10-year periods were selected to represent the past, present, and future conditions. The 10-year periods are not long enough to provide a good overview of the changes in the climate. It is suggested that in future research at least 30-year periods or continuous data series should be used instead of the 10-year periods.

In the current research, the mould risk was evaluated, based on the average of the maximum annual values. The deterioration risk due to insects and the chemical deterioration risk according to the *eLM* account for the average conditions during the whole decade under investigation. It is suggested that in future research special attention should be paid to the assessment of the extreme events and not only of the average conditions.

Acknowledgment

This work is a part of the HYPERION project. HYPERION has received funding from the European Union’s Framework Program for Research and Innovation (Horizon 2020) under grant agreement no. 821054. The content of this publication is the sole responsibility of Oslo Metropolitan University and does not necessarily reflect the opinion of the European Union. The climate data that support the findings of this study are derived from the online databases of the Copernicus climate change service and the Earth System Grid Federation (ESGF).

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