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A comparison of preservation metrics expressing mechanical, chemical and biological damage

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Abstract

Preservation metrics are used to estimate the risk of probable damage to an object or collection in relation to an institution's indoor climate, by translating a temperature and relative humidity dataset into an expression of risk/probabilities of material change, be it temporary or permanent. The types of material change considered are mechanical (e.g. cracks, deformation, swelling and shrinking), chemical (e.g. oxidation, colour changes and material decay) and biological (mould growth). The series of consecutive calculations that make up a preservation metric express what the change to a theoretical object or collection might be. This paper focuses on the differences between these calculations and their impact on the interpretation of the results.

INTRODUCTION

Risk analysis has become an essential guide for successful preventive conservation management. Numerically expressing risk in order to compare the preservation quality of diverse environments, based on measurements of temperature (T) and relative humidity (RH), has been attempted by different institutions, as part of the toolset developed for a broader analysis of the indoor climate.

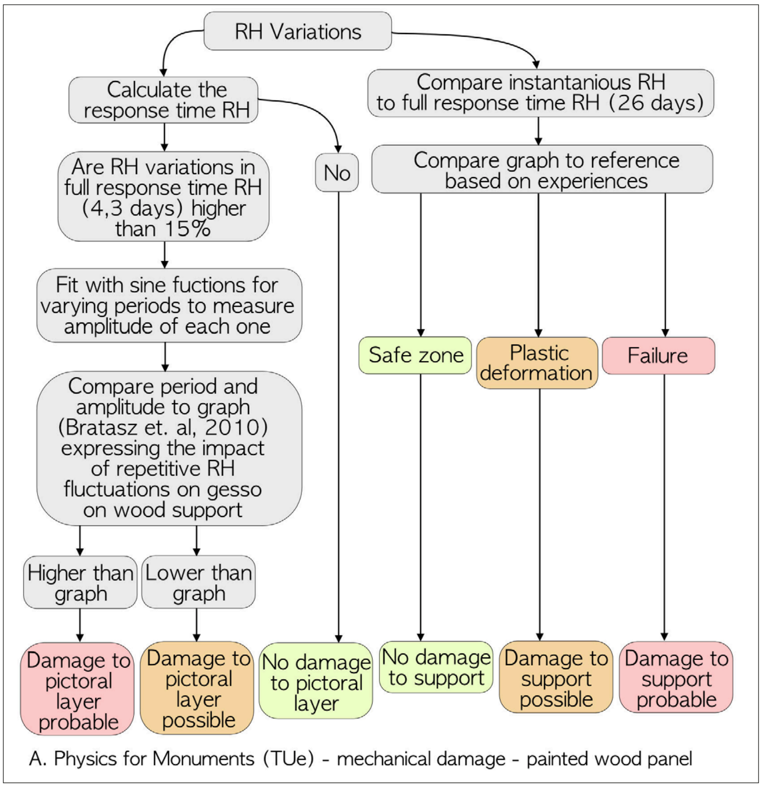
Conservation metrics are rarely used by conservation professionals, but this research shows that they can have a real impact on decision-making. Most of the metrics developed thus far are largely based on the same principles but the lack of transparency regarding their inner workings makes them hard to comprehend and compare, and may explain their minimal adoption. Understanding the equations used and their relation to real material changes is essential. Furthermore, with the growing use of programming languages in the field of conservation, it can be useful to contextualise preservation metrics for programmers or computer scientists who do not have a conservation background.

METHODOLOGY

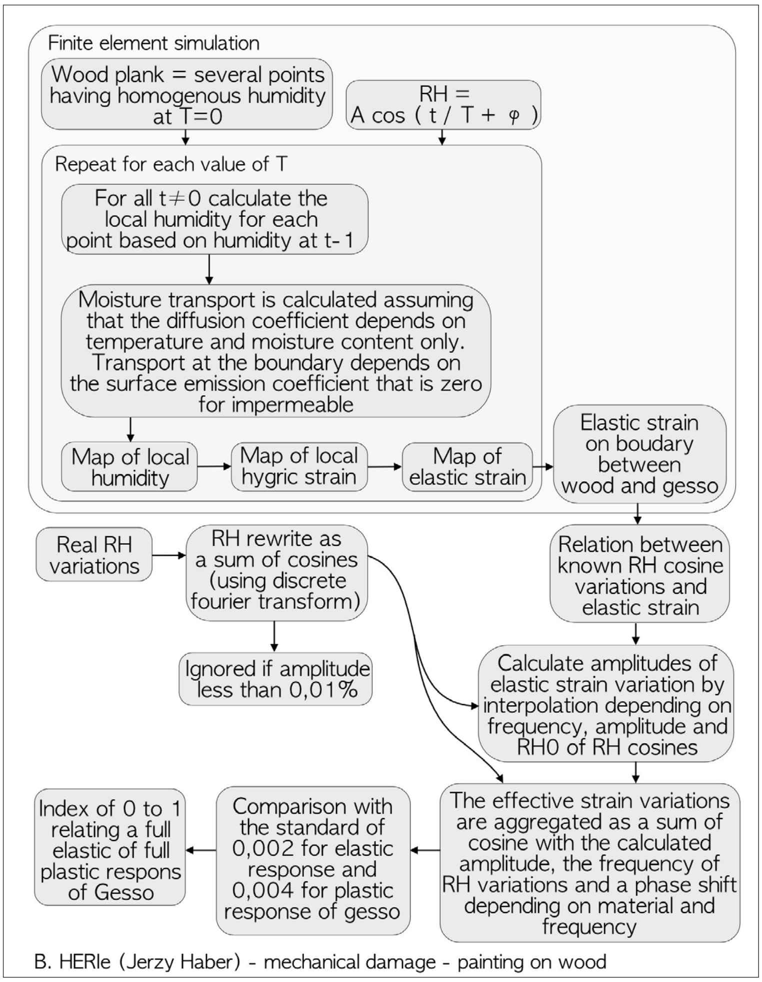
This paper compares the preservation metrics used by the Image Permanence Institute's (IPI) 'eClimate Notebook' (IPI 2022), Jerzy Haber Institute's (JH) 'HERIe' (Jerzy Haber Institute 2022) and TU Eindhoven's (TUe) 'Building Physics for Monuments' (Smulders and Martens 2022). A previous article provided a more comprehensive overview of these tools and their capabilities (Cosaert and Beltran 2021).

Each preservation metric was analysed with respect to the following:

- The theoretical sources that are referenced, the materials tested (e.g. wood, different wood species and wood thickness), how they were tested, by whom and for what purpose
- The formula's referred to and used in the calculations, with the most influential variables in that formula highlighted
- The subsequent outputs (i.e. the actual preservation metrics), the units they are expressed in and their relation to a physical, chemical, or biological response
- How the calculation is conducted in the back end (Figure 1).



A. Physics for Monuments (TUe) - mechanical damage - painted wood panel



B. HERIe (Jerzy Haber) - mechanical damage - painting on wood

Figure 1. While calculations of preservation metrics often use the same or similar source materials, their complexity has progressively increased. These visuals were made by the authors of this paper – with revision by the creators of the metrics– and provide a guideline on how the input information is processed on the backend to come to a numerical and/or visual output. (A) A schematic representation of TUe's calculation (released in 2014) for mechanical damage to a 'painted wood panel'. The green, red and orange shading is related to the risk level (safe, probable damage, possible damage), also shown in (B). (B) A schematic representation of the HERIe calculations (released in 2018) for mechanical damage to a 'painting on wood'

A detailed analysis of these calculations is available from the authors upon request. The fourteen different metrics that were analysed are listed in Table 1.

MECHANICAL DAMAGE

General description

IPI uses the percentage of dimensional change (%DC, shrinking and swelling) and an equilibrium moisture content (EMC) of a generic wooden object to express mechanical damage. Subsequently, empirical limits determined by calculating $\%DC_{max}$ or $\%EMC_{min}$ – respectively, the maximum size change between humid and dry periods and the minimal moisture during dry period – are used to determine whether the collection environment is acceptable or poses a risk. EMC_{max} is also used to express the risk of moisture-induced metal corrosion.

TUe has developed a set of metrics for painted wood, wooden furniture and sculpture that includes a comparison of real-time or delayed humidity

Table 1. Overview of all preservation metrics discussed, the programmes that use them (and the institutions that created them), the response (mechanical, biological or chemical) and their intended use (type of collection)

Preservation metric		Tools that use it	Based on	Intended use for
MECHANICAL				
1A	**Equilibrium Moisture Content (%EMC)**	eClimate Notebook (IPI)	Average species of (bulky) wood	Mixed collections
1B	**Max (%EMC)**	eClimate Notebook (IPI)	Average species of (bulky) wood	Mixed collections
2	**Dimensional Change (%DC)**	eClimate Notebook (IPI)	Average species of (bulky) wood	Mixed collections
3A	**Risk Index (RI), Wooden sculpture**	Physics of Monuments (TUe)	Lime wood/wooden sculpture (bulk)	Wooden sculpture
3B	**Risk Index (RI), Furniture**	Physics of Monuments (TUe)	° Lime wood/wooden sculpture (bulk) ° Japanese lacquer and lime wood protected by it	Furniture
3C	**Risk Index (RI), Painted wood panel**	Physics of Monuments (TUe)	° One or all of the following: panel pieces of pine, red oak and spruce ° Gesso on 1 cm of wooden panel	Panel painting
4A	**Risk Index (RI), Painting on wood**	HERIe (JH)	Different simulation for: ° Types of wood: poplar, lime, oak, pine ° Thickness of support: 5–40 mm ° Different cuts: radial and tangential ° Type of gesso: soft or stiff ° Water vapour transport: through one or two faces (should represent a bare wood panel)	Panel painting
4B	**Risk Index (RI), Restrained wood**	HERIe (JH)	Different simulation for: ° Types of wood: poplar, lime, oak, pine ° Thickness of support: 5–40 mm ° Different cuts: radial and tangential ° Water vapour transport: through one or two faces (should represent a bare wood panel)	Furniture and other types of wood where the movement of the panel is restricted
5	**Parchment Damage Criteria (PDC)**	HERIe (JH)	° Modern restraint parchment	Parchment
BIOLOGICAL				
6	**Mold Risk Factor (MRF)**	eClimateNotebook (IPI)	° Xerophilic (lower, ± over 60%, humidity needed for germination) ° Mildew	(environments housing) mixed collections
7	**Mold Growth (MG)**	Physics of Monuments (TUe)	° 20–30 types of mould common in buildings ° 10–20 toxic types of mould	(environments housing) mixed collections
CHEMICAL				
8A	**Preservation Index (PI)**	eClimateNotebook (IPI)	° Acetate film ('chemically unstable material')	Mixed collections
8B	**Time Weighted Preservation Index (TWPI)**	eClimateNotebook (IPI)	° Acetate film ('chemically unstable material')	Mixed collections
9	**Lifetime Multiplier (LM)**	Physics of Monuments (TUe)	° Paper ° Films (synthetic) ° Dyes	Mixed (organic) collections with a specific focus on paper, wooden sculpture, panel painting and furniture

(depending on the object type), with a delayed approximation of the humidity. The response time is considered to be different for every object (Figure 1a). For painted wood, the support and the pictorial layer are compared separately, and the impact of damage due to a cyclical humidity change is estimated (Bratasz et al. 2010).

The risk index (RI) from **JH** (HERIe) considers restrained wood, a painted wood panel and parchment. For restrained and painted wood, the humidity variation is compared to a simulation of the response of wood to obtain a value for strain. This value is then compared to the yield points of the different directional cuts (longitudinal and tangential) of the wood. The difference between restrained and non-restrained wood is the location of the measurement on the object (respectively in the centre or at the surface of the object). For painted wood, the yield point of gesso (a preparation layer consisting of binding medium and calcium sulfate) is taken into consideration (Figure 1b). JH also calculates the curling of parchment using its parchment damage criteria (PDC). This metric indicates a certain degree and reversibility of curling in direct relation to humidity (Jerzy Haber Institute of Catalysis and Surface Chemistry 2020).

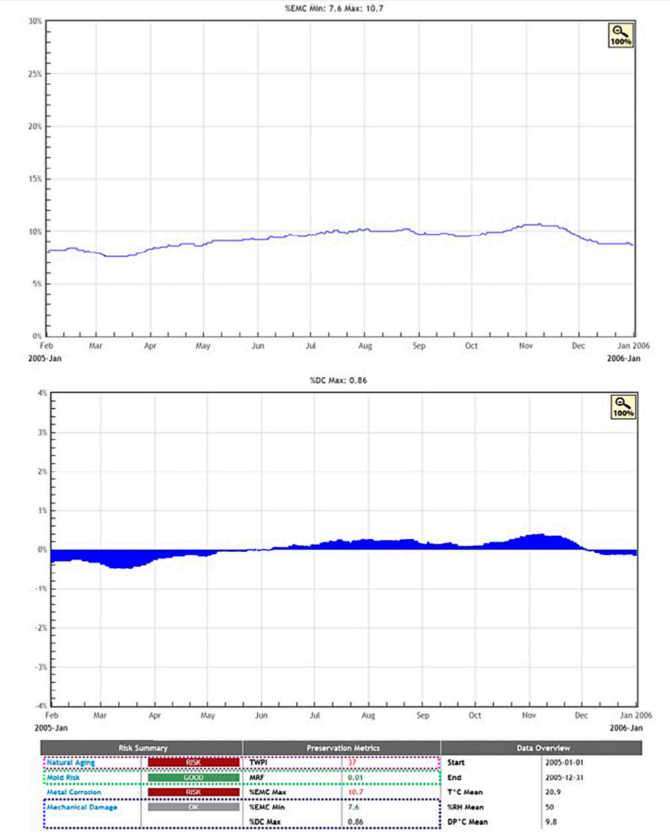
Similarities

All mechanical preservation metrics express the **dimensional changes** of an object. They relate to an object gaining or losing moisture, leading to swelling and shrinking, as a reaction to changes in **relative humidity (RH)**. These changes in RH can be related to short-term (typically 24 h) or long-term (typically 7 days, monthly or seasonal) fluctuations. This is expressed by a range and related to the **response time** (**τ_{response}**) of an object. None of the materials (except parchment) are considered to respond immediately to environmental changes in RH. Response times vary from approximately 10 h (surface response) to approximately 1 year (full object response). A final influential factor is the **yield point (or a derivative)** of the object, which is related to the ‘sensitivity’ of the object: it expresses when the object’s response (or change in form) is considered permanent. This can be an arbitrary choice (average) or a more precise choice (e.g. based on experiments and distinction between materials, radially or tangentially cut, etc.).

Differences

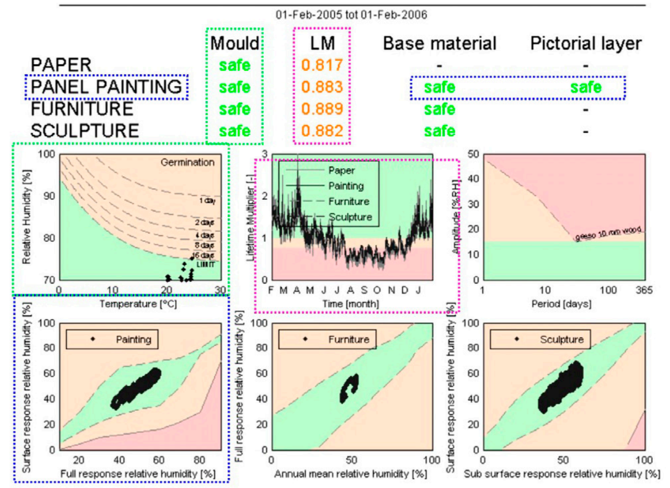
Representation of the results

The visual results as expressed by **IPI**’s eClimate Notebook (Figure 2a) represent physical responses in time. They indicate the dimensional change in %DC and thus a comparison of the original size of the object with its new dimensions. This can either be a negative (shrinking) or a positive (swelling) response. In contrast to HERIe and TUe, general deformation (e.g. undulation) is not considered by IPI. The %EMC compares the mass of water in the object to the mass of dry wood. The link to actual risk is expressed by a ‘traffic light system’ (green, orange and red). The thresholds set for the transition between ‘OK’ to ‘risk’ can be considered the chosen yield point. Different thresholds are chosen for organic objects and metal objects.



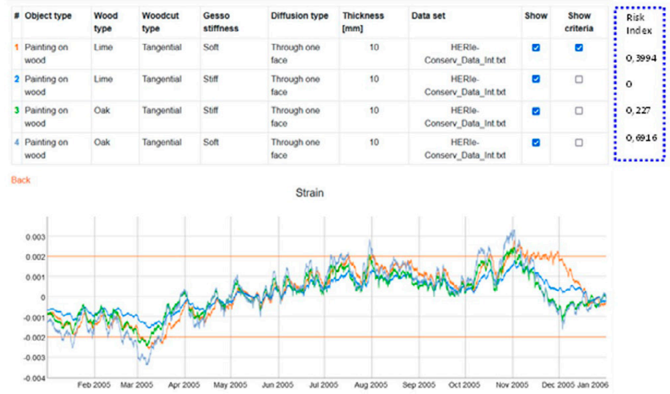
Risk Summary		Preservation Metrics		Data Overview	
Natural Aging	RISK	TWPI	37	Start	2005-01-01
Mold Risk	GOOD	MRF	0.01	End	2005-12-31
Metal Corrosion	RISK	%EMC Max	10.7	T°C Mean	20.9
Mechanical Damage	OK	%EMC Min	7.6	%RH Mean	50
		%DC Max	0.86	DP°C Mean	9.8

A. *eClimate Notebook – mechanical damage – % equilibrium moisture content (min) & % dimensional change (max.)*


01-Feb-2005 tot 01-Feb-2006

	Mould	LM	Base material	Pictorial layer
PAPER	safe	0.817	-	-
PANEL PAINTING	safe	0.883	safe	safe
FURNITURE	safe	0.889	safe	-
SCULPTURE	safe	0.882	safe	-

B. *TUe – mechanical damage – panel painting & gesso on 1cm wood*



#	Object type	Wood type	Woodcut type	Gesso stiffness	Diffusion type	Thickness [mm]	Data set	Show	Show criteria	Risk Index
1	Painting on wood	Lime	Tangential	Soft	Through one face	10	HERIe-Conserv_Data_Int.txt	☑	☑	0,3994
2	Painting on wood	Lime	Tangential	Stiff	Through one face	10	HERIe-Conserv_Data_Int.txt	☑	☐	0
3	Painting on wood	Oak	Tangential	Stiff	Through one face	10	HERIe-Conserv_Data_Int.txt	☑	☐	0,227
4	Painting on wood	Oak	Tangential	Soft	Through one face	10	HERIe-Conserv_Data_Int.txt	☑	☐	0,6916

C. *HERIe – mechanical damage – painting on wood (stiff & soft gesso on 1cm oak and lime panel)*

Figure 2. The difference in the results is shown based on a comparison of the expressions of mechanical damage as described by eClimate Notebook (A), TUe (B) and HERIe (C). In all of the figures, the blue lines represent the expression of mechanical damage, the green lines the results related to biological damage, and the pink line is related to the results of chemical damage

- Organic objects: environments with $EMC_{min} < 5\%$ or $EMC_{max} > 12.5\%$, and/or with a %DC > 1.5 are considered at risk. At high and low humidity and at a high 30-day running average of RH fluctuations, the risk of a permanent dimensional change will be higher.
- Metal objects: calculating the physical response of an organic material in order to predict the chemical response of an inorganic object can generate confusing results. At $EMC_{max} > 10.5\%$, a metal object is considered at risk. The interpretation of this result is that metal objects are at risk in higher humidity environments and/or are better maintained in cold and dry environment.

TUe builds further on the traffic light system and uses several visuals that illustrate a transition between different zones. Those zones indicate probable damage (breaking point), possible damage (plastic response) and a safe zone (elastic response). The visual result is illustrated for several datapoints in the set, with no direct link to a date or time (Figure 2b).

For wooden objects, the metrics calculate a (delayed) effective RH for two points on a theoretical object (similar to HERIe for strain). The larger the differences between those points, the higher the risk at any point in time. This means that the greater the impact of an object's response to RH fluctuations, the higher the risk. Thresholds are based on object group and a specific yield point (based on the measured RH data):

- Furniture: The %RH is the difference between RH_{avg} and the total RH responses (i.e. those of the object and the coating).
- Sculpture: The %RH is equal to the RH difference between surface and sub-surface RH responses.
- Wood support: The RH at the surface is calculated. The derived %RH is the RH difference between the surface RH and the total RH responses (i.e. those of the object and the coating).
- For gesso, the RH at the sub-oil-paint layer is calculated and the amplitude of the %RH (fluctuations) and the length of the cycle (days) of the delayed response are then derived. RH variations (%) are indicated when they are high enough to cause damage. The lower and less frequent the fluctuations, the lower the risk.

JH (HERIe) does not use the traffic light system but expresses the numerical results for different types of wood objects as strain (Figure 2c) and those for parchment as the degree of curling over time.

- Painting on wood: RH variations are expressed as strain and translated into a risk index. Strain is calculated on the boundary between the wood and the gesso. The maximum value of strain is compared to the yield point of gesso. The yield point for a plastic response is set at 0.004, and for an elastic response at 0.002. Repetition of these events also plays a role in the calculation. The result ultimately expresses the deformation of wood (in strain over time) due to repeated RH fluctuations that lead to damage to the pictorial layer.

- Restrained wood: The calculations are similar to those for paintings on wood, with the difference being the location on the object considered. Strain is calculated in the middle (of the cross-section) of the wood.

Because the object cannot move freely, the border of the wood is considered 'fixed' (total strain = 0). The result expresses wood deformation as the difference in the responses to RH fluctuations on different parts of the object.

- Parchment: The degree of curling is expressed as significant (1) or insignificant (0). Insignificant curling is limited to 1.5 m^{-1}, and significant curling to 3 m^{-1} (equivalent to the curvature of a cylinder with a radius of 1/1.5 m and 1/3 m respectively). The result expresses how repeated cycles of both high and low humidity influence the deformation of parchment.

The chosen response time

The response time of an object is related to its sensitivity to RH fluctuations. A longer response time will make the object less sensitive to short-term fluctuations.

IPI does not refer to a specific response time; rather, a 30-day running average of RH fluctuations is used such that the response time is presumably 30 days.

TUe has defined the response time as a function of the object and physical points on the object. For wooden sculpture, a surface response is considered to take 10 h and a sub-surface response 15 h. For furniture, a full object response is taken into account twice, over 40 days and one year. For panel paintings, the response of the support is considered, with a surface response of 10 h; the complete object response is 26 h and the sub-oil-paint response 4.3 days.

For wooden panels, **JH** defines the response time as the time needed to reach 63.2% (=1–1/e) of the new equilibrium moisture content of wood for a given panel thickness, water vapour transport (gesso on one or two sides) and temperature in response to a step change in RH. For thicker panels, lower temperature and gesso on only one side will lengthen the response time. For parchment, the response time is considered immediate, since it is shorter than most measurement intervals (e.g. 15 min).

CHEMICAL DAMAGE

General description

The first widely used metrics were **IPI**'s preservative index (PI) and its derivative, the time-weighted preservative index (TWPI). Both are based on the methodology embodied in Sebera's studies on isoperms (Sebera 1994). The Arrhenius equation with a modified activation energy is set to mimic cellulose triacetate deterioration. This metric generates the 'predicted lifetime' of a chemically unstable object (acetate film) as an early warning sign for (generally more stable) organic objects. The derivative TWPI uses an iterative average to express an expected lifetime over the whole period of the dataset. It is more suited for comparisons between datasets from different locations.

The main expression of chemical damage used is the lifetime multiplier (LM). The actual equations can differ (ASHRAE 2019) but the most commonly used one is Michalski's proposition for organic materials, which is based largely on experiments with paper (Michalski 2000). These experiments and calculations form the basis of the analysis by **TUe**.

In the LM, the calculations for chemical decay are run twice: once at a stable theoretical climate (20°C and 50% RH) and once based on the climate dataset. A comparison of the results expresses how much 'higher' or 'lower' the risk is compared to that of the same object under the stable climate. HERIe has recently integrated a similar analysis for chemical decay as part of their tools, but it is not considered in this article.

Similarities

All preservation metrics compare T and RH to the risk of the natural ageing of an object or its chemical decay. For all preservation metrics, **temperature** (T) is the most influential variable, with hotter climates being the least preferable. The dependency on temperature is always determined by the **Arrhenius law** (an empirical law that expresses the rate at which chemical reactions occur). The 'sensitivity' of the object is expressed by the **activation energy** (the minimum energy that must be delivered to a chemical system containing potential reactants to cause a chemical reaction) (Table 2). All of these metrics have a similar relation to risk between 20% RH and 60% RH.

Differences

Representation of the results

Visually, **IPI**'s PI expresses the expected lifetime in years at any point in time, while TWPI applies an iterative average to generate a result for the whole dataset (also in years). Given the sensitivity of acetate film to both

Table 2. Comparison of the methods proposed in conservation to assess chemical decay, with activation energy represented by E_A. Not all methods are directly used within these preservation metrics. This table was compiled by Lien de Backer as part of her doctoral thesis (De Backer 2018)

Method	Author	Equation
Isoperm method	Sebera (1994)	$\frac{k_1}{k_2} = \left(\frac{RH_1}{RH_2}\right)\left(\frac{T_1}{T_2}\right)10^{0.0523\,(E_a - RT)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$
Revised Isoperm method	Strang and Grattan (2009)	$\frac{k_1}{k_2} = \left(\frac{C_1}{C_2}\right)e^{\frac{E_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$
Preservation index	IPI (Reilly et al., 1995)	$PI = \frac{e^{\frac{95220 - 134.9RH}{RT} + 0.0284RH - 28.023}}{360} \quad (*)$
TWPI	IPI (1995)	$TWPI_n = \frac{n\,TWPI_{n-1}\,PI_n}{PI_n(n-1) + TWPI_{n-1}}$
Lifetime Multiplier	Michalski (2000)	$LM_x = \left(\frac{k_1}{k_2}\right) = \left(\frac{50\%}{RH_x}\right)^{1.3} e^{\frac{E_a}{R}\left(\frac{1}{T_x} - \frac{1}{293}\right)}$
Equivalent Lifetime Multiplier	Silva and Henriques (2015)	$eLM = \frac{1}{\frac{1}{n}\sum_{i=1}^{n} LM_i}$
Isoburn	Padfield (2004)	$\frac{k_1}{k_2} = RH_x.\,1{,}34.\,10^{16}e^{\frac{E_a}{R}\left(\frac{1}{T_2} - \frac{1}{293}\right)}$

* IPI has not published the equation. The probable equation was published by Tim Padfield (Padfield 2004). All equations are converted to have the same units: R = gas constant, 8.314 J/(K. mole);
E_A = activation energy [J/(mole)]; T = temperature [K]; RH = relative humidity (%)

high and low humidity, the results for other object types are unreliable for conditions below 20% RH and above 60% RH. Additionally, because T is the dominant variable in the calculation, cold climates (such as northern outdoor climates, even at high RH) result in preferable conditions, which is also not representative of acetate film.

The results from **TUe** are relative to the lifetime of the object at 20°C and 50% RH and are expressed numerically. If the value is equal to 1, the risk is equal to the risk at the theoretically stable climate (+1 is a very stable environment, 0 means total decay). The RH considered is not the one represented by the user's dataset; rather, it is the RH calculated to express the sub-surface object response (the RH response delayed by 10 h). This allows a consideration of the mechanical response and is (together with the difference in yield point) the main reason for the slightly different results for all wooden objects. For wooden objects, TUe is more cautious (damage will occur faster) than IPI because the discolouration of varnish (at a lower activation energy) is considered. The visual result generated by TUe (Figure 2b) is similar to the one generated by eClimate Notebook, but expressed by a LM on the x-axis, rather than in years.

Material testing and related activation energy

IPI has based their chemical metrics on tests with cellulose acetate film. The data are based on a table that expresses the predicted lifetime (years) at a combined T and RH (at any point in time). The information in the table is subsequently used to define the activation energy (Reilly et al. 1995).

TUe has based their results on material testing of paper, film and dyes (Martens 2012). For paper, an activation energy of 100 kJ/mol was chosen. For furniture, painting and sculpture, 70 kJ/mol was chosen to emulate the yellowing of varnish.

BIOLOGICAL DAMAGE

General description

The sources that provide insight into **IPI**'s calculations generating the mould risk factor (MRF) are limited (eClimate Notebook 2022), such that most of the information below is based on interpretations of the results generated by the tool. MRF is an accumulative metric that increases over time, if the temperature and humidity are high enough. The calculation is based on the behaviour of xerophilic mould and mildew. These are relatively common, resilient types of mould (tolerant of drier conditions and able to remain dormant for a relatively long period of time).

The calculations from **TUe** are far more transparent and are based on data from experiments with 20–30 types of common mould found in buildings and 10–20 types of toxic mould (Sedlbauer 2001). Two calculations are performed, one assumes that the surface type itself is nutritious for fungi, and the other that the porous nature of the surface allows it to store nutrients (e.g. dust).

For each T, the RH corresponding to each germination curve is calculated. The measured RH is compared to those calculated RH values. As soon as one of the RH curves exceeds the calculated RH, the mould germination factor (total continuous excess period of a curve divided by the time for spore germination specified for that curve) is determined. After the 8-day curve is exceeded for 8 successive days, the value is set to 1, indicating that the spores will germinate and will be able to grow.

For each combination of T and RH after germination, the growth rate, which is an integer between 0 and 5, is determined. Lastly, these growth rates are summed. The outcome is the total amount of mycelium growth (in millimetres) during the measurement period. If this amount is more than zero, there is a high risk of fungal growth.

Similarities

Biological damage is usually due to either mould or infestation, but all metrics consider the first factor only. This risk can be understood as the risk for germination and the rate of mould growth after germination. These metrics are most realistic in micro-climate environments or when T and RH are measured at the exact spot where the mould risk needs to be calculated. They both express that high RH and T values over longer periods of time increase the risk of mould growth.

Specific to mould development is that spores can remain dormant for a certain amount of time and become reactivated when a certain threshold is passed (depending on the timespan/range, T and RH). Both metrics take this into account.

Differences

Since there is a lack of details for the calculations of the MRF, a consideration of the main differences is limited to the material testing taken into consideration and the visual results that are generated.

CONCLUSION

Mechanical preservation metrics

With IPI's use of %DC and EMC, calculations on the back end have become more complex, with more variables being considered. The steady continuation of mechanical testing since 1994 has contributed to a more detailed understanding of (especially) wood and wood coatings (gesso or other) and their mutual interactions. Therefore, the analysis of mechanical risk can be considered as more diverse and specific than the other metrics.

Overall, TUe and JH provide more realistic results for mechanical damage to new or fully restored materials. TUe has adopted a more experimental approach, while JH uses a model that allows for a more detailed analysis based on the object's composition. IPI's metrics suffer from their main advantage: being non-specific. The analysis is therefore more complex (in the interpretation of the results) and, at the same time, more general. Additionally, the use of EMC_{max} for metal objects is a questionable choice.

Chemical preservation metrics

All preservation metrics mainly express the growing risk of chemical decay at higher temperatures. The PI and TWPI suffer mainly from their reference to acetate film, a relatively sensitive and specific material. Furthermore, their performances at low and high humidity are not realistic. LM has the advantage of expressing climate-related damage numerically and relatively, compared to a set temperature and relative humidity. It allows for a more nuanced comparison of results. However, unlike PI and TWPI, materials with very high or low sensitivity to humidity are not well represented.

Biological preservation metrics

Biological preservation metrics only consider mould development and ignore the influence of other types of biological damage. TUe uses a slightly more complex model that accounts for the germination time and mycelium growth of around 40 common (indoor) or toxic types of mould (Sedlbauer 2001).

There is no ubiquitous metric to determine the state of conservation of an object in relation to its environment. Each metric has its own strengths and weaknesses. It is therefore important to understand their respective limits and advantages. Nonetheless, because heritage collections are very diverse, preservation metrics will remain a limited analytical expression of the risk to individual objects. However, they can help to make decisions about the conservation environment, diagnose problems and serve as an indicator of potential damage.

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