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A CONDITION MODELLING TOOL FOR CULTURAL HERITAGE OBJECTS

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Abstract

A modelling tool was developed, as a tutorial and for research purposes, to predict the future condition, lifetime, and time before repeated conservation intervention for cultural heritage objects, depending on their historical condition, present conservation and changes in the environment. Model application was illustrated for a locomotive exposed outdoor at the Warsaw Railway Museum, Poland, and for the Oseberg Viking ship in the Museum of Cultural History in Oslo, Norway. The modelling suggested, tentatively, that the lifetime without future conservation of the locomotive surface would be from 6 to 30 years, but that the object could last many hundred (~800) years. To maintain the locomotive in the present condition conservation intervention would be needed every seven to 14 years. Shielding of the locomotive from precipitation could increase its lifetime, and time between conservation interventions, with 40%. One present conservation intervention could increase the lifetime with 20%. The lifetime of the Viking ship was suggested to be from 74 to 234 years. Conservation intervention was suggested every 15 to 66 years. Improvement of the air quality in the museum could increase its total lifetime, and time between conservation interventions, with 6%. One present conservation intervention could increase the lifetime with 26%. The most critical risk factor for the future preservation of the objects, excluding possible risks for sudden catastrophic events, was found to be to rate of any accelerating degradation processes.

Keywords: *Cultural heritage objects; Condition modelling; Condition assessment; Conservation; Preventive conservation; Environnemental impact; Dose-response equation; Air quality.*

Introduction

It is important for institutions and individuals, who have valuable cultural heritage objects in their custody, to understand the risk to the objects from the environment, and how they can protect the objects in the best way against future damage. This understanding should be based both on evaluation of the past and present object condition and on the expected future environment for the objects. From characterization of the past to present change of object condition, the historical rate of damage to an object can be deduced.

This work presents a tool assistant for the assessment of environmental risk to heritage objects and their likely future condition. The tool was developed both to be a tutorial to guide thinking about, and to assist in actual, environmental risk and condition assessment. The modelling tool only calculates a generalized degradation rate, future condition and lifetime. The tool uses input from detailed conservation investigations, and can complement such investigations, but does not itself provide physical object information. Heritage objects are often

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subject to different more or less frequent and invading environmental stresses and to direct and preventive conservation interventions. Their present condition is a results of complex past histories of environmental and human impact. Detailed descriptions of this past are usually needed to understand the condition of objects. Such qualitative and quantitative investigations, analysis and descriptions can be found in the conservation literature. See for example Wiłkojć [1].

The presented tool was, by purpose, not developed to a higher level of complexity, for example by including more options for materials or elements (apart from the "structure" and "surface") or the effects of more human interventions. By keeping the model simple it can give a first guidance and a complementary assessment, which can be improved by applying more exact input supplied by other methods of investigation, analysis and measurement.

Method

General condition assessment for cultural heritage objects

The historical damage that affects an object can have both intrinsic and environmental causes. The environmental degradation is caused by the interaction between the object and the physical, chemical and biological influences in its surroundings, which include such diverse factors as light radiation, climate, air pollution, fungi and physical impact. When assessment of the future likely condition of an object is based on its historical condition, all these effective degradation factors can be included.

The conditions of heritage objects in collections are very different. Some have suffered little through time or have recently been restored or conserved, and are in good condition. Other objects are much degraded, to the limit of becoming totally damaged and lost. The present condition of any object can be suggested to represent some percentage of its "new" condition, which could be for example when it was newly produced, just acquired, or freshly restored. The assessment can be, for example, a qualitative judgement about the total object condition or a quantitative assessment of one or more well defined properties. The difference between the "new" (condition = 100%) and the present observed condition (< 100%) would then represent the damage. Alternatively the "new" condition could also include the possibility of previous degradation to a condition of less than 100%. When an object approaches total damage or loss its condition would be close to 0%. The assessment of physical condition addressed in this paper should be distinguished from discussions about value and significance of objects [2].

Simple visual inspection and handling can give much information about the condition of a heritage object, especially when comparison to a similar well preserved or conserved object is possible. The condition could, for example, be recorded along a semi quantitative scale from the less to the more degraded. Such descriptive categorizations of properties are commonplace [3, 4]. A simple example of method that can combine qualitative, semi quantitative or quantitative techniques is the comparison of object colour with standard colour scales. The colour evaluation can be made by direct visual judgment and ranking, or by some instrumental method and numerical ranking.

An advantage of combined qualitative, semi quantitative methods over quantitative single parameter measurements may be that they can give better assessment of the total object condition with much less use of resources. Qualitative and semi quantitative methods do however have inherent limitations. They may lack well fixed references and the detection by visual observation or handling of early degradation or of particular forms of degradation, such as e.g. structural degradation which cannot be seen on the surface of an object, may be difficult. Therefore, instrumental techniques which measure chemical or physical properties are often used for early and detailed detection of degradation. Such techniques will often give precise values for particular degradation parameters. However, to understand critical properties related to object condition and risk, the selection of which properties to investigate, is essential.

Heritage objects are often unique objects of high value. Any deterioration can signify a large loss of value and its early and correct assessment is important to implement appropriate preventive and object conservation. Different approaches should probably be used depending on the need to provide initial information about objects, or to investigate particular objects in detail. Complicated and expensive instrumental and, or laboratory methods can be very useful research tools, but general condition assessment, as presented in this paper, will profit from tools that can realistically be used in the field and, or are simpler and less expensive, and are thus more likely to find widespread application. The increased accessibility of advanced instrumentation that can be used in the field has decreased the gap between these approaches [5].

The application of dose-response functions to determine future object condition

In some cases the future expected object condition can be calculated from a dose response-equation. Environmental dose-material response relationships relate the individual environmental influences quantitatively to their impact, i.e. the expected damage, on the materials:

$$\textit{Object condition} = f(\textit{environmental dose}) \qquad (1)$$

Some quantitative dose-response equations, for example for atmospheric corrosion damage, has been derived. With these equations the conservation-restoration cost due to impacts of air pollution and climate can be calculated, mapped and compared with threshold levels [6, 7]. Good dose-response equations are, however, only available for a smaller selection of cultural heritage materials.

Also, available dose-response equations can be difficult to use to assess the future object condition, for several reasons.

Dose response equations may be derived from experimental samples that are different from the objects. Atmospheric chemical weathering on small stone samples, which may have been exposed for only a few years, is likely to be different from long time weathering on real large building façades. Corrosion crusts that change the degradation mechanism and rate may develop differently on the facades. Environmental influences such as frost, salt crystallization and biological growth may have less impact on experimental samples, than on more complex facades.

It may be difficult to relate the response parameter to the object condition, due to uncertainty about the practical importance of the response parameter, or due to the complexity of the objects.

For example, it has been observed that exposure of newly applied varnishes to NO_2 and organic acids increase the oxidation of the varnishes. This is measured as an increase in the amount of triterpenoids in the varnishes and in physical characteristics such as glass transition temperature, which indicates stiffening of the varnish. These effects could affect the appearance of a painting, the time before the object needs re-varnishing and the ease with which the re-varnishing can be performed [8, 9]. However, it is difficult to measure these parameters outside of the laboratory and relate them to properties that can be more easily observed and used in condition assessment.

The complexity of objects can make it difficult to calculate their future condition from dose-response equations. A small amount of surface corrosion on objects with more complicated surfaces and valuable surface features, such as reliefs and ornaments, can be more damaging than on a copper roof. For more structurally complicated objects, e.g. made from several different materials by different working techniques etc., it can be difficult to realistically calculate the expected condition by the use of dose-response functions. Useful dose-response equations may not exist for all the materials, and the environmental impact on the structure and combination of materials may be different from that on the separate materials.

In practice conservators therefore need simpler tools, than dose-response equations, to easily assess the likely effect of environments and conservation action on future object condition. Such a tool could combine available information about the historical and likely future environment for an object with assessment of the historical, present and likely future condition of the object.

The application of the historical degradation rate to determine future object condition

The likely future condition of an object can be derived from information about its historical environment, and its past and present condition, by linear extrapolation of the past degradation rate into the future considering possible changes in the environmental impact. The degradation rate may however not be constant with time. The degradation of a fresh surface can be fast, but slow down with time, as is typical for atmospheric corrosion [6]. On the other hand, the degradation rate is usually increasing when a protective coating is damaged, or when a structure has lost its initial integrity [10, 11]. Assessment of the future likely degradation, based on historical records from extended, rather than short, periods of time, decades or centuries, would often give more realistic values for the expected future condition. Fig. illustrates schematically the historical change of condition of the Nidaros cathedral in Trondheim, Norway, when maintenance was not sufficient to preserve it (1150 -1800), due to a single catastrophic fire (1531), due to recent restoration (1880-2000), and into the future depending on conservation action and adaptation to climate change (2000-?). The figure illustrates the possibility to predict long time average degradation, but obviously, not sudden events.

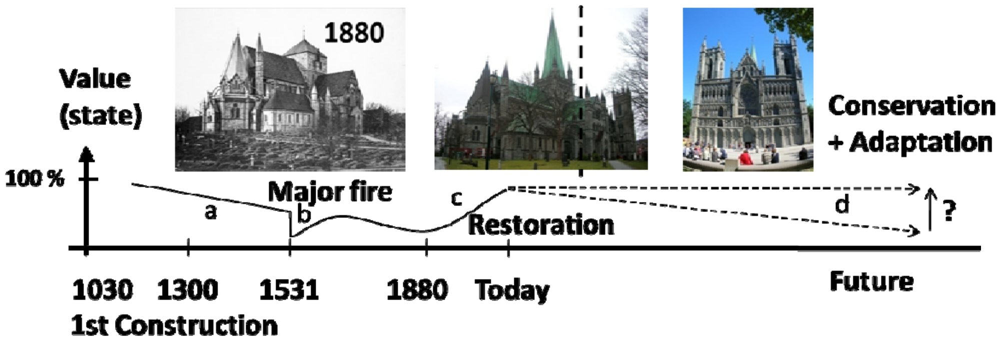

Fig. 1. The historical condition of the Nidaros cathedral in Trondheim, Norway, due to lacking maintenance (a), a catastrophic event (b), restoration (c) and future possible scenarios (d). The vertical dotted line distinguishes the front part (photo to the right) which was added during the conservation from the 1880s.

The larger the object the more needed may be to separate condition assessment of the different structural, for example building-, elements. It would then usually also be possible and, or necessary, to implement conservation and restoration element by element.

Derivation of a model for assessment of future likely object condition

The modelling tool considers the long term gradual impact of the environment on an object by frequent repeated events and, or more or less fluctuating influences, and not due to singular e.g. catastrophic events. It is distinguished between the surface and the structure of the object. The immediate impression and protection of an object is offered by its surface, whereas the structure gives form and support. Obviously, the condition of the surface and structure are closely connected. However, as the surface and structure offer different qualities to an object, this seems like a useful first distinction that can “guide the thinking” about damage risk, vulnerability, object condition, and conservation priorities. It is suggested here that the object condition, *C(obj)*, is an undetermined function of the condition of the surface, *C(sf),* and the structure, *C(st),* and that the condition of an object can be evaluated by condition assessment of the structure and surface:

$$C(obj) = f\,(C(sf),\ C(st)) \qquad (2)$$

The modelling assumes that the object exists as long as some of its structure is present, and as the surface cannot exist without the (some) structure, that the lifetime for the object will always be equal to that of the structure. The (heritage-) surface may, however, be lost before the structure is lost.

The likely future conditions of the surface *C(sf),* and structure, *C(st)*, can be derived by simple extrapolation of the past degradation rate into the future, considering possible changes in the future environment:

$$C(sf,\ st)_p = C(sf,\ st)_{h.ref} - B_h \cdot t_h^x \qquad (3)$$

$$C(sf,\ st)_f = C(sf,\ st)_p - B_f \cdot t_f^x \qquad (4)$$

where $C(sf,\ st)_{h.ref,\ p,\ f}$ are the historical reference (*ref*), present (*p*) and future (*f*) condition of the surface *(sf)* and structure *(st),* in%. The historical reference condition could be, for example, for the year when a museum object was included in a collection. *B* is the rate of change of condition with time, *t*, and *x* is a power factor, which determines how the condition changes with time. When $x = 1$ the change is linear. When $x < 1$ the change of condition is becoming less with time, as for example when corrosion processes slow down after formation of a patina. When $x > 1$ the change of condition increases with time, as when structural disintegration of for example a building increases the impact of the environment and the rate of damage. It is difficult to know the value of *x* for real objects. For some corrosion processes the values of *x* are available from published dose-response functions [6, 7]. It is likely that $x > 1$ for many objects, as some initial damage will make them more susceptible to further damage impact. Empirical studies or experiments would in most cases be needed to find the value for *x* for specific degradation processes. When no data are available from the literature the best starting point is probably to set *x* equal to one, and then discuss the consequence for the future condition of different values for *x*. Other formulas for the condition dependence on time, than (3), may be used.

When the historical reference condition, $C(sf,\ st)_{h.ref}$, the present condition, $C(sf,\ st)_p$, and time between them, t_h, have been determined then the historical rate of change, B_h, can be found from the rearrangement of (3) for any value of *x*.

If the environment is not expected to change then $B_f = B_h$, and the future condition, $C(sf,\ st)_f$, is calculated from (4). If the environment is expected to change, for example due to active mitigation measures to improve it or relocation of the object, then the future condition at any time, *t*, is calculated using the future rate of change, B_f, which is calculated by:

$$B_f = B_h \cdot (E_f/E_h) - \Delta B\,, \qquad \Delta B = (B_f - B_h)(1 + f_E), \qquad 0 \leq f_E \leq 1 \qquad (5)$$

where E_h and E_f are the historical, ideally measured, and future expected impact environments, i.e the levels of the environmental factors that cause the degradation. Finally, the change in the past to future environment described by E_h and E_f may not represent all the impact factors, which explain the past degradation. Therefore (5) allows for the adjustment of the past to present rate of change in condition, ΔB, by the fraction, f_E, of the total degradation, which is explained by the environmental impact factors E_h and E_f. If $f_E = 1$ then the factors, E_h and E_f, are judged to cause the total degradation. If $f_E < 1$ then the factors, E_h and E_f, are judged to cause only a part of the total degradation. A change in the value of the factor of E_h to that of E_f will then, correspondingly, give less change in the effect on the future condition.

The model allows for one instant change in condition at the present time, due to a conservation intervention (or other effect). The likely time interval until the next expected conservation intervention can then be calculated. This is then determined by the future point in time when the condition has again been reduced to the similar as present "non-conserved condition". The expected future condition, at any future point in time, and lifetime of the object, with and without the conservation intervention, are calculated. When $x > 1$ it is assumed that a conservation intervention gives an improved condition with a degradation rate reduced to the rate similar to that at the historical starting point (reference time). As, for example, when application of new paint offers increased protection for some time. When $x \leq 1$ it is assumed that the degradation rate does not change due to a conservation intervention, which implies that the conservation intervention does not "open up" the structure and increased the exposure and degradation, as can happen for example if a corrosion patina is removed.

It is important to stress that the model is a "condition evaluation tool" and does not claim to predict the real future of objects, which will usually be affected by repeated interventions and other occurrences. Objects will often be subject to many smaller and larger, more or less frequent, future interventions. Objects can also be subjected to particular occurrences and dramatic events that the modelling cannot, obviously, predict.

Modelling results

The model was applied tentatively to two objects. A locomotive located at the Warsaw railway museum and the Oseberg Viking ship at the Museum of Cultural History in Oslo (Fig.). The modelling is based on information about the objects from open public sources and from some acquaintance with them from environmental monitoring in their locations [12, 13]. It must be stressed here that these modelling examples are not based on the thorough investigations of the historical and present condition, the conservation history and the environmental impact on these objects, which would be needed to provide more precise values for the input data and results for the condition assessment. Such investigations would most probably lead to modification of the input values and results. It is mainly the aim here that the presented modelling results will illustrate the application of the tool, but also that they can give useful information about the two objects that can stimulate further investigation into their condition and conservation. The two objects are shown in Fig..

Fig. 2. Locomotive at the Warsaw Railway Museum (left) and the Oseberg Viking Ship (right)

The steam locomotive at the Warsaw Railway Museum is reported to be a locomotive of the TKh1 series no. 13, manufactured in Germany by Orenstein & Koppel AG, Berlin-Drewitz in 1920. It was built for a local line Weidenau-Deuz. In 1942, it was transferred to the Upper

Silesian industry. Since February 1955, it was used in Zakłady Celulozowo-Papiernicze (Pulp and Paper Works) in Włocławek. In 1973, it was handed over to the Railway Museum [14].

The Oseberg ship was built from oak around 820 AD. The ship was excavated in 1904 from a mound in south eastern Norway. The hull was broken into hundreds of small pieces by the great pressure from the mound above, but it was possible to reconstruct it with a high degree of accuracy. The carvings of the stem and stern are the most beautiful and extensive ever found on any Viking ship. The art and craftsmanship is outstanding and have given name to the "Oseberg style" and the "Gripping beast" style, one of the main art categories from the Viking period. It took 21 years to prepare and restore the ship and most of the finds. The ship was dried out very slowly before being put together. Great emphasis was placed on using the original timber and more than 90% of the fully reconstructed Oseberg ship consists of original timber. The ship was rebuilt in University shelters in the center of Oslo. In 1926 it was moved to the new built Viking ship museum located at the small peninsula of Bygdøy in Oslo, where it has been located since then, most of the time in open exhibition [15, 16]. The input values used for the modelling are presented in Table 1.

Table 1. Input data to the condition modelling for two objects

Object	**Locomotive at Warsaw railway museum**		**Oseberg Viking ship in Oslo**	
Input parameters	Structure (object)	Surface	Structure (object)	Surface
Condition at acquisition to the museum (possibly after restoration) (%)[1]	100	100	100	100
Present condition (%)[2]	70	50	70	80
Condition after possible present conservation (%)[2]	75	85	75	90
Age in the museum. (years)	42	10	89	89
Environmental quality in the historical (past) exposure location – in museum (%)[1]	100	100	100	100
Time until assessment of future condition (years)	100	100	100	100
Possible improved future environmental quality relative to 100%[3]	51	51	49	49
Fraction, f_E, of change in object condition likely to be explained by the environmental parameters suggested to be modified[2]	0.8	0.9	0.1	0.2
Power factor, x. = Rate of change of condition with time. Values in brackets are for the non-linear modelling (see Table 3) [2, 3]	1 (2)	1 (0.54)[4]	1 (2)	1 (2)

[1] Set = 100%
[2] Tentative suggestion
[3] See Table 2 and explanation below
[4] [7]

The values for the historical as compared to the probable future impact environment, E_h and E_f, provide a numerical comparison of the environmental loads that are known (or suspected) to have significant influence on the degradation of the objects. The change in object condition, *B*, will be a function of the influencing environmental dose exposure and impact. For example, if dust deposition and soiling is judged to be the major cause for degradation of an object, then its future condition can be predicted from information about its past and present condition and the past and future dust levels.

For the locomotive, which was located outdoors at the Warsaw Railway Museum, it is suggested that the degradation rate was likely to correlate with ISO corrosive categories for carbon steel. The levels of air pollution at the Railway museum location were found to be relatively low in 2011, equal to an ISO 9223 level “zero” [13, 17]. The corrosion of steel objects stored outdoors at the Railway museum, would then mostly be determined by the time of wetness, which is given by the amount of precipitation. Thus, for the locomotive the time of wetness was used to represent the main degradation factor in the historical and possible future location for the locomotive.

The gradual degradation of the Oseberg Viking ship is likely to be caused by several influences, such as the load of the object itself, the handling of the object, vibrations, physical and chemical changes in the structure related partly to previous conservation treatments, influences of temperature, humidity, light, UV radiation and air pollutants, and fluctuations in these environmental factors. It could be possible to construct a numerical index for the degradation impact based on these many factors. The assessment performed here will however illustrate the impact of air quality only, and apply typical values for E_h and E_f, representing the impact of air quality on organic objects. For this purpose typical levels for environmental impact reported for the so-called EWO (Early Warning Organic) dosimeter, which is sensitive to nitrogen dioxide, ozone, UV light and temperature [18], and measures for the dust exposure, were used. A change in the measurement results for the EWO dosimeter and for dust deposition in the Viking ship museum close to the Oseberg Viking ship would signify a change in the air pollution load on the Viking ship. Table 2 gives the environmental levels for past and possible future locations for the two objects.

Table 2. Environmental impact levels used for the assessment of the effect of change of environment on the future condition of the locomotive at the Warsaw Railway Museum and the Oseberg Viking ship

Locomotive at the Warsaw Railway Museum		Oseberg Viking ship	
ISO 9223 corrosivity category	Mass loss of carbon steel (g / m^2 year) - corresponding to (Time Of Wetness, as annual hours)	EWO: Typical locations and corresponding measurement values (ΔE = change in UV absorption through the dosimeter polymer [18])	Dustiness (% coverage)
1. Very Low (indoor)	< 10 (< 10)	Archive store, < 1[a]	Clean, < 4%
2. Low (outdoor sheltered)	10-200[a] (10-250)	Purpose built museum, 1-4[a]	A bit dusty, 4-7%[a]
3. Medium (outdoor unsheltered)	200-400[a] (250-2500)	Historic house museum, 4-6	Fairly dusty, 7-9%
4. High	400-650 (2500-5500)	Open indoor structure, 6-9	Very dusty, > 9%[a]
5. Very high	650-1500 (5500-8760)	External store, 9-13	

[a] *Input values to the modelling. See derivation in text.*

Based on climate data from the Warsaw Targowek meteorological station the Time Of Wetness (TOW), calculated as the number of hours where RH > 80% and temperature > 0ºC [17], for Warsaw in the year November 2010 to November 2011, was found to be 2755 hours per year [19]. The total annual precipitation at the Targowek station was 542mm in 2011 [20]. The annual average total precipitation in Warsaw is about 515mm [21]. Thus the TOW calculated for November 2010 to November 2011 should be quite representative for the average Warsaw meteorological situation.

The locomotive at the Warsaw Railway Museum has historically been located outdoors freely exposed to precipitation. In the modelling it was assumed that in the future the locomotive could be relocated to a shelter with a roof. This would probably reduce the TOW from the present 2755 hours per year to 250 hours per year, representing a reduction in the corrosion rate from 400 to 200g/m^2 year, equal to ~50% (Table 2) [17]. The atmospheric corrosion of the locomotive is expected to represent a major part of the degradation impact, and the impact of the Time of Wetness relative to the total degradation, f_E, was set to 0.8 for the structure and 0.9 for the surface. For the locomotive the calculation was performed with a power factor, x, for the time dependence of the degradation equal to one, assuming a constant linear degradation rate, and then equal to two for the surface and equal to 0.54 for the structure. The value of $x = 2$ represents an initially protecting paint layer. The value of $x = 0.54$ represents establishment over long time of a protecting corrosion layer on carbon steel [7], which would offer some protection to the locomotive and reduce the degradation rate.

EWO dosimeter and dust deposition measurements were performed inside the Oseberg Viking ship from February to May 2010 (Fig.), giving a EWO results value of 2.5 ± 0.5 ΔUV-light adsorption units (ΔE), and dust coverage after three months of 9.7% [12].

Fig. 3. Air quality measurements in the Oseberg Viking ship, spring 2010.

The Viking ship museum has natural and quite high ventilation. Although the level of air pollution impact measured by the EWO dosimeter was quite low the dust accumulation on the ship deck was very high. An improvement in the air quality could be possible for example by making changes to the building and its ventilation system, by changing the natural ventilation regimes in the present building, by changing the visitor regimes, by shielding off the ship from drafts and visitors, etc. It was assumed that a future improvement of the EWO level from 2.5 to 1, which would be equal to 60% reduction, and of the three months dust deposition from 9.7% to 5% coverage, which would be equal to 48% reduction, could be achieved (Table 2).

It was assumed that the dust deposition was the more critical factor of the two, representing 75% of the load, whereas the EWO-air quality would then only represent 25% of the load. The weighted average improvement of the air quality, representing these two impact factors, would then be 51%. However, most of the historical degradation of the Oseberg Viking ship as a museum object was probably caused by other factors than air quality. An exact judgment about relative contributions of the impact factors is hard to make, and it is not the intention, or possible, here, to make an assessment with high certainty. The impact, f_E, of the air quality, represented by the EWO and dust measurements, relative to the total degradation, was set to 0.1 for the structure and 0.2 for the surface (Table 1). For the Oseberg ship the power factor, x, for the time dependence of the degradation, was set equal to one, assuming a constant linear degradation rate, and then equal to two, assuming an acceleration of the degradation with time.

The calculation of the future likely condition for the two objects, without and after a present conservation intervention, and for the situations without and with future improvement of the environment, was performed in an Excel worksheet according the derivation above with the input date from Table 1. By performing the calculation both for a linear (x = 1) and a suggested non-linear ($x \neq 1$) change of object condition, results intervals were obtained, which illustrates the uncertainty and is more likely to include the future actual condition of the objects. Table 3 gives the modelling results for the two objects.

Table 3. Modelled present and future object condition, time until repeated conservation and total lifetime until the object is lost, for a locomotive at the Warsaw Railway Museum and the Oseberg Viking ship. Values in brackets are for a situation without any future change in the surrounding environment of the object. "With conservation" signifies one present, and no future, conservation interventions.

		Future object condition - in 100 years (%)		Time until repeated conservation (years)		Future lifetime until object is lost (condition = 0) (years)	
		Model					
Without (-) or with (+) present conservation	St = Structure (object) Su = Surface	Linear	Non-linear[1]	Linear	Non-linear[1]	Linear	Non-linear[1]
Locomotive at Warsaw Railway museum							
-	St	27 (0)	53 (42)			161 (98)	740 (350)
-	Su	0 (0)	0 (0)			18 (10)	10 (6)
+	St	32 (4)	58 (47)	12 (7)	24 (14)	173 (105)	820 (386)
+	Su	0 (0)	0 (0)	13 (7)	11 (8)	30 (17)	20 (14)
Oseberg Viking ship							
-	St	38 (36)	0 (0)			219 (208)	78 (74)
-	Su	60 (58)	17 (10)			396 (356)	120 (112)
+	St	43 (41)	39 (37)	16 (15)	37 (36)	234 (223)	146 (142)
+	Su	70 (68)	67 (65)	50 (45)	66 (63)	446 (401)	200 (190)

[1]The non-linear modelling used the power-factor (*x*) given in the brackets in Table 1.

Figure 4 and Figure 5 show condition modelling diagrams for the Locomotive at Warsaw Railway museum and the Oseberg Viking ship.

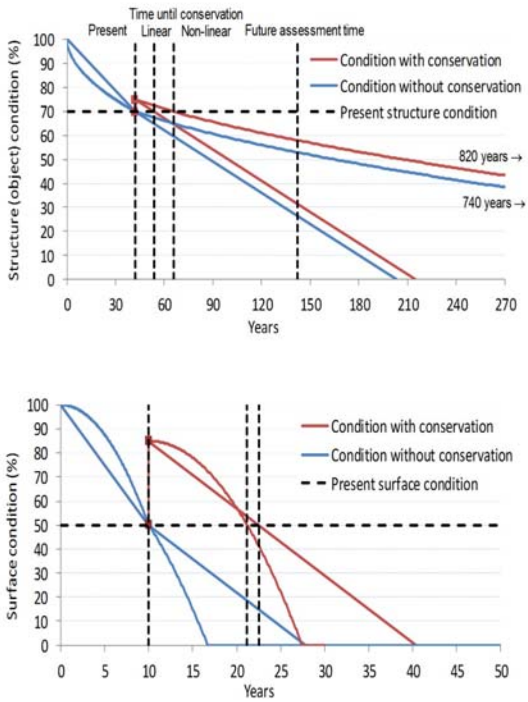

Fig. 4. Condition results diagrams for the Locomotive at Warsaw Railway museum, showing the assessment of past and future condition for the object structure and surface, based on the input from Table 1.

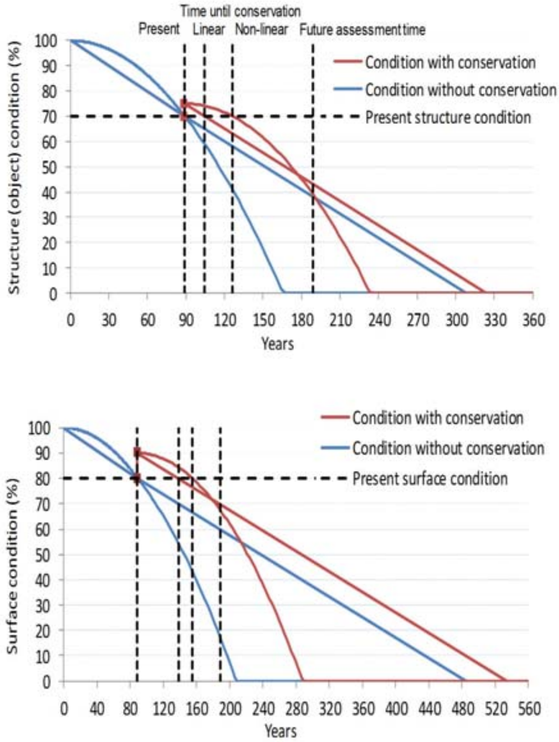

Fig. 5. Condition results diagrams for the Oseberg Viking ship, showing the assessment of past and future condition for the object structure and surface, based on the input from Table 1.

Discussion

The most critical factors in the modelling prediction of the future lifetimes are the historical condition records, which determine the rate of change of condition with time, B, and the time dependence of the degradation rate, i.e. the *x*-factor (3, 4). If historical records of condition are available from more (than one) points in time, then the values of *x* and *B* can be found from fitting the model equation (3) to the recorded condition values. This should give better predictions. If only the present condition as compared to some historical initial condition can be determined, or suggested, as in the modelling examples for the locomotive at the Warsaw Railway museum and the Oseberg Viking ship, then the time dependence, *x,* must be determined from available dose-response equations for materials, or some approximation must be made. However, dose-response equations are not generally available for more complex objects. Without application of reliable historical records of condition, results values from predictions into the future should probably not claim to have high certainty, but rather to report ranges of probable lifetimes depending on the degradation rate factor, *x*, open for the reader to evaluate. Such ranges of lifetimes (depending on probable values for x, as given in Table 1) are reported in this paper, and summarized below in the conclusion chapter, for the locomotive at the Warsaw Railway museum and the Oseberg Viking ship.

The large variation in the predicted lifetimes, and time until conservation, of the structure of the locomotive at the Warsaw Railway museum, reflect the uncertainty about the damage mechanism (i.e. the value of the time factor, *x*). It is very important to know if the locomotive is subjected to some accelerating damage process ($x > 1$) or only to the slow corrosion processes ($x < 1$). Probably some structural collapses can happen as the corrosion process progresses to give an intermediate lifetime. The short lifetimes predicted for the surface, as compared with the structure, indicates the large importance of the surface conservation. The structural degradation probably happens especially to less accessible parts with lacking surface protection. Figure 6 shows surface and structural corrosion of a locomotive at the Warsaw Railway Museum.

Fig. 6. Surface corrosion (left) and structural corrosion (right) on a locomotive at the Warsaw Railway Museum.

If there was proper continuous surface protection on all the outer and inner parts of the locomotive exposed to the atmosphere, it is likely that the structural damage would be less.

The modelling suggested that non-linear increasing degradation of the Oseberg ship could totally damage it in about 100 years, whereas total damage would only happen 200 to 400 years from now if the degradation is steady and linear, with the structure being most at risk. This reflects the assumed better present state of the surface than the structure. However, as the surface is not likely to be preserved, or only partly preserved, without the structure, the lifetime prediction of the structure (~100-200 years) is more relevant. Relatively frequent need for conservation of the structure is suggested. It is a critical question how and if such structural conservation is possible. As for the locomotive, it is very important to understand the accelerating degradation processes, which may be critical for the preservation of the ship, to optimise its future conservation and lifetime.

Conclusion

The locomotive at the Warsaw Railway museum

The modelling of the condition of the locomotive at the Railway museum in Warsaw suggests that the likely lifetimes of the structure (object), without present or future conservation, would be between 98 and 350 years, and that this could change to 105 to 386 years by one present conservation intervention. If the locomotive is relocated to a roofed shelter the lifetime predictions are 161 to 740 years without present conservation, and 173 to 820 years with present conservation. The likely lifetime of the surface is suggested to be shorter than this: Between six and 10 years without present conservation, and between 14 to 17 years with present conservation. If the locomotive is relocated to a roofed shelter these values for the surface change to, between 10 and 18 years without present conservation, and between 20 to 30 years with present conservation. To maintain the locomotive in the present condition it was suggested that conservation intervention would be needed every seven to 14 years for the structure, and every seven to eight years for the surface. The modelling suggested that shielding of the locomotive from precipitation could increase its total lifetime without future conservation interventions, and time between conservation interventions, with 40%, and that one present conservation intervention could increase the lifetime of the surface and structure with 45% and 8%, respectively.

The Oseberg Viking ship

The modelling of the condition of the Oseberg Viking ship in Oslo suggests that the likely lifetime of the structure (object), without present or future conservation, would be between 74 and 208 years, and that this could be increased to 142 to 223 years by one present conservation intervention. If the air quality in the Viking ship museum is improved, the lifetime predictions are 78 to 219 years without present conservation, and 146 to 234 years after present conservation. The likely lifetime of the surface is suggested to be longer and span a wider interval than this: Between 112 and 356 years without present conservation, and between 190 to 401 years after present conservation. If the air quality is improved these values change to, between 120 and 396 years without present conservation, and between 200 to 446 years after present conservation. The likely time before a new conservation intervention is needed, is suggested to be between 15 and 36 years for the structure and between 45 and 63 years for the surface. The modelling suggested that improvement of the air quality in the Viking ship museum could increase its total lifetime without future conservation interventions, and time between conservation interventions, with 6%, and that one present conservation intervention could increase the lifetime with 26%.

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