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RESEARCH ARTICLE

Predicting Future Condition and Conservation Costs from Modelling Improvements to the Indoor Environment: The Monumental Munch-Paintings in the University of Oslo's Aula Assembly Hall

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The aim of this work was to assess how improvements to the indoor environment could affect the future condition, frequency and costs of major conservation-cleaning campaigns on the monumental paintings (1909–1916) by Edvard Munch, centrally located in the Aula assembly hall of the University of Oslo. A lower soiling rate is expected to reduce the need for frequent and major cleaning campaigns. Estimations were performed using the freely available NILU-EnvCul web-model. The conservation of these large, mostly unvarnished, oil paintings is challenging, and it is important to understand the potential benefits of preventive conservation measures. The results from the model suggested benefits from preventive conservation in protecting the paintings, and as a cost-efficient strategy to reduce the soiling and cleaning frequency. The model results indicated that an improvement in the indoor air quality in the Aula, of 50–80% as compared to the 1916–2009 average, would increase the time until the next similar major conservation cleaning campaign from approximately 45 years to between about 85 and 165 years. This should give a 45–70% reduction in the respective conservation costs. This saving was probably initiated by improvements in the recent past, before the last Aula campaign in 2009–11.

Keywords: Edvard Munch; Public paintings; Indoor environment; Condition prediction; Conservation costs; Modelling; Preventive conservation; Soiling

1. Introduction

Large efforts and resources are invested in invasive and preventive conservation to protect cultural heritage, such as the monumental paintings (1909–1916) by Edvard Munch, centrally located in the Aula assembly hall of the University of Oslo. This reflects the high value assigned to their societal benefits. The paintings are considered to provide non-material benefit in terms of their artistic value and by communicating historical-psychological, social and cultural expressions and insights. The benefits also include economic gain related to the presentation of Munch's art to an international and national audience, which contributes to the attraction and income of Oslo and Norway from tourism and other activities.

Conservation professionals generally use the term "cultural property" for objects that are considered particularly precious to humans (Appelbaum, 2013). Munch's Aula paintings can be considered a prime example of such cultural property. They are the only known monumental expressionist paintings that still exist in their original location (Berman, Pettersen and Ydstie, 2011), and they served as a backdrop for historical events such as the Nobel Peace Prize from 1947–89 (TNNI, 2018). The many types of value (historical, artistic, cultural, etc.) imply that they deserve to be preserved for as long as possible, and that at least in an ethical sense, they are the property of humanity (Appelbaum, 2013). But, due to the location of the Aula paintings in a public building, and the methods Munch used to paint them, there are issues that challenge their future preservation.

This paper presents a method and model, "NILU-EnvCul" (2017: http://envcul.nilu.no/), for calculating the preservation of condition and savings in costs for invasive conservation, obtained by implementing preventive conservation to reduce the negative impacts of the environment surrounding an object. In the development of appropriate strategies for the future care and preservation of the Munch paintings in the Aula, models such as EnvCul could be useful tools to demonstrate how the integration of preventive conservation measures can lead to more cost-efficient and sustainable management of these paintings in the long run.

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It is important to communicate the value of the conservation of the paintings to decision makers and the public in a simple way. This should improve awareness and prioritisation. Descriptions of conservation work, especially for prestigious and well-known objects such as the Munch Aula paintings, the Oseberg finds with the Viking ships, or the Nidaros (Trondheim) cathedral, in Norway, attract much interest and attention. With limited resources, prioritisation is essential to the development of suitable conservation strategies. What is "most suitable" is not just a political, but an economic and technical question. The political process will often, when the ownership is public or receives public support, be important in determining prioritisation of the conservation work and the budget. The choice of conservation techniques is a separate topic, which depends on budgets. Priorities are, presumably, largely based on cost-benefit considerations (see for example Naverud and Ready, 2002).

The cost analysis that was performed in this work must be seen in the larger context of benefits and valuation (Gierløff, *et al.,* 2017; Dahlin, *et al.,* 2013a). Decision makers acquire information about possible alternative conservation actions and their cost. At the University of Oslo they would be in the central University administration, which has an assigned art curator employed for the University Art Collection, and, ultimately, the national Ministry of Education and Research and national politicians who decide the budget for the University. The aim is, ideally, to achieve the maximum preserved "significance/condition" (Russell and Winkworth 2009, UNESCO 1972) with the least expense. The significance, value and benefit of cultural heritage is a large topic, which will not be further debated here. Suffice it to say, a benefit analysis is expected to compare benefits from activities between and within sectors by some explained/defined measures. A benefit analysis should give the basis for prioritisation. The perceived benefit will strongly influence the amount and distribution of conservation funding, within possible overall budget limits. A cost analysis will suggest the resources needed for conservation. The cost analysis should include evaluation of invasive and preventive, immediate and future, conservation actions.

Once prioritisation has been made, regular maintenance and preventive strategies are fundamental for long-term preservation (Lithgow and Lloyd 2017). Still, the conservation of cultural heritage objects often consists of remedial treatments that are carried out *after* damage has already occurred. In many cases, the extent and total cost of treatments could be reduced by improving environments, monitoring the condition of objects and conducting regular assessments of structural and aesthetic damage, such as the degree of soiling (Caple 2012, Nazaroff *et al.,* 1993, Thomson 1986). Different methods can be used to assess the degree of soiling. One significant challenge is the local variation in the distribution and amount of soil present on objects, such as large paintings. The most obvious method to assess the amount of soiling, would be direct visual observation and comparison with some standard, such as a grey-scale. The assessment could be made on the entire painting or on a selection of smaller areas of the painting to determine variation. To obtain more accurate results, some optical observation technique such as reflectometry could be used. Furthermore, various chemical analytical techniques could be applied to characterise the composition and abundance of compounds in the soil. The damage could then be addressed in the early phases of development, thus, limiting the need for major and invasive conservation campaigns/interventions, and reducing conservation costs, as shown by the EnvCul-estimations presented below.

The EnvCul model estimations are presented for the case of general long term soiling and related surface damage (the "extent of soiling") of the monumental Munch paintings in the University of Oslo's Aula assembly hall (**Figure 1**, see also UiO 2018). The "soiling" is defined here as the deposition of solid substances on the painted surface and accompanying changes in visual appearance. It does not distinguish between soiling caused by deposition of particles of different sizes from the air (such as ultrafine, fine and coarse particles (Grau-Bove and Strlič 2013)), or soiling that may historically be due to factors other than air pollution (see section on conservation history below). A simple distinction between soot and dust was made. The term "soot" is most often used to describe small, fine (mostly <1–10 μm in aerodynamic diameter) and dark carbonaceous particles. Such particles come primarily from outdoor pollution and combustion sources, such as industrial production, car engines and wood burning for domestic heating, but may also derive from indoor sources, *e.g.,* cooking and cigarette smoking. The term "dust" is generally used to categorise larger particles (>10 μm in aerodynamic diameter, and often much larger) having mostly indoor sources (Grau-Bove and Strlič 2013). It was not the aim of this work to physically characterise the airborne pollutants and soiling found indoors. It is, however, apparent that the observed soiling of the paintings was caused by both fine, dark "soot" particles and larger size "dust" of a lighter colour. In the text below the terms "soot" and "dust" are employed, as they are commonly used, to describe the soiling of these paintings.

There is much information in the scientific literature about indoor particles and dust, their characteristics and their impact on cultural heritage (*e.g.,* Anaf, *et al.,* 2015; Grau-Bove and Strlič, 2013; Daher, *et al.,* 2011; Lloyd, *et al.,* 2007; de Bock, *et al.,* 1996), the cleaning, treatment and conservation of soiled paintings, and mitigation and management strategies (*e.g.,* Wilson and van Snick, 2017; Ormsby and Learner, 2016; Mecklenburg, Charola and Koestler, 2010; Lithgow, *et al.,* 2005), including economic considerations related to housekeeping (Lloyd, Brimblecombe and Lithgow, 2007). But little information, and to our knowledge few case studies, is available about the relationship between the historical air quality, observed soiling, preventive mitigation actions and future predicted conservation costs for canvas paintings, which is the topic of this study.

Waller (2016) gives an overview of the status and general procedure for risk assessment, developed and being performed in different institutions (English Heritage; the ABC scales of the Canadian Conservation Institute; Heritage Preservation; the University of California Berkeley Library; the Cultural Property Risk Analysis

Figure 1: The monumental Munch paintings in the University of Oslo's Aula, seen during a concert performed in 1955. An uneven deposition of dirt can be seen on the left of the painting *History* in the form of dark, horizontal stripes. Photo Courtesy: Oslo Museum.

Method (CPRAM) of the Canadian Museum of Nature). He goes on to explain briefly the CPRAM model as being "the most fully developed and described model". The CPRAM model applies a system-based approach considering risk through the sources (*e.g.,* environment), paths (*e.g.,* environmental exposure) and effects (*e.g.,* environmental damage), through three main sub-systems of the collection management: development, preservation and use of collections. The methodology includes consideration of variability and random incidences/risks, and such factors as: facilities management (*e.g.,* building technical factors), collection care (*e.g.,* prioritisation between objects) and conservation science (*e.g.,* damage functions), which should "work together to characterise, identify, and manage risks". In this framework, the EnvCul model could be considered to belong to the preservation sub-system. It is suited to assess future condition improvements and conservation cost savings that could be obtained by inputing information about the historical condition and most probable past and future environmental impacts on an object (or property). The authors are not aware of similar freely available predictive web-models, which can be used from a very general level to detailed analysis of objects and properties, depending on the quality of the input data. As such, application of the model can provide information for the overall evaluation of risk and collection management, such as described by Brokerhof, Ankersmit and Ligterink (2017) and Michalski and Pedersoli (2016).

The Aula paintings have previously been used as a case-study in assessing the optimal period between conservation treatments of unvarnished paintings (Hutchings and Ashley-Smith, 2008). That study used data from the conservation records, supplemented by evidence from practical experience, to estimate inter-cleaning periods for the National Gallery, Oslo (and Tate, UK). The results suggested that the inter-cleaning period should be increased by a factor of three, from an average of once every 14 years in the past. The aim of the study was to recommend optimal realistic intervals for cleaning to reduce related risks for damage, such as abrading the surface or removing pigments.

Complementary to this, the current study assesses the increase in duration of major conservation-cleaning intervals and reduction in costs for invasive conservation that could be obtained by environmental improvement. This could be due to preventive actions, or for other reasons, such as implementation of air pollution health regulations. The study does not discuss possible improvements in invasive conservation practices.

A first version of the EnvCul model is freely available for users as a web-based model (EnvCul, 2017; Grøntoft, 2015). The model can be used as a tutorial or for detailed analysis, depending on the quality of the input data.

2. The monumental Munch paintings in the University of Oslo's Aula – historical condition and conservation

The material composition, condition and treatment history of the Aula paintings have been the subject of several publications in the last decades (see MAP 2017), which provides a context for the present study. Edvard Munch created his monumental Aula paintings over a period of seven years until they were mounted in the Aula assembly hall of the University of Oslo in 1916. Munch's work consists of eleven unvarnished oil paintings on canvas, which cover about 223 m^2 of the walls of the Aula. Their dimensions range from 4.5 × 1.65 m^2 for the two smallest paintings, up to 4.5 × 11.63 m^2 for the two largest. The paintings' location in a public building, large sizes and unprotected surfaces, make them especially vulnerable to factors such as environmental pollutants, adverse fluctuations in temperature and relative humidity, and mechanical stress. Their complicated conservation history is a testimony to the challenges involved in preserving cultural heritage, especially with regard to soiling and cleaning issues.

The Aula paintings have been remounted three times, in 1926, 1946 and 2010–11. In 1940 they were cut down during an evacuation and stored rolled until 1945/46, when they were marougflaged onto semi-rigid boards and re-mounted on the walls of the Aula (Frøysaker 2007). Subsequent surface cleaning, mainly by rolling bread loaf back and forth over the surface (until the loaf turned grey) took place approximately every 10th year until 1986 (Frøysaker 2007), when three of the paintings were cleaned (Frøysaker 2008). Despite the high frequency of cleaning, the soiling progressed (see **Figure 1**). By 2008 the degree of soiling was again considered unacceptable.

At the same time as the Aula-building underwent refurbishment (before the 200-year anniversary of the University of Oslo in 2011), a major conservation campaign (2009–2011) was initiated through the Munch Aula Project (MAP 2017, **Figure 2**). New investigations supported earlier observations (unpublished treatment reports 1973, 1986) that related the soiling and poor condition of the paint and ground primarily to the poor insulation of the paintings and indoor conditions of the Aula. An uneven darkening effect of soiling, similar to that reported in 1973 and 1986, was again observed (**Figure 3**) and the paintings were surface cleaned anew using dry polyurethane sponges (Frøysaker 2008, 2017). In addition to the surface contaminants from soiling, chemical degradation products in the form of non-visible zinc oxalates and metal soaps' formation within the paint, were also identified (Frøysaker, Miliani and Liu, 2011). The circulation of airborne pollutants, in combination with large seasonal variations in relative humidity (8–80% RH) and temperature, were considered driving-forces behind the soil retention and the formation of oxalates and metal soaps (Frøysaker 2008). Due to the historical application of a zinc white-containing coating to the *verso* of the canvasses in 1925–26, which is visible in some areas on the front of the paintings, the formation of zinc soaps and oxalates may be progressing across vast areas (Frøysaker, 2015; Frøysaker, *et al.,* 2015). In addition to these issues, other damage, such as water stains caused by former roof leaks, were also observed (Scharffenberg, 2014; 2015). Increased awareness of the devastating effect of soiling on the visual and chemical stability of the paintings meant that the presence of airborne pollutants had to be addressed. Historically, visitors' cigarette smoke and old-fashioned heaters were considered major sources of pollutants inside the Aula. At several points during the 20th century, the levels of air pollution in Oslo, *e.g.,* soot from domestic heating, industry and road traffic, were much higher than they are today (Lindberg, 1968). As a result, the ventilation system in the Aula had filtration installed in the 1970s. However, the additional influx of air through cracks and crevices in the old building still brought airborne pollution into the auditorium and to the painting surfaces. During the refurbishment of the Aula in 2009–2011, measures to reduce the air exchange and

Figure 2: Conservation work being performed in 2009. Conservation on the monumental Munch paintings, *Geniuses in Lightstream* and *Awakening Men in Lightstream*, by Mirjam Liu and Hanne Moltubakk Kempton. Photo: Karen Mengshoel, 2009.

circulation of airborne particles in the room were implemented, including most of the improvements suggested by Hutchings and Ashley-Smith (2008, see also introduction). Structural improvements to the paintings, such as improved thermal insulation between the paintings and the brick walls, resulted in a significant reduction in the amount of particles deposited on the surfaces (Frøysaker, 2016). However, the removal of surface dust during condition assessments in 2017 and 2018, using a soft brush and low-vacuum parallel to the surface (unpublished reports, 2017 and 2018, **Figure 4**), showed that the gradual soiling of these paintings is still a concern (Stoveland, *et al.,* 2019).

Figure 3: (a) Infrared spectrum of the painting The *Source* showing thermal bridges formed by a wooden framework behind the paintings. Photo: Dag Dysthe, Olav Gundersen and Karen Mair, 2006. **(b)** Uneven, thermal soiling caused by the framework. Photo Karen Mengshoel, 2009.

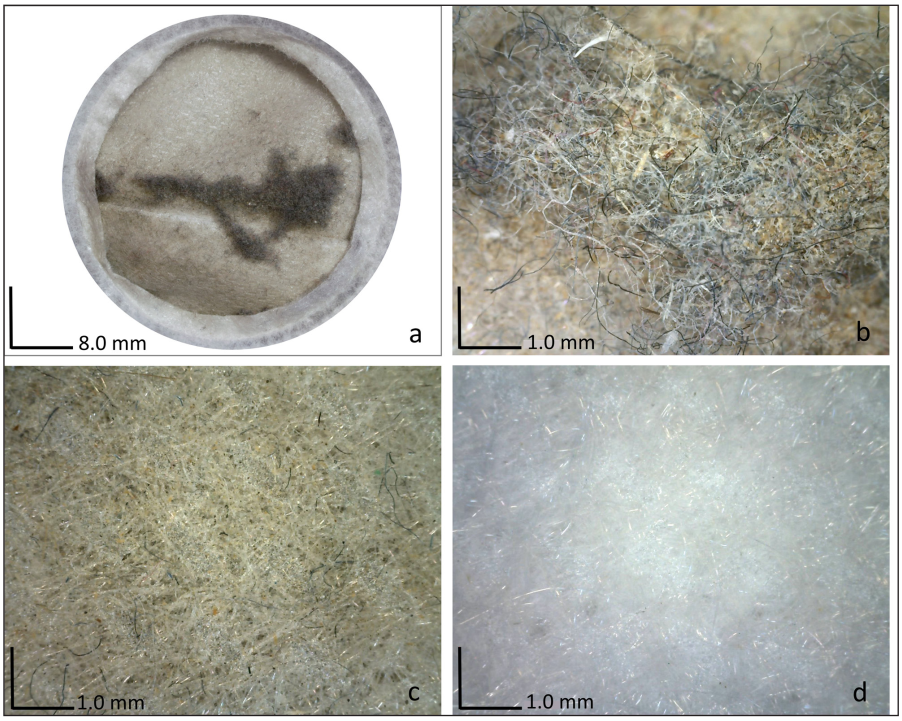

Figure 4: Soil particles from vacuum cleaning. Hose opening of vacuum bag with visible dirt content **(a)**, and the inside surface of a vacuum bag showing large fibrous **(b)** and smaller **(c)** dirt particles collected with a brush and low-vacuum from the Aula painting *Alma Mater*, compared to **(d)** a clean reference area. DinoLite, 55× magnification.

In 2013, an exposure experiment started involving the mounting of many small (3 × 3 cm^2) test samples in the Aula with the purpose of monitoring and examining the soiling and degradation progress over time. Samples were prepared to simulate the zinc white-containing *recto* and *verso* paint application, similar in composition to some of Munch's original grounds and the restorers' reverse side coating (Frøysaker, *et al.,* 2015). Although the current soiling state of these has not been analysed, the samples can provide useful information about the present and future load on the paintings, and a basis for risk analysis. They can also inform decisions about future conservation needs and be compared with assessments such as that with the EnvCul-model given below.

3. The EnvCul-model. A method for calculating future condition and conservation costs for objects of cultural heritage

The EnvCul condition model for cultural heritage was developed based on needs identified in the EU MEMORI (2013a) and other projects. These were undertaken to understand the damage risk to cultural heritage from different environmental factors and the importance of measurements and mitigation of their impact (Grøntoft, *et al.,* 2016; Rosenberg, *et al.,* 2015; MEMORI, 2013b; Tétreault, 2003; Thomson, 1986). The detailed technical explanation and mathematical derivation of the general model was provided by Grøntoft (2015), with examples of model assessment for two objects (a locomotive and the Oseberg Viking ships). Such model predictions generally require information/data about: 1) the historical change in condition, and/or; 2) the degradation mechanisms involved, so called exposure/ dose(environment)-response(condition) relationships/functions (ERF's or DRF's) (Strlič, *et al.,* 2013; Grøntoft, *et al.,* 2010), and; 3) the historical, as compared to the future, impact of the exposure environment. The future, as compared to the historical, deterioration rate can then be calculated for the object or property of interest, and changes in conservation costs can be derived.

The best available data, or evaluations, for points one to three were used as input for the EnvCul model estimations on the Munch paintings in the Aula of the University of Oslo. The model assessment provided results for: 1) the expected future soiling condition; 2) the expected time before (or between) the next major cleaning intervention(s); 3) the indicated total lifetime without future cleaning campaigns; 4) the cost of cleaning treatments for situations without and with expected improvements in the environment, as compared to the average historical environment in the Aula, and; 5) the respective saving that could be obtained by the improvement in the environment.

Condition assessment and recording is an important part of good collection management (Cultural Heritage Agency, Netherlands, 2014). Recording is needed to understand the occurrence and development of damage, as well as the best-suited conservation methods. Assessment can also be the basis for anticipating the development in the condition of objects or collections, and predicting the cost of conservation measures. Condition data should as far as possible be collected from measurements made with appropriate methods and instrumentation. It could involve repeated comparable documentation or standardised recording of the soiling extent.

The gradual deterioration of objects, often consisting of several materials, is a result of highly complex and interacting processes between materials and the environment. It can be a considerable scientific challenge to describe even the degradation of more uniform materials, such as varnishes, paper or metals (Dahlin, *et al.,* 2013b; MEMORI, 2013a; Graedel and Leygraf, 2000). Soiling is one of many mechanisms that deteriorate paintings, but is still a complex process. Relevant exposure data to understand the soiling could come from measurements of air pollution, humidity in the air and on surfaces (condensation), temperature, light or other degradation factors.

For the paintings and environment in the Aula, only qualitative historical condition data and outdoor values for the air quality were available. Future environmental scenarios were estimated. The EnvCul estimations further applied some simplifications and generalisations. It was assumed in the model assessment that reduction of the extent of soiling on the paintings by cleaning was possible. "Preserving the condition" then implies that cleaning can bring the extent of soiling closer to a previous historical level. The model applies a practical approach where it is assumed that invasive conservation, by repeating best practice, can retain such a physical condition. Possible changes in the quality or significance of this physical status are not discussed.

Due to uncertainty in input parameters and the soiling mechanism, and variations in the properties of the microclimate and the paintings in the Aula, the EnvCul model assessment was performed for a high and low scenario of the input parameters, and the results are presented as a range of possible future degrees of soiling. This could be considered as simple dichotomous probabilistic modelling (Strlič, *et al.,* 2013), and should be more realistic than providing a single result with unknown uncertainty.

The EnvCul model is simple to use. After plotting the necessary input data the results are immediately shown on the front page. An information and guidelines page, and storing and reporting functions are available. The model languages are English or Norwegian.

4. EnvCul-model parameterisation

The probable future extent of soiling (%) of the Munch paintings in the Aula was estimated (modelled) for the two different scenarios – "low soiling" and "high soiling" – by applying the following input parameters (1–6) and values for the historically observed, or assumed, change in condition, and the historical and future environment and soiling impact.

1. The start condition was set equal to 100% (no soiling, clean) in 1916, when the paintings were mounted. No systematic measurement recording of the extent of soiling has been performed in the past (before 2009). Based on visual observation during conservation, the current degree of soiling varies between

the different paintings and depends on factors such as surface roughness, absorbency, and the materials ability to transfer heat. The modelling performed here considers the average overall situation for the paintings.

2. The "present average extent of soiling" at the start of the building renovation and cleaning campaign, in 2009, was assessed to be 80%.
3. It was evaluated that the "average extent of soiling" after the conservation-cleaning in 2009–2011 was improved to 90%.

It was not possible to precisely determine the extent of soiling for the years between 1916 and 2009, or the effect of each previous cleaning operation on the extent of soiling. It was, therefore, assumed that each cleaning episode improved the condition by a considerable amount (set to 8%), but that the (mainly) visual condition had again further deteriorated by 10% before the next cleaning action. These values illustrate the expected short-term effect of the cleaning. The expected long-term effect of cleaning was that the average soiling rate since the mounting in 1916 until the last major cleaning in 2009–2011 was reduced (to a condition not less than about 80% in 2009). Even with repeated cleaning, darkening due to embedded particles from historical soiling could be observed on the paintings after the cleaning in 2011. However, if regular cleaning had not been performed since 1916 then the situation would have been much worse. The assessment assumes that such frequent maintenance by removing loosely adhered dust will continue in the future.

4. The expected change (%) in the impact of important environmental factors resulting in soiling in the future as compared to the average impact from 1916 to 2011.

If damage impact is proportional to the values for the environment, as given from the equation $I = a{\cdot}E$, where I is the damage impact, E is the value for the environmental factors, and a is a proportionality constant, then this damage impact can simply be calculated as the change in the presence of the influencing environmental factors. If the degradation is not proportional to the values of the environmental factors, it may, for example, have an exponential form, then the expected change in the degrading effect must be given as input.

A main cause for soiling and related surface damages to the munch paintings was the deposition of particles and polluting gases from the air. The uncertain, and less directly observable, contribution of gaseous pollutants are treated together with the particulate soiling effect, assuming similar relative reductions in the concentrations and damaging effects of all airborne pollutants in the aula. The general expression for this process is $F = v{\cdot}C$, where F (amount per area per unit time) is the flux of the pollutants to the surface of the painting, v (distance per unit time) is the deposition velocity, and C (amount per volume of air) is the concentration of the air pollution (Grøntoft, 2004; Cano-Ruiz, *et al.,* 1993). This is similar to the general case ($I = a{\cdot}E$). The deposition velocity typically varies by several orders of magnitude depending on the pollution species, movement of air and the properties of the surfaces (Grøntoft and Raychaudhuri, 2004). The proportionality will still be valid for the sum (integral) of all these situations. Generally, a larger deposition rate and extent of damage is expected when reactive, airborne pollutants are transported swiftly through open spaces, for example, due to high ventilation or in airstreams over heating sources, to cold and uneven/rough surfaces.

It was assumed in the model assessment that the change in the extent of soiling, due to air pollutants, of these Munch paintings was proportional to the flux of pollutants to the paintings, and, thus, with the concentration of airborne pollutants in the Aula. A certain percentage reduction in the concentration of such pollutants would then, similarly, reduce the resulting soiling and surface damage.

5. The fraction (%) of the observed historical soiling and related surface damage that was assessed to be caused by the air pollutants. That is, from a soiling extent = 0% (condition = 100%) in 1916 to a soiling extent = 20% (condition = 80%) in 2009.
6. The form of the historical damage progress (t^x, $x > 0$: t = time, x = form of the time dependence)

There may be other reasons for the damage assessed by the modelling (the apparent soiling of the Aula paintings) than the impact factor (air pollution) that was evaluated. The value for (5) would, thus, be less than 100%. The modelled effect of a change in the environment, by a reduction in the concentration of airborne pollutants in the Aula, was weighted with this "impact fraction" set to 90% (= 0.9). It was assumed in the model assessment that this fraction did not change in the future as compared to the historical situation. An alternative to excluding such unexplained effects (the 10%), if they were well understood, would be to include them in both the evaluation of the change in the object condition and the environmental impact (in which case a value of 100% could be used for (5)).

To calculate expected future cleaning costs, the last (2009–2011) major cleaning expenditure (in a currency unit, for example EURO), which improved the condition of the paintings, should then be given as an input. As monetary costs for the campaign were not available, a value of 100 (currency units) was simply used as an input to the model assessment.

The following results were then obtained:

- The expected future costs of cleaning to a similar reduced extent of soiling as in 2009–2011, relative to 100 currency units used in the cleaning campaign in 2009–2011 divided by the duration of future conservation intervals, in 2009 prices (currency unit, or %/year)
- The expected time until the next cleaning campaign (years)
- The indicated expected lifetime until the extent of soiling = 0 (completely soiled, years), for a situation

without future major cleaning campaigns. An extent of soiling = 0 would presumably imply that the painting was non-discernible through the soiling layers.

Table 1 gives the input values for the parameters described above.

It was evaluated that the damage related to soiling on the paintings in the Aula, from airborne pollutants in synergy with the present indoor environment, will have been reduced from 2009–2011 by between 80% and 50% as compared to the average from 1916 to 2009. The model calculations were performed for situations without, and with, a changed future environment (scenarios one and two) in the Aula. The difference between the two scenarios gave the values for the expected range of probable increases in time between future major cleaning campaigns and of respective savings in conservation costs, due to the expected improvements in the environment (from 2009).

Figure 5 shows the front page of the EnvCul web-model for scenario one, with input data and results for the soiling damage (condition, life times and conservation costs) of the Munch paintings in the University of Oslo's Aula.

5. Results

Figure 6 shows the EnvCul model projection (Excel version) of the extent of soiling and time to the next major cleaning intervention on the Munch paintings in the University of Oslo's Aula for the situation with no change, and the two scenarios (one and two). The web model (**Figure 5**) shows, and separately stores, results from a model assessment. The suggested effect of the repeated historical cleaning is illustrated in the diagram. The results assume that this relatively frequent cleaning will continue in the future.

Table 2 reports the results from the estimates shown in **Figure 6**.

Figure 6 and **Table 2** show that a reduction in the air pollution loading in the Aula of between 50% and 80%, as compared to the historical (1916–2011) level, could increase the "lifetime" before a new major cleaning campaign (comparable to that in 2009–2011) by between 80% and 260% (from 47 years to between 85 and 166 years). The costs for cleaning would be reduced accordingly by between 45 and 70% (as compared to a similarly evaluated need for cleaning for the average situation between 1916 and 2011). This situation was probably partly achieved already before the renovation and conservation from 2009–2011, due to environmental improvements before 2009. Some of the improvements are, however, expected to result from preventive actions taken as a part of, or after, the 2009–2011 campaign.

The expected lifetimes before complete visual obscurity reported in **Table 2** only consider the development of soiling. The paintings are subjected to other degradation mechanisms and their total lifetimes without conservation would probably be shorter.

Net savings could be calculated by subtracting the costs for the preventive conservation that contributed to the improvements to the environment (as the cost per year for the time between cleaning campaigns, after the improvements have been implemented).

6. Discussion

With the expected reduction in the future extent of soiling (as compared to the average from 1916 to 2009) the lifetime to the next major necessary cleaning campaign was calculated to increase two- to three-fold. Together with the respective reduction in invasive conservation costs of 45–70%, these are considerable improvements. This corresponds to the recommendation given by Hutchings and Ashley-Smith (2008) that the rate of dirt deposition should be reduced, and, thus, the cleaning interval increased, by a factor of three for this vulnerable group of paintings. The assessment of Hutchings and Ashley-Smith (2008) was based on statistical evaluation of cleaning frequency in the National Gallery, Oslo (to between 32 and 46 years), and the assumption that conditions (environments, perceptions and management processes) were sufficiently similar in the Aula of the University of Oslo for a situation to be established with a similar cleaning frequency. Our results show that the implemented and expected environmental improvements may increase the time between cleaning intervals for the Aula paintings

Table 1: Model parameters and input values.

Parameter	Value	Explanation
Start condition in 1916 (%)	100	No soiling on the paintings at mounting in 1916
Condition before cleaning in 2009–2011 (%)	80	20% perceived soiling in 2009 (subjective assessment of overall soiling, which was very variable)
Condition after cleaning in 2009–2011 (%)	90	10% improvement in the "soiling condition" due to cleaning
Reduction in air pollution concentrations from "average 1916–2009" to "average after 2011" (%)	Scenario 1, "Low": 50 Scenario 2, "High": 80	Two scenarios with different future air pollution levels were applied: Reduction to 50% and 20% of the air pollution particulate load on the paintings
Importance of air pollution for observed soiling (%)	90	10% of the observed apparent soiling was attributed to unexplained causes other than air pollution
Time dependence ($0 < x < 1$)	1	Linearity of the historical, and predicted future, change in the soiling condition was assumed.

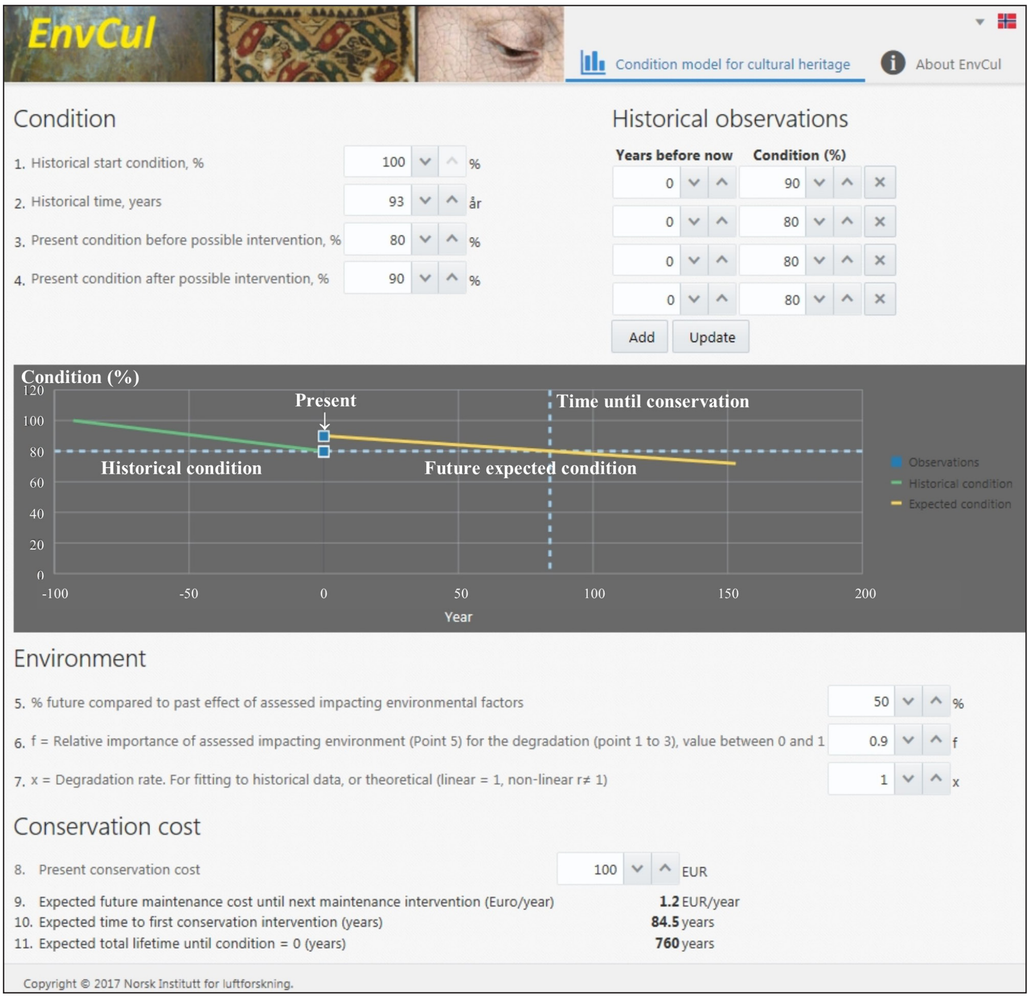

Figure 5: Front page of the EnvCul web model. The model of the soiling damage of the Aula paintings according to Scenario One is shown. Additional explanatory text is included on the model diagram. The only direct observations available from the time until the conservation in 2009–2011 are the extent of soiling before the "present" conservation campaign in 2009, which was judged to be 80%, and after the campaign, which was judged to be 90%.

to be similar to that historically recorded for paintings in the National Gallery in Oslo. Even if the model assessment considered changes in intervals between major cleaning campaigns, rather than the more frequent, non-invasive cleaning actions, such as surface dusting (which were assumed to be carried out in a similar manner after 2011), the benefits of the environmental improvements could probably be observed by extensions to the shorter or longer cleaning intervals. With less frequent regular cleaning, for example each 40th year rather than each 14th year, a more extensive campaign may still be required about every 3rd time (every 120 years), but this will likely depend also on other factors in addition to soiling.

However, the environmental loads and soiling-damage mechanisms may change in the future in ways that are difficult to predict. The present focus on improved urban environments may further reduce air pollution loads. Climate change, which is predicted to result in periods of more rain and probably higher relative air humidity (Hanssen-Bauer, *et al.*, 2015; Sabbioni, Brimblecombe and Cassar, 2010), may work in the opposite direction by increasing indoor humidity (Huijbregts, *et al.*, 2012) and, thus, soiling. Unexpected events and developments can also happen. The sensitivity and progression of damage on the paintings may also change. The approaches, methods, and costs for interventive object conservation, such as the cleaning of paintings, will surely change in the future. The reporting of the results as ranges, therefore, seems most realistic, but still uncertain. Some aspects related to the uncertainty in, and the conditions for, the model assessment and results are discussed below.

6.1. Uncertainty about the input parameter values

There is considerable uncertainty concerning the input parameter values. It is difficult to estimate this uncertainty, but this should be taken into account when evaluating and using the results.

The air pollution, deriving from both indoor and outdoor sources, has probably accounted for most of the soiling damage observed on the paintings prior to 2009. Soiling is a direct result of particle ("dirt") deposition from the air. Having contact with (mainly) no other medium than room air, the paintings were primarily soiled by air pollution. However, the reasons for some of the observed discolouration interpreted as soiling may have been different. Thus, the uncertain assumption that the air

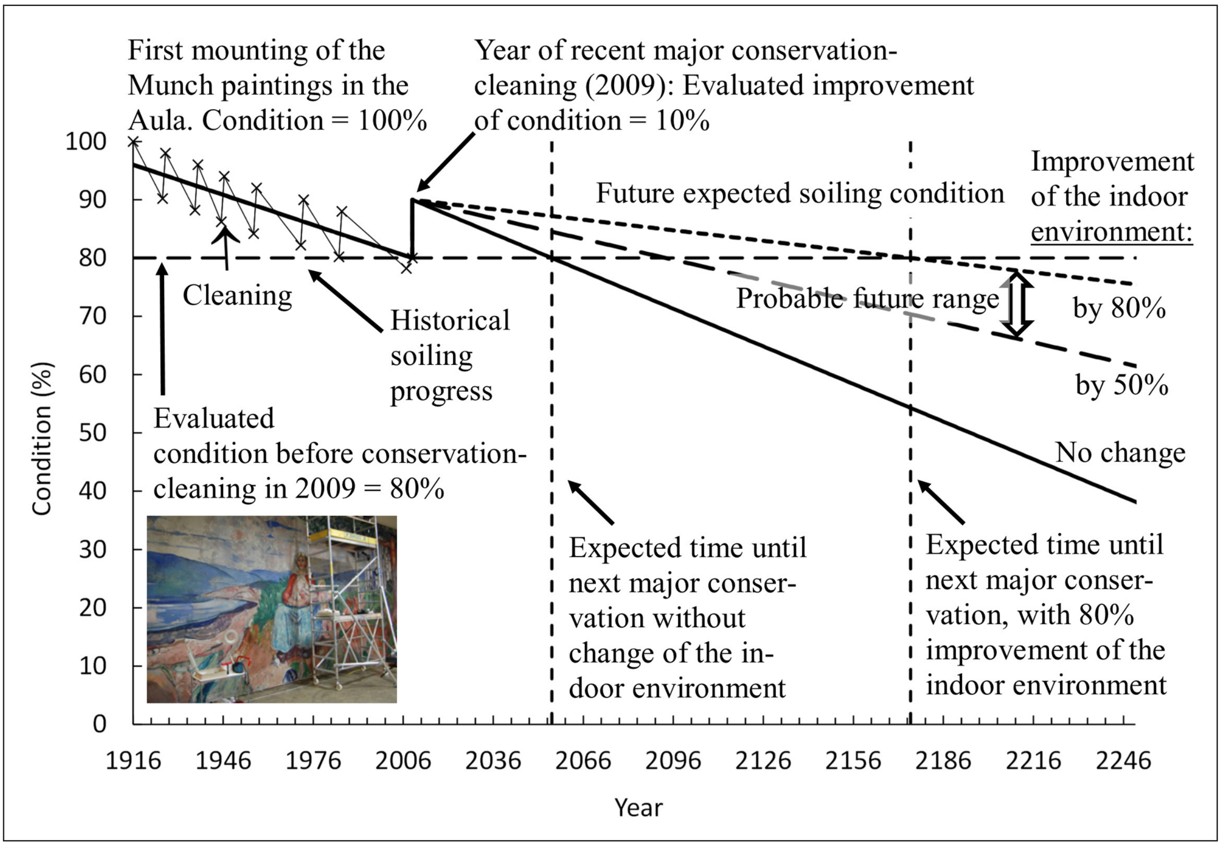

Figure 6: EnvCul modelling projection for the Munch paintings in the University of Oslo's Aula. Projection of the expected extent of soiling and time until the next major cleaning campaign. Situations with no change and two scenarios with change in the future indoor environment are shown. Photo: Olaf Christensen, The Aula-project: https://www.hf.uio.no/iakh/forskning/prosjekter/aula-prosjektet/.

Table 2: EnvCul estimates of future cleaning costs and lifetimes, due to soiling, for the Munch paintings in the University of Oslo's Aula.

	Without change of the indoor environment	**With reduction (%) in indoor air pollution**		**Saving/change by improvement of the indoor environment, with 50% to 80%**
		50%	**80%**	
Expected future cost for invasive cleaning campaigns *(Currency unit, C/year per 100 C investment)*	2.2	1.2	0.6	1.0–1.5 (45–72%)
Expected time until the next major cleaning treatment *(years)*	47	85	166	38–120 (82–257%)
Expected (indicated) lifetime before the object would be completely visually obscured by soiling and related effects – if no future major cleaning treatments were implemented *(years)*	418	760	1494	342–1076 (82–257%)

pollution caused 90% of the observed soiling was made in the model calculations (see Section 4).

The soiling (and other) damage to the Aula paintings have probably not developed gradually and linearly, but rather, before 2009, in periods depending on the air quality and the use of the Aula. The air quality has varied much over time, strongly affected by the ventilation of outdoor air into the Aula, by visitors' cigarette smoke and the old heating systems. The air quality is not currently being measured in the Aula, and measurements have not been performed in the past. The air quality has, however, clearly improved. Smoking has for a long time been prohibited, the old heating system has been replaced, and the Oslo air is cleaner than during the 20th century. Large reductions in air pollution happened in Oslo before 2009. Air quality data from for Oslo can be found for smoke and sulfur dioxide (SO_2) from the end of the 1950s (Lindberg, 1968). Until 1964/65, maximum mean winter concentrations up to about 400 $\mu g/m^3$ SO_2 and 150 $\mu g/m^3$ "smoke" were recorded in the centre of Oslo at a traffic station 600 m away from the Aula. The period of highest air pollution concentrations in Oslo seems to have been from the 1950s through the 1960s and 1970s. From the beginning of the 1980s to years after 2000 the concentrations of SO_2, nitrogen dioxide (NO_2) and particles with aerodynamic diameter less than 10 µm (PM_{10}) were reduced from typical values of 100 (SO_2 and NO_2) and 50 (PM_{10}) µg/m^3 (Larssen and Hoem, 1990), to below 5 µg/m^3 (SO_2), and about 50 µg/m^3 (NO_2) and 25 µg/m^3 (PM_{10}) (Luftkvalitet.info, 2018). The large reduction in the concentration of, especially, SO_2 has resulted in a significantly reduced load and improved preservation of all kinds of exposed materials and objects (Grøntoft, 2016; Tidblad, *et al.,* 2017). Cigarette smoking, as a source of indoor air pollution, may have had a maximum at about the same time as the outdoor air pollution.

Without further evidence about the progress of the soiling-related damage in the historical environment, it was considered most realistic to assume that it developed in proportion to the air pollution exposure dose (concentration multiplied by exposure time). Even if the extent of soiling may have increased more in some periods, there does not seem to be a predictable systematic variation in the historical progress of the soiling, which would be representative for the future. In this perspective, the variation with time of the environmental loads on the paintings could be considered coincidental. To apply the historical development of damage from the mounting in 1916 until 2009, in order to predict future risks, it seemed most appropriate to assume a linear change in the soiling extent of the paintings, until it had reached the assessed value of 80% in 2009. The more frequent cleaning was assumed to have reduced the general degradation rate (not to fall below 80% in 2009) and have resulted in shorter periods of improvements (see **Figure 6**). This overall linear dose-response relationship was then assumed valid also for the future.

This linearity assumption is an approximation. The form of the time dependence (x) can in principle be determined from historical condition observations or from information about the damage mechanism. The corrosion rate of, for example, a metal surface often reduces with time ($x < 1$, concave damage progress, "valley"), whereas the degradation rate for the structure of an object can increase when the object starts to break up ($x > 1$, convex damage progress, "hill"). The degradation mechanism and rate for a complex object can change with time. For example, the degradation rate can increase after the damage of a paint film, which has offered protection for some time ($x > 1$), but a new corrosion patina on the material, for example a metal being exposed under the paint, can still, after some time, reduce the continued rate of degradation ($x < 1$). In the modelling for the Aula paintings a concave or convex soiling progress could have been applied, if there was evidence for this from historical condition data or known damage mechanisms.

The modelling algorithm considers the conservation to take place in one year. The year when the conservation was initiated, 2009, was used for the Aula paintings. The modelling of the future probable change in condition started then from 2009, rather than 2011 when the remounting was finished. Considering the large span between the future scenarios, from 50% to 80% improvement in the environment, and other uncertainties, these two intermediate years of conservation treatment, until 2011, were considered not to significantly affect the results.

The EnvCul model can only handle the progress of one damage mechanism at a time. A more complex progress could, if known for the paintings, be approximated by repeated consecutive modelling.

6.2. Uncertainty about the condition assessment

Uncertainty about input parameters implies that there is considerable uncertainty about the impact of the environment and the relative importance of damage mechanisms. Failure processes are often modelled probabilistically with stochastic models (Strlič, *et al.,* 2013). Although the incremental progress of soiling damage could be well described by deterministic models, there will usually be an amount of natural variation, which is difficult to account for. The presentation of the model result as a range of possible future degrees of soiling takes these factors into account.

It is a simplification to evaluate the "degradation of the paintings", or even the "degradation due to soiling of the paintings", as one process. The soiling will have depended on factors such as the composition, structure and conservation state of the surfaces, and may or may not have happened similarly on, for example, rough and smooth, thinly and thickly painted, dark and light or warmer and colder areas of the paintings. There seems to be an inherent uncertainty in evaluations of the relative importance of different sub-processes for the overall change.

The model assessment assumed that the condition, defined as "the physical state" of the paintings as affected by the soiling, could be distinguished from its quality (including its significance). It can be difficult to distinguish between physical state and quality. Objects will with time, and after some conservation interventions, not be exactly the same. Major interventions, for example consolidation or cleaning, can result in large changes. Reflections about how cleaning may influence the quality of the Aula paintings (or other objects) must be made independently from the presented model estimations.

7. Conclusion

The NILU-EnvCul model estimations suggested that a future improvement in the indoor air quality in the University of Oslo's Aula of between 50% and 80% as compared to the average from 1916 to 2009, could increase the time until the next major cleaning of the surfaces of the monumental Munch paintings in the Aula by a factor of two to three (from about 45 years to between about 85 and 165 years). This would result in 45–70% reduction in the respective conservation costs. These are significant savings, which shows the importance of preventive conservation. As there is considerable uncertainty about the impact of the environment and the relative importance of damage mechanisms, a probable range was calculated rather than one value. Loads and damage mechanisms may change in the future, giving a different result. We still think the estimations illustrate, and realistically quantify, the importance of improved air quality and the making of arrangements and establishing routines to assure a good future indoor environment in the Aula. This environmental improvement would correspond with the recommendation given by Hutchings and Ashley-Smith (2008) that the rate of dirt deposition should be reduced, and, thus, the cleaning interval increased, by a factor of three for these vulnerable expressionist paintings.

Future monitoring of the particle air pollution concentrations in the Aula are recommended, preferably with continuous monitoring to obtain time and particle size resolved data. This could show if the particle concentrations continue to be reduced, and be most useful to diagnose the sources of the particles and implement further efficient mitigation measures. Such measurement instruments are today relatively affordable and easy to operate. Further, chemical analysis of the collected particles are be recommended.

The NILU-EnvCul-model offers help to conservators (and others) in performing analysis of risk, condition and costs, and in the evaluation of the importance of preventive conservation. The model offers a simple available framework for the use of registered data for object condition and environment for this purpose. An EnvCul user can easily describe, store, retrieve and report model estimations as required.

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Competing Interests
The authors have no competing interests to declare.

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