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Assessing and predicting sustainability for maintaining silver collections

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Abstract

Sustainability data for materials and electric energy consumed vary with national location. Additionally, local climate can have a dramatic effect on the amount of energy needed to maintain cultural heritage environments. The first part of this research focused on the energy needed to maintain a showcase at 55% RH. Measurements with a Munters dehumidifier were made in different locations. The variability of the showcase was removed by estimates from a developed model. The variability from the building fabric was removed by estimates from an Energy Plus model. The focus of the second part of this research was silver tarnish and its prevention. Performance models allowed geographic location effects to be estimated, and a simple model was developed mainly from existing data on the rate and prevention of silver tarnish. Small areas of missing data were investigated. Carbon footprint information was developed and added to the model to allow predictions of different interventive, preventive and mixed scenarios.

INTRODUCTION

Reducing the planet's carbon footprint is essential to maintaining an acceptable climate. Several other areas of sustainability are also being recognised as critical. In 2018–2019 the arts and cultural sector in the UK had a carbon footprint of 114,547 tonnes CO_{2eq} and 41% of that originated from museums (Arts Council England 2021).

Carbon footprints are calculated from life cycle assessments (LCAs, ISO 2006), which measure or estimate the greenhouse gas equivalent (GGE) in CO_{2eq} from all stages of a process, including disposal/recycling. That from raw material extraction, transport and processing for materials or equipment is called embedded carbon. The measured or modelled electrical power used by machines can be converted into GGE by referring to published factors for the electricity supply used. In some conservation areas, predicting sustainability is now possible. In the following, this is illustrated for the maintenance of silver collections, by considering the carbon footprints of interventive, preventive and mixed methodologies. For decision-making, it is important to be able to predict performance and to compare approaches.

Improving sustainability relies on information that is accurate enough to discriminate between different approaches. Whilst case studies are useful, there can be issues in transferring their conclusions to other situations. For environmental preventive conservation there is an added complication, as climates and pollution vary widely. Geographic location determines several aspects of a material's sustainability and almost all commercial LCA software starts with the input of location. Calculations and measurements have been undertaken to assess the impact of location on environmental control.

Silver tarnishing rate

The decision to clean silver tarnish is most commonly based on observations related to the aesthetic appearance of the affected object. To this end, the preferences of a wide range of conservation professionals were surveyed and threshold values determined (Thickett and Hallett 2021a). Several aspects of silver tarnishing and treatment have already been investigated. An indoor damage function was developed linking the silver tarnish rate to hydrogen sulfide, hydrogen chloride, sulfur dioxide and nitrogen dioxide concentrations as well as to average temperatures and relative humidity

(RH) (Thickett et al. 2012). Both 30-day and 30-minute damage functions were determined. If sufficient measurements or estimates are available, the tarnish rate can be estimated. Concentrations can be measured with diffusion tubes. These are tubes with a reagent at one end; the other end is opened when the tubes are exposed and sent to a laboratory for analysis. However, the hydrogen sulfide concentration is a major contributor to the tarnish rate and whilst commercial diffusion tubes are able to detect higher concentrations of the gas, they cannot quantify the levels found in about a third of cultural heritage situations. Another option is to use silver coupon colourimetry, silver-coated quartz piezo-electric crystals (PQC) or silver resistivity sensors. The feasibility of using 30-day measurements to estimate an annual cycle has been investigated and a considerable body of tarnish rates measured in museums has been published (Sacchi and Muller 2005, Thickett et al. 2013, Thickett and Hallett 2021b). A simple method to measure the tarnish rate using a colourimeter was also developed (Thickett 2008). An international standard exists to rank the silver tarnish rate for indoor heritage environments based on standardised measurement methods (ISO 2005), but other methods for measuring tarnish rates are available as well (Costa 2001, Capelo et al. 2013).

Preventive conservation measures

Preventive conservation measures can be taken to reduce the tarnish rate of an untreated object in an open room. The performances of a range of approaches have been determined, such as the influence of showcases, sorbents, the use of pumps and the application of Frigilene lacquer.

A study of the influence of showcases on silver tarnish reduction provided a general graph of tarnish rate reduction vs. the air exchange rate that was incorporated into a model (Thickett and Hallett 2021a). Passive sorbents were found to work well only in limited situations (Bradley 2005, Thickett 2021b) and were not considered in the model. Sorbents are, however, much more effective when deployed in pumps. The tarnish reduction rates obtained with two pumps, Camfil and Dymax 5, were expressed as a percentage (Thickett and Short-Traxler 2011, Thickett and Hallett 2021a). The lowest performance values in terms of tarnish rate reduction from 14 and 12 instances were used in the model. The performance of Frigilene FR65150 lacquer was also investigated, along with its ageing properties and expected lifetime in different environments (Luxford and Thickett 2007). The reversibility of lacquer treatment after ageing was not assessed, but additional work has been undertaken to determine whether it would reduce the effective lifetime of the lacquer.

Combining the tarnish rate with the performance of a showcase, a showcase with a pump, or lacquer with the visual threshold gives a lifetime after which the silver will need cleaning. The data form the basis for a simple performance model for silver in a particular environment, with which the level of tarnish and number of cleans required over a certain time span can be calculated. When combined with sustainability data, the carbon footprint and other indices – abiotic depletion, abiotic depletion (fossil fuels), acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, ozone depletion, photochemical oxidation and terrestrial ecotoxicity – can be predicted. Little sustainability data have been published, but work has been undertaken to provide basic information.

Three cleaning methods were assessed: Pre-Lim surface cleaner, acidified thiourea silver dip and Goddard's long-term silver cloth (Selwyn and MacKinnon 2021). In a recent worldwide survey of conservation practice, Pre-Lim was identified as the most frequently used commercial mechanical cleaning agent. Mechanical cleaning agents were used by 49% of respondents and chemical agents by 38% (Palomar et al. 2018). Whilst thiourea-based dips appeared to be the most commonly employed products in the chemical agents category, reservations about their use were common. Solutions of sodium or ammonium thiosulfate and formic acid were the next most frequently chosen materials. However, as these are not used in English Heritage, it was not possible to undertake useful research on them. Moreover, exactly how materials are used can have dramatic impacts on the LCA, but no LCA has been published for these materials (GreenDelta 2022). Cellulose nitrate is listed as forthcoming on the Sustainability Tools in Cultural Heritage website (FAIC 2022); hence, estimates were made from the mass of the components.

The embedded carbon content for showcases was previously reported (Thickett 2019, Thickett 2022). Only manufacturers can provide accurate cradle-to-gate data for their products, as they know where the raw materials were sourced and how they were processed. Standards provide for an alternate approach when this information is not available, which is unfortunately most often the case. Embedded carbon can be estimated using tables of data on the mass of materials present in a product (BSI 2050) and this method was employed in the present study.

METHODS

Impact of the location climate on the carbon footprint

The energy needed to maintain a showcase below 55% RH with a Munters MG50 dehumidifier was estimated using an extensively tested model. To determine how much time the dehumidifier would need to run per hour of a year to reduce the RH to 55% in a showcase with a defined air exchange rate, the room RH was used with an iterated manufacturer-produced dataset (Thickett 2022). These calculations were undertaken in ten rooms in buildings across England with measured temperature and RH data. Five locations had dehumidifiers installed, and the energy usage was measured for a year with plug monitors to assess the accuracy of the calculations. The volume and air exchange rates of the installed showcases were measured. Average values of 0.70 m^3 and 1.06/day were used to model showcases in rooms where they did not exist. A well-validated Energy Plus model for Brodsworth Hall (Taylor et al. 2005) was applied to ten other UK locations and modelled as before. This building modelling approach uses external weather data and building and materials properties to calculate the internal temperature and RH of rooms.

Silver collection management sustainability

Previous measurements obtained with Onguard 2000/3000 systems and AirCorr loggers (commercial loggers based on mass gain and reduction in cross-section respectively) that measure the silver tarnish rate (in nm thickness per day) were assessed to determine whether a 30-day measurement interval would provide a reasonable estimate of the annual silver tarnish rate in a space. If a full year's measurement is required, the method is much less applicable. The rate over 30-day moving windows was calculated, multiplied by 12 and compared to the annual tarnish rate.

The embedded carbon in Munters MG 50 dehumidifiers, Camfil, Dynamx and Blue Clima pumps was determined (BSI 2011). The units were disassembled and the components were analysed with Fourier transform infrared spectroscopy (FTIR) and X-ray fluorescence (XRF) and weighed. The carbon footprints were derived from published tables (Swedish Environmental Research Institute 2015). The energy usage of each system was monitored with Maxcio Dual Tariff Power meters. The filter replacement rates were tracked over several years and averages calculated. The embedded carbon was calculated as for the machines themselves. The overall carbon footprint was defined as the embedded carbon for the machine, plus however many filters need replacing, plus that of the energy used.

The performance of the Munters MG50 dehumidifier and Blue Clima unit was assessed by running the unit in a storeroom with a Purafil Onguard 3000 logger. Similar data were obtained from an adjacent storeroom and the reduction in the tarnish rate between the two rooms was calculated. Initial measurements without the units running had shown only a small difference in the tarnish rate (that in the filtered room was up to 7% higher). The dehumidifier was set to 50% and clearly reduced the RH, which would impact the tarnish rate. The 30-minute damage function was used to correct the measured tarnish rate for the RH at each measurement interval and to estimate the tarnish rate reduction due to a lowering of the RH and the removal of pollutant gases.

Frigilene FR65150 was cast both as free films on polytetrafluoroethylene blocks and on silver coupons and as gold-plated glass slides. The films were aged under UV-filtered light in a Microscal light fastness tester, with an MTL 4000 bulb. Specimens were removed after selected times to give doses equivalent to 10, 15 and 25 years at 200 lux. A second set of films was aged at 60°C and 50% RH. Published activation energies for the decomposition of cellulose nitrate are around 105 kJ/mol (Selwyn 1988). Specimens were removed at periods calculated to be equivalent to 10, 15 and 25 years at 20°C. After ageing, solubility was determined by swabbing the specimens with acetone. After the specimens had dried, they were analysed with a Perkin Elmer 2000 FTIR with Durascope Amplif-IR multiple bounce reflection absorption accessory. A calibration curve was produced by sequentially diluting Frigilene in the recommended solvent. A controlled volume (0.1 µL) was pipetted onto a 10 MHz piezo-electric quartz crystal (PQC, Open QCM) in the central 5 mm diameter gold-coated area. The PQC was allowed to dry for 14 days in a fume cupboard.

The parameters of environmental relevance, listed previously, for Frigilene were calculated from published values for cellulose, nitric and sulfuric acid and from a preparation protocol and published values for the solvents propan-1-ol, butyl acetate (ethanoate), butan-1-ol and xylene (dimethylbenzene). Those for silver dip were calculated from published values for sulfuric acid and thiourea, and those for Pre-Lim from chalk, white spirit and water. The components for the long-term silver cloth were taken from the manufacturers' 2017 information (SC Johnson 2023). The amounts of materials needed were determined by observations and measurements from conservation practice.

RESULTS AND DISCUSSION

Impact of the location climate on the carbon footprint

The results of the energy calculations with measured room data are shown in Table 1. The room temperature and RH are shown as 90% intervals and as median values of the data, as the showcases were not affected by short-term fluctuations. There was a large variation in the energy consumption calculated, over 200%. For those spaces with dehumidified showcases in place, the measured values were close to the calculated values (within 15%), thus validating the energy modelling for dehumidifiers. Different buildings as well as different local climates will obviously impact the results. The modelling removes differences between showcases, highlighting these differences. The models can also be used to optimise showcase performance. Temperature and RH had the largest effects on energy consumption, with consumption increasing as the volumetric air exchange rate (AER × volume) increased.

Table 1. Predicted and measured energy used to keep showcases below 55% RH with Munters MG50 dehumidifiers. Note: lower rows are calculated values from the model alone

	Room conditions (90% of results, median value)		Showcase details		Energy usage, (kWh) per year	
	Temp (°C)	RH (%)	AER (/day)	Volume (m³)	Calculated	Measured
Lullingstone	7.1–25.2, 15.11	54–86, 75.48	1.35	1.2	214	201
Kenilworth	13.7–23.1, 16.73	50–71, 58.87	0.89	0.48	89	95
St Peters	10.2–22.6, 15.67	62–76, 68.54	0.54	0.87	114	121
Dover 1	17.4–21.73, 18.87	39–74, 50.78	0.85	0.47	53	61
Dover 2			1.65	0.47	102	87
Wrest	16.7–22.5, 20.67	36–78, 45.87	1.06	0.70	83	Modelled
Audley End	11.3–23.5, 19.54	52–65, 55.43	1.06	0.70	58	Modelled
Wellington	16.2–19.3, 17.75	31–81, 54,63	1.06	0.70	132	Modelled
Rangers	16.0–23.2, 18.54	40–71, 51.65	1.06	0.70	61	Modelled
Eltham	16.1–23.1, 17.21	26–57, 42.65	1.06	0.70	43	Modelled

Table 2 shows the calculated internal environments for the Brodsworth Library Energy Plus model. The energy consumption calculated from these values using the showcase model with its parameters is shown in the second part of Table 1.

The variations were again large. Brodsworth is ten miles from Finningley, thus demonstrating the potential impact even of relatively short distances on the results. The present UK energy mix has a GGE of 0.21 kg CO_{2eq} per kWh (BEIS 2021). The carbon footprint for the calculated kWh is

Table 2. Calculated energy usage and greenhouse gas emissions for modelled room environments

	Calculated room conditions (90% of results, median value)		Modelled energy usage (kWh) per year	GGE (kg CO_{2eq}) per year
	Temp (°C)	RH (%)		
Aberdeen	12.4–20.7, 10.59	48–86, 67.71	153	32.2
Aughton	11.0–20.4, 11.93	50–89, 69.30	174	36.6
Belfast	11.0–19.1, 11.48	52–90, 70.86	210	44.1
Birmingham	11.0–22.0, 11.93	44–75, 6703	137	28.7
Brodsworth	11.3–23.1, 15.89	46–88, 59.87	113	23.7
Finningley	11.0–21.1, 11.61	46–78, 65.89	156	32.8
Hemsby	11.0–21.1, 12.03	52–89, 71.18	186	39.0
Jersey	11.0–20.4, 13.26	52–92, 75.20	292	61.4
Leuchars	11.0–20.0, 11.12	47–86, 67.43	142	29.9
London Gatwick	11.0–23.0, 12.00	45–71, 68.00	182	38.3
Oban	11.0–21.1, 11.78	44–73, 66.17	135	32.6

included in Table 2. Excluding the impact of the building, the variation in greenhouse gas warming potential was large, over 250%, due to the geographic microclimate.

Silver collection management sustainability

Figure 1 shows a 12-month measurement of the silver tarnish rate from an AirCorr logger. The two 30-day periods used to calculate the tarnish rate are shown along with the corresponding estimated annual rate and the percentage of those rates compared to the measured annual rate. For the 45 data sets with continuous data over 12 months, in 41 different locations, the 30-day tarnish rates are shown in Figure 2. Each 30-day rate was ratioed to the annual rate.

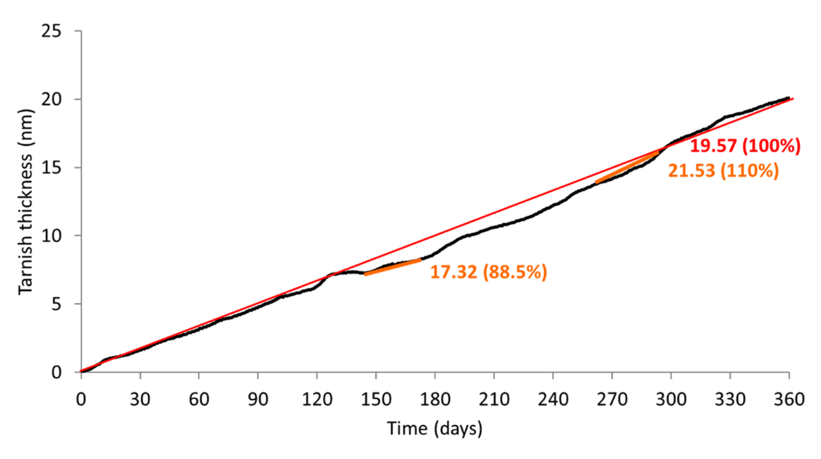

Figure 1. Measured years of silver tarnish rate

The labels include the tarnish rate class according to the international standard ISO 11844 (2005). The 30-day rates were compared to the equivalent measured 12-month rate as a percentage and are shown in numerical order. For Class I (tarnish rate < 15 nm/year) and Class II (15–50 nm/year) environments, the values were between 85% and 122%, indicating a reasonable estimate based on the 30-day data, as longer monitoring data were not available. Thus, for these classes the tarnish reaction was approximately linear. The difference increased with Class III and Class IV environments, but it could perhaps be argued these are

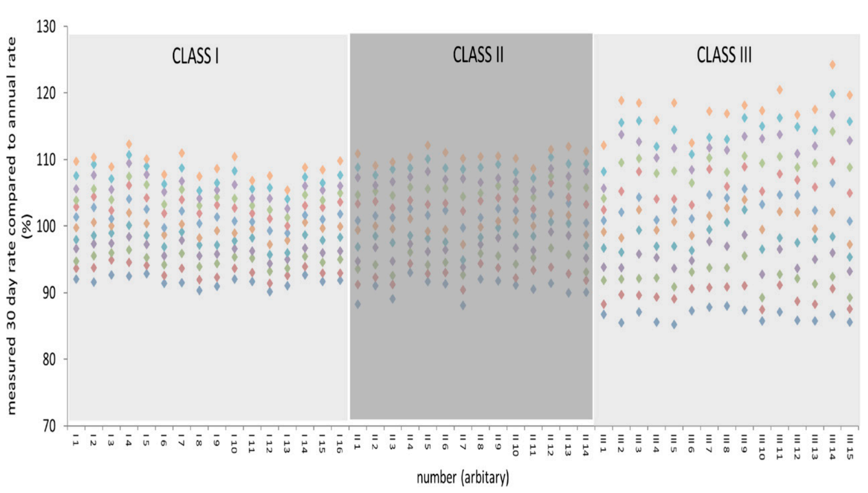

Figure 2. Assessment of 30-day periods as predictors for annual tarnish rate

Table 3. Calculated embedded carbon and the measured performance of filtration systems

	Embedded carbon (kg CO_{2eq})	Performance	Average filter replacement period (months)	Energy usage (kW/day)
Munters MG50 dehumidifier	93	91		Calculate
Filter	0.35		12	
Blue Clima	123	65		0.98
Filter	20		24	
Camfil pump	51	97		0.113
Filter	5		24	
Dynamx 5 pump	35	97		0.085
150 g Puraspec 2040 plus charcoal cloth	0.75		24	

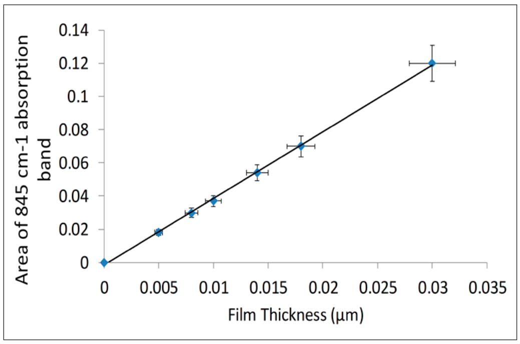

Figure 3. Calibration of AMPLIFIR FTIR of Frigilene against film thickness

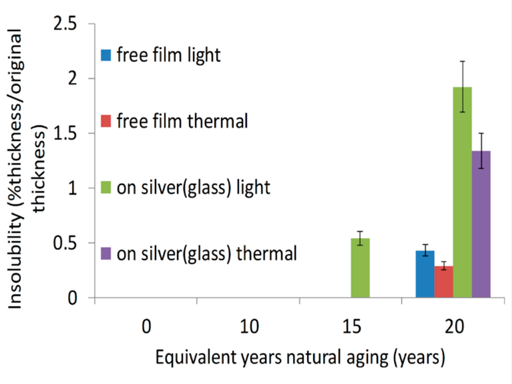

Figure 4. Reversibility of aged Frigilene

problematic for silver collections anyway such that the class is perhaps more important than the actual number.

The Onguard measurements showed that the Blue Clima unit reduced the tarnish rate by 63% compared to the similar room and used slightly under 1 kW electricity/day. The Munters MG50 reduced the tarnish rate by 91% and used 2.6 kW/day in this situation. Of that, the damage function calculations indicated that 16% was due to the RH reduction and the remaining 84% to the gas-pollution filtration performance.

The calculated embedded carbon values are shown in Table 3, which presents the performance data as a percentage reduction in the tarnish rate compared to unconditioned air. The energy consumption for Munters dehumidifiers must be calculated from the room temperature and RH, the set-point RH, the showcase air exchange rate and the volume (Thickett 2022). Energy consumption for the Camfil and Dynamax 5 pumps and Blue Clima unit was consistent through time.

The FTIR calibration for Frigilene thickness is shown in Figure 3. The calibration produced a good straight fit. Errors were estimated from multiple FTIR measurements of the same area and the manufacturer quoted error on the PQC.

Figure 4 shows the percentage residue (compared to the initial film thickness after application and drying) for aged samples, calculated from the calibration in Figure 3. No residues were detected after acetone swab cleaning for an equivalent of 15 years of the thermal ageing of Frigilene on glass and silver and of light ageing on glass. Residues can be problematic as their presence can affect both subsequent treatment and the lifetime of treatment, which impacts both economics and sustainability. The 15-year light ageing on silver showed a 0.6% residue. All samples showed residues after an equivalent of 20 years of ageing, with those on silver being greater. These experimental lifetimes were longer than the effective lifetimes reported previously (Luxford and Thickett 2007), with the exception of light ageing. This has implications for the lighting policies of many institutions, which typically allow higher light levels on metal objects (Derbyshire et al. 2002, BSI 2014).

LCAs employ different measures for sustainability and sometimes different units. The parameters in Table 4 were assembled from published data for nitric acid, cellulose, sulfuric acid and xylene for Frigilene; mineral spirits, chalk and cotton cloth for Pre-Lim; and sulfuric acid for silver dip. No values could be found for thiourea.

Table 4. Parameters of environmental relevance for cleaning and lacquering systems

Index		Silver dip*	Pre-Lim	Goddard's long-term silver cloth	Frigilene FR16525
Abiotic depletion	kg Sb_{eq}		0.00000	0.00008	0.00104
Abiotic depletion (fossil fuels)	MJ		3.46780	0.35469	4.23002
Acidification	kg SO_{2eq}	0.00400	0.01000	0.25781	0.03067
Eutrophication	kg PO_{4eq}	0.00180	0.00180	0.11068	0.00129
Fresh water aquatic ecotoxicity	kg 1.4-DB_{eq}		0.00000	0.07594	0.00189
Global warming	kg CO_{2eq}	0.08892	2.48892	0.03655	3.09259
Human toxicity	kg 1.4-DB_{eq}		0.05800	14.95312	0.09667
Marine aquatic ecotoxicity	kg 1.4-DB_{eq}	0.16700	0.17100	0.06000	0.01969
Ozone depletion	kg CFC-11_{eq}		0.00000	0.00016	0.00000
Photochemical oxidation	kg C_2H_{2eq}	0.00010	0.00010	0.00759	0.00847
Terrestrial ecotoxicity	kg 1.4-DB_{eq}		0.00000	4.3140	0.03400

* Data for sulfuric acid only.
Empty cell: no data available.
Value all zeros: below 10^{-7}.

Some data were not readily available and some parameters were very small. The per kg data in Table 4 were converted into average usage per m^2 of silver surface based on observations of conservation practice and on measurements. Conservation treatments were monitored (86 for Pre-Lim cleaning, 235 for Goddard's long-term silver cloth, 120 for silver dip and 290 for Frigilene lacquering and 198 for its removal) and the average amounts of material per area of silver were calculated per treatment. These values were used in the spreadsheet for cleaning and lacquering treatments. The values for alternative methods can be used to aid in selecting a method or at least for understanding the impact in sustainability terms.

Figure 5 shows the scheme for silver tarnish measurement. The period decided for the assessment can significantly alter the results. For example, if the average lifetime of a pump is 19 years, the embedded carbon will appear only once if the period is 15 years, but twice if the period is 20 years, as the pump will need to be replaced. The prediction uses present sustainability data, which would be expected to improve with time. Initially the tarnish rate, in terms of layer thickness, is determined. This is converted into an equivalent L* or b* value from the data published by Ankersmit et al. (2004). Both colourimetric values have been shown to have some utility in describing human perception of silver tarnishing (Thickett et al. 2021a). This is assessed with the previously determined perception thresholds for when silver would need cleaning. Three values are possible: the average for Western observers, that for Eastern observers and the threshold characteristics inputted by users based on their organisational practice. The cleaning lifetime is calculated from these data and modified by the performance data of different approaches as scenarios. The number of cleans required in the period is then calculated. The carbon footprint is calculated for that number of cleans with the selected method and added to the carbon footprint for the scenario.

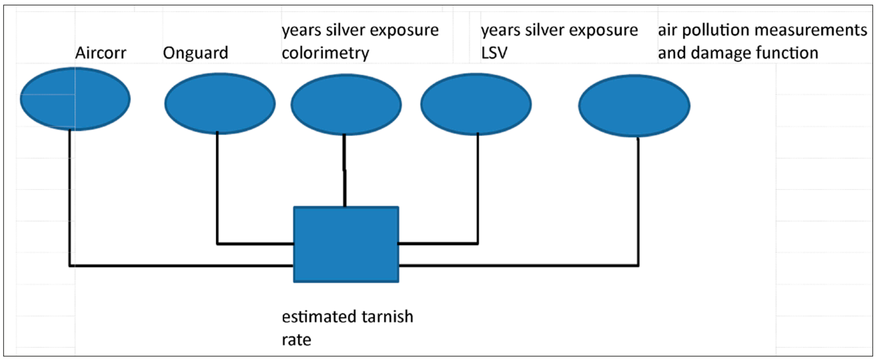

Figure 5. Simple scheme to assess and predict the carbon footprint of maintaining silver collections. Measurements of the tarnish rate

Table 5. Example inputs and outputs from the scheme

Time period	20 years				
Tarnish rate measured	30.4 nm/year				
b* Rate	3.2/year				
Cleaning threshold (western average)	7.3				
Cleaning lifetime	2.28 years				
Silver surface area	100 m^2				
	No change	**Room filtered**	**Lacquered**	**Showcase (1.23/day)**	**Plus Camfil pump**
Embedded		223	3.71	210	266
Running		1430			165
Calculated cleaning requirement in period	8	5	1	3	0
Cleaning Pre-Lim	1.68	1.05	0.21	0.63	0
Total carbon footprint	1.68	1561.05	4.71	210.63	432

The scheme was developed into a spreadsheet that gives the carbon footprint information for each approach. Table 5 shows the inputs for the spreadsheet and the outputs for five scenarios.

The measured tarnish rate and cleaning threshold indicated that the silver objects in the room would need to be cleaned every 2.28 years, without any interventions. From a carbon footprint perspective, simply going ahead

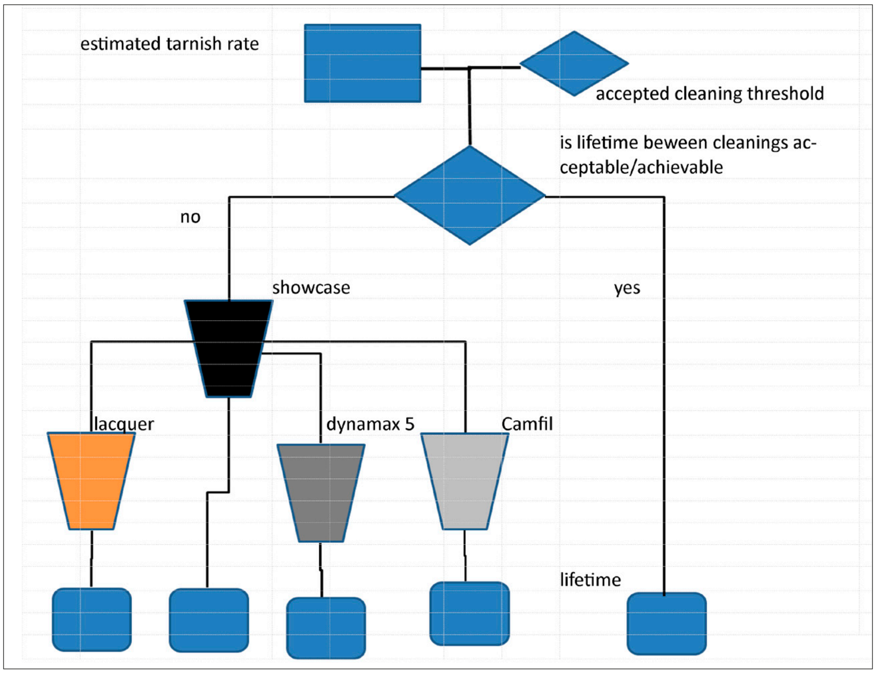

Figure 6. Simple scheme to assess and predict the carbon footprint of maintaining silver collections. Assessment of the cleaning frequency and the impact of room interventions

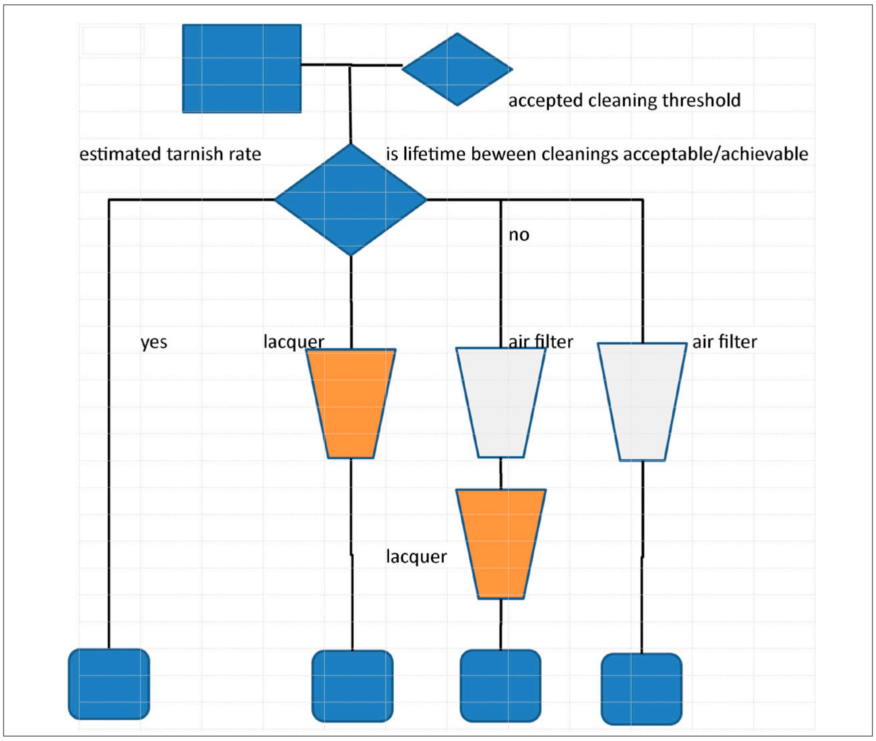

Figure 7. Simple scheme to assess and predict the carbon footprint of maintaining silver collections. Assessment of the cleaning frequency and impact of showcase interventions

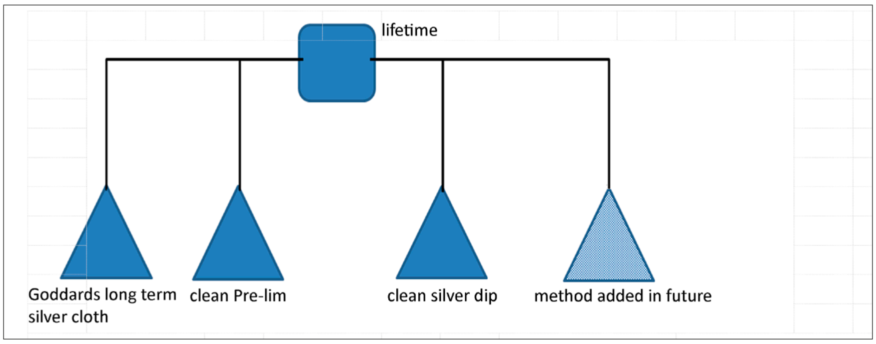

Figure 8. Simple scheme to assess and predict the carbon footprint of maintaining silver collections. Cleaning methods

with regular cleaning results in the lowest carbon footprint; however, each clean will cause some level of loss from the silver.

Generally, interventive treatments, including lacquering, have lower carbon footprints as their embedded carbon is much lower than the steel and components used in the equipment or showcases. Energy consumption has a very dramatic effect with filtering of the whole room.

This method allows a simple prediction that combines the environment and acceptable change (from professionals' perception of silver tarnish levels). The sustainability data are limited, as they had to be determined by identifying materials and using published tables. In the spreadsheet, initial values are reported but they can be updated as better information becomes available. The decision to exhibit silver in a showcase is generally due to security concerns, but the scheme can still be used. The spreadsheet produces carbon footprints for all possible included scenarios. The scheme allows comparison of different approaches to help decide which is most appropriate in a particular situation.

The main issues with the scheme are the limited approaches it considers. At present, only three cleaning methods are included. Twenty-nine methods were reported in the recent survey (Palomar et al. 2018) and the scheme would benefit greatly from the inclusion of data from these alternative methods. In addition, although the scheme is based on tarnish rate measurements of relatively pure silver, most objects have at least some copper in the alloy. If a year's worth of tarnishing data are available for the silver composition of interest, this information can be used. Measurements on object surfaces have been reported and are generally lower (Thickett and Hallett 2021a). Measurements have also been made for sterling (92.5%) and 91% silver/copper alloys and will be added to the scheme in the future. The limitations for the methods of estimating carbon footprints have been described and manufacturer cradle-to-gate data will greatly improve these estimates when available. The spreadsheet is readily transferable and adaptable for other institutions and users. Improved or other data can be incorporated as they become available.

The newly started GoGreen Project: Green Strategies to Conserve the Past and Preserve the Future of Cultural Heritage will investigate the wider aspects of sustainability and the transition of the conservation profession to green practices. It includes producing and testing greener materials for silver cleaning and preventive conservation strategies (GoGreen Project 2023).

CONCLUSION

Variations in energy usage between locations (even quite close locations) and building types were estimated and measured for a relatively simple situation (Munters MG50 dehumidifier controlling a showcase to below 55% RH). The results emphasise the need to take location into account. Case studies are crucial to any sustainability assessment, as details in the use phase significantly alter the outcomes, and they will therefore likely remain the main approach. It is, however, potentially misleading to transfer case study results between locations.

A simple model was developed using sustainability data to predict carbon footprints for different conservation approaches to managing silver tarnish. It will certainly benefit from improvement as new and more precise data becomes available. Initial applications indicate a low carbon footprint for passive measures (showcases) and a much lower one for interventive measures. A wider range of applications in different situations is required to draw general conclusions but it may be the case that any such conclusions will be compromised by local situations. However, these can be explored and different scenarios investigated using the model, thereby moving beyond reporting measurements of existing situations.

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