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A Comparison of Preservation Management Strategies for Paper Collections

Cristina Duran-Casablancas[1], Matija Strlič[1], Gabriëlle Beentjes[2], Gerrit de Bruin[2], Jaap van der Burg[3] and Josep Grau-Bové[1]

[1]Institute for Sustainable Heritage, University College London, London, UK; [2]Nationaal Archief, The Hague, Netherlands; [3]Helicon Conservation Support, Zoeterwoude, Netherlands

ABSTRACT
This paper proposes the use of simulation modelling to explore the effect of conservation strategies on the preservation of paper collections. Agent-based simulation was chosen as the simulation approach in order to capture the individual characteristics of the collections, their size, and the values of pH and degree of polymerisation (DP) for individual items. This approach enabled the simulation of the chemical degradation of different types of collections during their lifetime and under different preservation scenarios. We conducted a series of computational experiments on three types of collections, acidic, modern, and mixed, to explore the effect of slightly lowering the temperature and relative humidity in the repositories, the deacidification of part of the collection at different rates, and the delay in making the decision to start a deacidification treatment. The results indicated that a small change, lowering the storage conditions from 18°C to 16°C and from 50% to 40% RH, can protect up to 30% of the collection from reaching the critical DP of 300 within a time horizon of 500 years. On the other hand, to obtain similar results through deacidification, 45% of the mixed collection and 70% of the acidic collection should be deacidified within a period of 100 years. The experiments also indicated that better results are obtained when the priorities for deacidification are acidic records with a pH value below 5. This study shows that modelling the heterogeneity of the collections can support preservation management, particularly if the concern is not the preservation of a part of the collection but the collection as a whole.

KEYWORDS
Preservation management; preventive conservation; deacidification; simulation modelling; agent-based modelling; archives and library collections

Introduction

Acid-catalysed hydrolysis has been identified as the most important degradation mechanism in paper (Zou, Uesaka, and Gurnagul 1996; Zervos 2010). This is particularly the case for collections dating from the nineteenth century when lower quality wood fibres and alum-rosin sizing were introduced into paper manufacture, resulting in acidic pH values of paper. In order to manage the useful lifetime of collections containing acidic paper, preservation strategies have been proposed, consisting of a single or combined application of two preservation measures: lowering the storage temperature (T) and relative humidity (RH), and the deacidification of (part of) the collection.

In order to support preservation planning, research has been conducted to quantify the effect of these preservation options on the lifetime of collections. Regarding the study of the effect of changing the storage conditions, different models have been proposed to simulate the degradation of paper based on the Arrhenius equation (Ligterink and Di Pietro 2018; Tétreault et al. 2019). One of the proposed models is the damage function for acidic catalysed degradation of cellulose along with isochrone charts which show the lifetime expectancy of paper with a certain initial degree of polymerisation (DP) and pH value in different environmental conditions (Strlič et al. 2015b). If data is available on the DP and pH of individual items, then the expected lifetime expectancy of the whole of the collection can be calculated for long-term preservation planning. Whereas surface pH measurement does not require sophisticated equipment, the measurement of the DP is complex, and requires destructive sampling. However, in the last decade advances have been made with the development of a tool that derives DP values from the correlation between near infrared (NIR) spectra and analytical data obtained on a reference collection (Strlič, Kolar, and Lichtblau 2007), and commercial initiatives have become available that can be used during collection surveys (Duran-Casablancas et al. 2019).

On the other hand, research has also shown that deacidification can increase the lifetime of paper by a factor of 3 (Balazic et al. 2007). Although these results show the effectiveness of deacidification, they do not necessarily provide information on how it could be applied strategically, i.e. to optimise the preservation outcome. Usually, a (small) part of the collection is

CONTACT Cristina Duran-Casablancas cristina.casablancas.14@ucl.ac.uk Institute for Sustainable Heritage, University College London, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK

selected for deacidification, depending on the available budget. However, the benefits of such a strategy on the whole of the collection and whether the same results could be obtained by other strategies have not been explored yet.

In view of this, the focus of this paper was to explore the effect of preservation options, in particular deacidification, when they are tested in realistic scenarios, taking into account the type and size of the collection. First, we analysed the importance of the selection criteria for deacidification. Although paper with pH below 7 is eligible for deacidification, institutions opt to prioritise papers with a lower pH value, with 5.5 as the upper limit (Porck 2006; Shenton 2006). Similarly, some institutions would only select records for the deacidification treatment when paper is still strong and flexible enough, excluding brittle paper that will not benefit from the treatment as long as strengthening is not part of the treatment (Grossenbacher 2006). After identifying the best selection criteria for deacidification, we explored how similar preservation outcomes can be achieved either by deacidifying or by improving the environmental conditions of storage. Lastly, we assessed the long-term effect of delaying the decision of implementing a certain preservation strategy.

A model to examine these questions should meet two requisites: firstly, the degradation processes as well as the implementation of preservation options should be simulated over time, and secondly, the model should capture the individual characteristics of items of the collection. In order to capture the dynamic behaviour of the collections over time, we used mathematical modelling, specifically computer simulation. The mathematical formulation makes it possible to explore how changes of parameter values impact the overall behaviour of the model.

Regarding the importance of capturing the characteristics of the items to model the degradation of the collections, there are two main simulation approaches: system dynamics (SD) and agent-based simulation (ABS) (Schieritz and Milling 2003). SD takes an aggregate view. Stocks of population represent different states of the items with different probabilities. However, archival and library collections are a composition of individual items, with their own values of pH and DP. In order to capture the heterogeneity of the collections and the behaviour that follows from the individual characteristics, then a higher level of detail is needed. In that case, agent-based simulation seems the most appropriate approach, as ABS has been defined as 'a modeling and computational framework for simulating dynamic processes that involve autonomous agents' (Macal and North 2014). In ABS a composite of agents with individual characteristics and behaviour is modelled (Weimer, Miller, and Hill 2016), in order to capture the heterogeneity of the agents across a population. In our case, if the population is an archival or library collection, then agents are a single or a group of inventory numbers. Another important element in ABS is the 'environment' which affects the agent's behaviour. In the case of heritage collections environment, it may refer to the storage conditions or other preservation measures.

By using ABS, we were able to conduct simulations of what-if scenarios with a high level of detail, where each parameter regarding the selection of the agents to be treated, the level of treatment, and the timespan of the treatment could be adjusted at initialisation of the run or any given timestep during the run.

Methodology

Modelling

The first step of the modelling process consisted of the creation of a population of agents. In this model, the population is the whole archive or library collection, while agents are the inventory numbers (archival records or books). A population can be created with any desired number of agents. However, in order to make the simulation computationally efficient, but still close to the daily practice in institutions, we created a population of 2000 agents. This implies that in the case of a population representing a collection of 50,000 linear metres, an agent is equivalent to 25 metres of archival records, and that the minimal amount of metres to be selected for deacidification per year is 25 metres, or in the case of a collection of 15,000 linear metres, one agent is 7.5 metres.

Then the individual characteristics of the agents were defined. An initial DP and pH value and a state (good, fair, and critical) was attributed to each agent: good condition if the DP value is higher than 800, fair condition if the DP value is between 301 and 800, and critical condition if the DP has reached the critical value of 300. This classification follows the characterisation proposed by Strlič et al. (Strlič et al. 2015a) of fitness-for-use, where papers with a DP lower than 300 are defined as unfit for purpose due to their poor mechanical properties. During a run, the condition of the agents may change depending on their actual DP. As default, the agents were not deacidified, in order to compare the effect of deacidification to other preservation strategies.

As the focus of this study lay on the management of the chemical degradation of paper collections, the model included two conservation options: changing the environmental conditions and deacidification. The environment was controlled by modifying the values of temperature and humidity. Deacidification was controlled by setting three parameters: the number of metres deacidified per year and the pH and DP values used to select the agents to be deacidified.

The impact of the inputs on the behaviour of the agents was modelled using the damage function developed for acidic catalysed degradation of cellulose (Strlič et al. 2015b). This damage function calculates the actual DP yearly, which decreases depending on the pH of the paper and the storage temperature (T) and relative humidity (RH). In order to model the effect of deacidification, when an agent was selected for deacidification, then the pH value of the agent was returned to a value between 7 and 9.5, following a theoretical uniform distribution. As shown in the study conducted by Ahn et al. (Ahn et al. 2011), depending on the applied deacidification method different frequency distributions of the surface pH after treatment are obtained. Although it is not further explored in this paper, the model allows one to test different distributions to study the uncertainty related to the effectiveness of the deacidification treatment.

The output of the model was the annual percentage of the collection in a certain state, as well the percentage of collection deacidified. The experiment had a run time of 500 years. Other time horizons could be chosen if so desired. In addition, in every time step the input values could be varied. This allowed us to choose the duration of a certain measure as well as the time of implementation.

AnyLogic® simulation software, version 8.5.1., was used to build and run the simulation model.

Modelled data. To explore the impact of preservation measures on different types of collections, we created model datasets, representing archival and library collections. To build the archival collections, the SurveNIR historic reference paper collection (665 samples) (Strlič et al. 2015b) and data from 431 papers of the collections of the Amsterdam City Archives and the Dutch National, collected using the SurveNIR instrument (Lichtblau e.K., Germany) (Duran-Casablancas et al. 2019) were used. First, the frequency distributions of the DP of three datasets were created to represent: a collection with mainly papers with low DP and pH values (mostly groundwood paper), a second collection dating from 1850 containing groundwood paper and bleached pulp papers, and a third collection containing rag, bleached pulp, and groundwood paper. Then the pH values were created with randomly generated data following a normal distribution. Different input values were introduced for different DP values:

(1) mean = 5.150; SD=0.5169 if DP $<$ 1000
(2) mean = 5.704; SD=0.6466 if 1000 $\leq$ DP $>$ 1500
(3) mean = 6.167; SD=0.6209 if 1500 $\leq$ DP $>$2000
(4) mean = 6.34; SD=0.5907 if DP $\geq$ 2000

The three generated datasets can be described as follows (Figure 1):

(1) Acidic archival collection (C.1): The first dataset represents a collection of mostly groundwood paper, solely including papers with a pH value below 6 (31% of them with a pH value below 5). Consequently, the DP frequency distribution is clearly positively skewed, with a mode peak around 700 and mean DP of 859.
(2) Modern archival collection (C.2): In this dataset the DP frequency distribution is slightly positively skewed and the peak value is around 1000 to represent the chemical characteristics of groundwood and bleached pulp papers dating after 1850. Compared to a mixed collection the percentage of acidic paper is higher (71% with a pH value below 6 and 22% below 5).
(3) Mixed archival collection (C.3): This dataset represents a collection containing rag, bleached pulp, and groundwood paper. This results in a bimodal DP frequency distribution, with a first wave representing acidic paper with a peak value around 600 and a second wave for rag paper and good quality modern paper with a higher peak value around 1800. Regarding the pH, 61% of the collection has a pH value below 6, and 17% a value below 5.

In addition to the acidic collection described above, which represents acidic collections in archives, two more datasets were created to characterise acidic library collections dating from 1850. In this type of collection, up to 90% of the printed books are acidic, and the folding endurance is low (Bajzíková, Hanus, and Bukovský 2008; Vinther Hansen and Vest 2008). Figure 2 shows the DP frequency distribution of a library collection (L.1) with a mean DP of 444, and a second library collection (L.2) with an even lower mean DP of 398. The acidic archival collection (C.1) shown in Figure 1 is also included as comparison. The Minitab-18 program (Minitab Inc., PA, USA) was used to create the datasets.

Description of experiments

A collection of 50,000 metres was chosen to calculate the number of metres that are deacidified depending on the strategy. However, the calculations are shown as relative values (i.e. percentages of the collection) rather than absolute values (metres). As a result, the model is applicable to collections of any size. The percentage of the collection unfit for the purpose of handling (DP $<$ 300) during or after 500 years was used to evaluate the output of different model runs.

The experiments conducted to explore the selection criteria for deacidification and to compare the impact of changing environmental conditions in repositories versus deacidification are described in Table 1. A

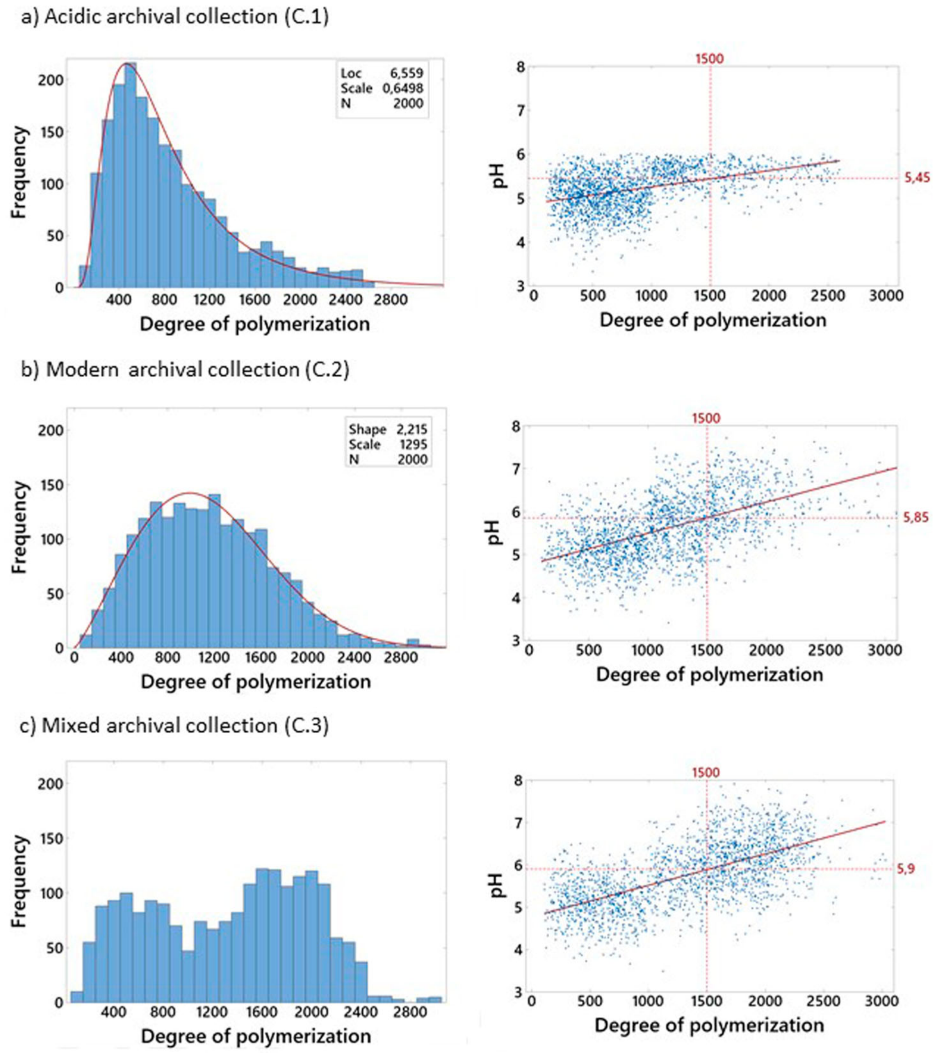

Figure 1. Generated datasets for (a) acidic (C.1), (b) modern (C.2), and (c) mixed (C.3) collections. The graphs show the DP frequency distribution and the individual values of DP and pH of a population of 2000 agents.

deacidification rate of 100 m of the collection in 100 years, equivalent to the deacidification of 20% of the collection, was chosen in order to obtain a noticeable difference in the results between the baseline (no deacidification) and the deacidification experiment.

Two series of experiments were also conducted on the archival collections (C.1, C.2, C.3) to explore the effect of delaying the decision of deacidification. In the first series, experiment 3.4 was repeated changing the duration of the treatment between 50 and 350 years. In the second series, the deacidification treatment conducted during 50 years to obtain the same results as in 3.4 was delayed with time steps of 50 years.

The experiment results were compared using the Minitab-18 program (Minitab Inc., PA, USA).

Results

Criteria of selection for mass deacidification

In the first experiment, we explored the long-term effect of a deacidification strategy that prioritises the

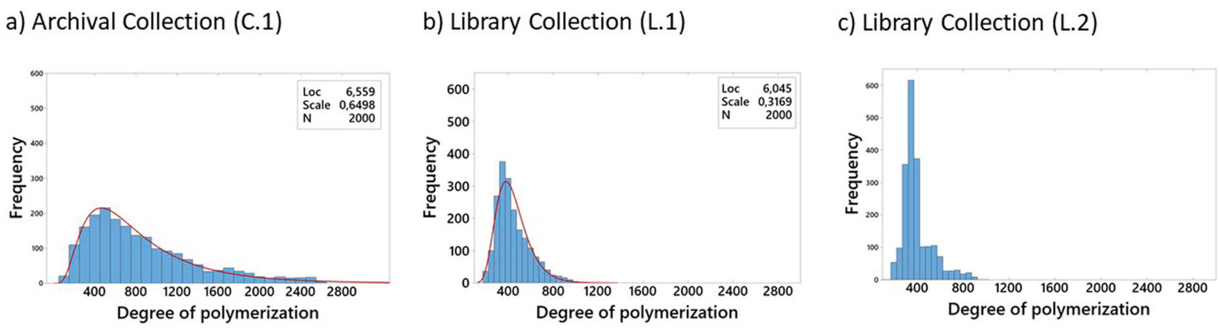

Figure 2. Generated datasets for three acidic collections with different DP frequency distributions of a population of 2000 agents.

Table 1. Description of the experiments.

Experiment	Collection	T (°C)	RH (%)	Deacidification Rate (m/year)	duration (year)	delay (year)	pH	DP <300
Experiments to explore selection criteria deacidification								
Baseline 1	C.1 C.2 C.3	18	50	100	100	0	<6	included
1.1	C.1 C.2 C.3	18	50	100	100	0	<5	included
1.2	C.1 C.2 C.3	18	50	100	100	0	<6	excluded
1.3	C.1 C.2 C.3	18	50	100	100	0	<5	excluded
Experiments to compare environmental conditions vs deacidification								
Baseline 2	C.1 L.1 L.2	18	50	0	0	0	–	–
2.1	C.1 L.1 L.2	16	40	0	0	0	–	–
2.2	C.1 L.1 L.2	5	40	0	0	0	–	–
2.3	C.1 L.1 L.2	18	50	whole collection	1	0	–	–
Baseline 3	C.1 C.2 C.3	18	50	0	0	0	–	–
3.1	C.1 C.2 C.3	16	45	0	0	0	–	–
3.2	C.1 C.2 C.3	16	40	0	0	0	–	–
3.3	C.1 C.2 C.3	18	50	100	100	0	< 5	excluded
3.4	C.1 C.2 C.3	18	50	metres to obtain results as in 3.2	100	0	< 6	excluded

most acidic records. In the case of acidic and modern collections, the rate of the treatment, 100 m per year during 100 years, resulted in the deacidification of 20% of the collections. In the case of mixed collections, the treatment could be solely implemented on 17% of the collection, as this is the total percentage of the collection with a pH lower than 5.

The results indicated that, in all three types of collections, lowering the pH value to 5 as the selection criterion leads to a lower percentage of the collection in critical condition in the long-term (Table 2). Modern collections seem to benefit the most from this strategy. When the DP value is used as a selection criterion, the results indicate that excluding items which are too brittle has little impact on the overall effectiveness of the treatment. In summary, in these scenarios, using pH as the selection criteria for deacidification is a better strategy than using the DP.

Storage conditions vs deacidification

In the following series of experiments, preventive preservation measures related to the storage conditions were compared to the conservation measure of deacidification of the collections. In the first experiment, we tested the best results that can be achieved if it were feasible to deacidify the whole collection within one year and with no delay. The tests were conducted on the three acidic collections, C.1, L.1, and L.2 (Table 3). At the beginning of the run (time 0), the percentage of the collection with a DP lower than 300 was 10% for each of the collections. In the case of the acidic collection with a higher DP average (C.1), if deacidification is conducted, then just 14% of the collection would reach the state of being unfit for purpose. The same results were obtained if the collection is kept in storage conditions of 5°C and 45% RH, which were also equivalent to the results obtained when the storage conditions are 8°C and 40% RH. However, in the case of the other two acidic collections, we observed that the lower the DP average of the collection the larger the differences in effectiveness between the preservation strategies. In these two cases (L.1 and L.2), even if the whole collection was deacidified, more than 25% of the collection reached a DP lower than 300 after 500 years. To achieve a better level of protection, cold storage (storage T below 5°C) seems to be the only option.

When considering archive collections as a whole, it would not be affordable to implement deacidification on such a scale, within a short time, or to change to cold storage. Therefore, in the following experiment, we explored scenarios that are more realistic: a small change in the repository conditions, assuming 18°C and 50% RH as baseline; or the deacidification of a

Table 2. Comparison of the effect of a deacidification treatment on the percentage of the collection unfit for purpose after 500 years when different selection criteria for deacidification are applied. The last column shows the difference in the end results between the baseline and the experiment.

Type collection	Experiment	pH	DP < 300	Collection deacidified (%)	Unfit for purpose (%)	Difference Baseline-Experiment (%)
C.1: Acidic	Baseline 1	< 6	included	20	52.9	0
	Exp. 1.1	< 5	included	20	46.9	6
	Exp. 1.2	< 6	excluded	20	51.9	1
	Exp. 1.3	< 5	excluded	20	44.9	8
C.2: Modern	Baseline 1	< 6	included	20	29.1	0
	Exp. 1.1	< 5	included	20	20.5	9
	Exp. 1.2	< 6	excluded	20	28.7	0.4
	Exp. 1.3	< 5	excluded	20	19.6	9.5
C.3: Mixed	Baseline 1	< 6	included	17	25.2	0
	Exp. 1.1	< 5	included	15	19.7	5.5
	Exp. 1.2	< 6	excluded	17	24.6	0.6
	Exp. 1.3	< 5	excluded	15	19.6	5.6

Table 3. Comparison of strategies for three acidic collections after a time horizon of 500 years. The last column shows the difference in the end results between the baseline and the experiment.

Type collection	Experiment	Experiment description	Unfit for purpose (%)	Difference Baseline-Experiment (%)
C.1	Baseline 2	18°C – 50%	62.5	0
	Exp. 2.1	16°C – 40%	31.2	31.3
	Exp. 2.2	5°C – 40%	12.5	50.0
	Exp. 2.3	deacidification	14.4	48.1
L.1	Baseline 2	18°C – 50%	94.7	0
	Exp. 2.1	16°C – 40%	68.2	26.5
	Exp. 2.2	5°C – 40%	20.1	74.6
	Exp. 2.3	deacidification	28.9	65.8
L.2	Baseline 2	18°C – 50%	97.3	0
	Exp. 2.1	16°C – 40%	80.2	17.1
	Exp. 2.2	5°C – 40%	25.4	71.9
	Exp. 2.3	deacidification	39.4	57.9

part of the collection. The results showed visible differences in an early stage of the experiment conducted on acidic collections (C.1) (Figure 3). In the case of the other two collections (C.2 and C.3), the differences became visible after 100 years. The largest impact on the preservation of the collection was observed when temperature and RH are lowered, particularly in the case of acidic collections (C.1) (Table 4). In the case of mixed collections (C.3), similar results were obtained between the deacidification of 15% of the collection and lowering the T and RH to 16°C and 45%.

These experiments illustrate that similar results can be obtained by lowering T and RH and by deacidifying a certain percentage of the collection, depending on the type of the collection, i.e. the percentage of acidic paper within a collection. In the next experiment, we calculated how many metres need to be deacidified during a period of 100 years to obtain the same results as when storage conditions of 16°C and 40% RH are met. The experiments showed that it is not feasible to achieve these results by deacidification of records with a pH < 5 exclusively. For example, in the case of the acidic archival collection (C.1), if only records with a pH lower than 5 were deacidified (37% of the collection) then 38% of the collection would reach a DP lower than 300. To obtain the same results as the ones obtained by storage conditions of 16°C and 40% RH (ca. 31% in critical condition), then records with a pH value up to 6 need to be included. Table 5 shows the percentage of the collection during 100 years that needs to be deacidified to obtain the same results as storage conditions of 16°C and 40% RH.

Effect of delay in decision-making

In the prior experiment (Table 5), a number of metres were deacidified during a period of 100 years to obtain similar results compared to storage conditions of 16°C and 40% RH. However, similar results can also be obtained by following other strategies. Figure 4 shows the number of metres that need to be deacidified of for each of the archival collections (C.1 – C.3) if another timespan for the treatment is chosen in order to obtain the same results as stated in Table 5. The longer the timespan the lower the number of metres that needs to be deacidified per year.

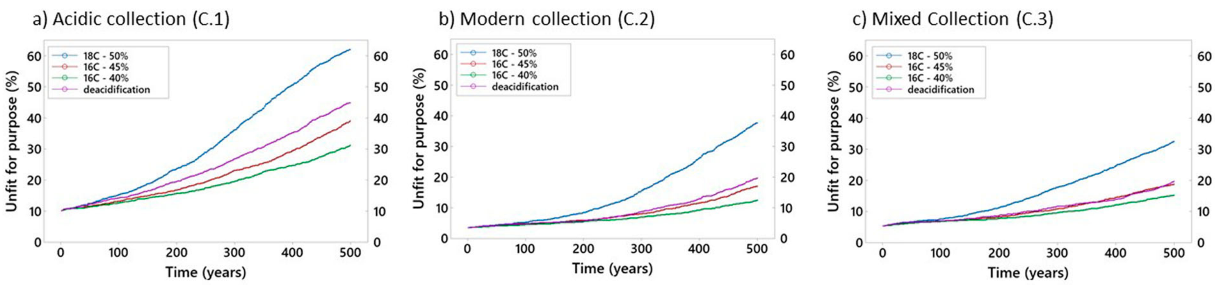

Figure 3. Results of four preservation strategies conducted on (a) acidic, (b) modern, and (c) mixed collection, in the time horizon of 500 years.

Table 4. The preservation strategies presented in Figure 3 are compared at the end of the time horizon of 500 years. The last column shows the difference in the end results between the baseline and the experiment.

Type collection	Experiment	Experiment description	Unfit for purpose (%)	Difference Baseline-Experiment (%)
C1: Acidic	Baseline 3	18°C – 50%	62.5	0
	Exp. 3.1	16°C – 45%	39.1	23.4
	Exp. 3.2	16°C – 40%	31.2	31.3
	Exp. 3.3	20% deacidification	44.9	17.6
C2: Modern	Baseline 3	18°C – 50%	37.8	0
	Exp. 3.1	16°C – 45%	16.9	20.9
	Exp. 3.2	16°C – 40%	12.4	25.4
	Exp. 3.3	20% deacidification	19.6	18.2
C3: Mixed	Baseline 3	18°C – 50%	32.5	0
	Exp. 3.1	16°C – 45%	18.7	13.8
	Exp. 3.2	16°C – 40%	15.6	16.9
	Exp. 3.3	15% deacidification	19.6	12.9

Table 5. Number of metres that need to be deacidified per year during a period of 100 years to obtain similar results on the preservation of the collection of 50,000 metres compared to storage conditions of 16°C and 40% RH.

Type collection	Deacidification (m/year)	Collection deacidified (%)
C.1: Acidic	350	70
C.2: Modern	300	60
C.3: Mixed	225	45

However, as the collection degrades over time, and the part that that has not been treated yet degrades even faster, slowing the treatment rate will have the consequence that a higher percentage of the collection will need to be treated to obtain the same results.

In the last experiment, we explored the consequences of delaying the decision to deacidify. As an example (Figure 5), we delayed in steps of 50 years the strategy of deacidifying the collections within 50 years (first strategy in Figure 4). The effect of the delay in implementing a preservation measure is most noticeable in acidic collections, where the percentage of metres unfit for purpose increases linearly with the delay. The effect is also clear in the case of modern collections, but rather than being linear, the consequences are more severe further in the future. Similar results were obtained when the implementation of lowering in T and RH in the repositories was delayed.

Discussion and conclusion

Simulation modelling was used to examine the impact of different preservation strategies on the chemical degradation of paper collections within a time horizon of 500 years. The aim of this study was to explore whether the positive effect of a small change in the storage environmental conditions on the preservation of paper collections could be achieved by other means, namely deacidification, following different selection strategies.

The experiments showed that the prioritisation of the most acidic records, with a pH value below 5, has a noticeable positive effect on the effectiveness of the treatment. In this study, effectiveness is measured in terms of preventing records reaching the critical DP of 300. Naturally, by narrowing the records eligible for deacidification, the probability of selecting those records which would benefit the most increases.

When dealing with limited financial resources, the prioritisation of those records that would benefit from a deacidification treatment the most becomes relevant. In this case, the records that would benefit the most are those with a higher rate of degradation due to the low pH value, and a DP value close to the critical DP value of 300. To illustrate the scale within which chemical degradation occurs, according to the damage function for acidic catalysed degradation of cellulose (Strlič et al. 2015b), it is expected that DP loss for records with a pH value of 6 will be 120 in 100 years, and 220 for records with a pH value of 5, assuming storage conditions of 18°C and 50% RH (Figure 6). Although the benefits of a comprehensive selection are clear, such a detailed selection can be extremely time-consuming, particularly when inventory numbers are a composite of different types of paper. Institutions must therefore balance the thorough process of selection against the chance of treating part of the collections with a lower priority leading to higher costs of deacidification.

We showed that when the goal is to optimise the preservation of the whole of the collections, depending on the percentage of acidic papers within the collection, similar results could be achieved if the entire collection is deacidified or alternatively kept in a cold storage of 5°C and 40% RH. However, when dealing with acidic collections with a mean DP lower than 500, such as in the case of library collections, the same level of protection cannot be achieved by deacidification, with cold storage the most effective measure, in agreement with the

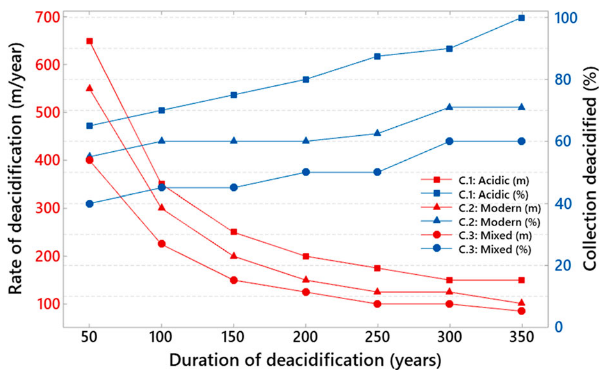

Figure 4. A comparison of strategies for deacidification with the same effectiveness as storage conditions at 16°C and 40% RH. The strategy is described by the number of metres that need to be deacidified per year (*y* left axis) and for how long (*x* axis). The resulting percentage of deacidified collection after the treatment is also shown (*y* right axis).

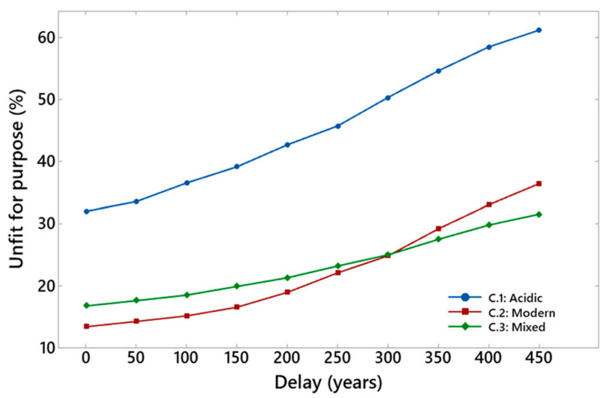

Figure 5. Effect of the strategy of deacidifying part of the collection in 50 years (delay 0 years) and the effect of the same strategy if implementation is delayed in steps of 50 years.

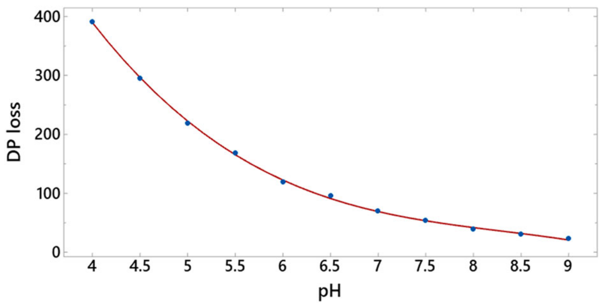

Figure 6. Expected DP loss in 100 years depending on the pH value of the record, assuming storage conditions of 18°C and 50% relative humidity, according to the damage function developed for acidic catalysed degradation of cellulose (Strlič et al. 2015b).

predictions presented in other studies (Vinther Hansen and Vest 2008).

We also explored various less demanding scenarios, for example decreasing the T to 16°C and the RH to 40%. Results indicated that all types of collections would benefit from a small decrease in the T and RH in the repositories. When dealing with acidic collections, differences in preservation were already visible within the timespan of the next 100 years. The improvement was most noticeable for acidic collections, with a mean DP of 800. However, we observed that when dealing with collections with a mean DP lower than 500, a small decrease in T and RH has a limited impact and more rigorous measures, such as cold storage, are the only option to keep the percentage of brittle paper lower than 25% of the collection.

Compared to deacidification, changing the environmental conditions seems to be more effective as the whole collection benefits from this preservation measure. Moreover, when the concern is the preservation of the collections as a whole, deacidification might turn into a highly expensive option. For example, institutions holding small size mixed collections have the option to deacidify a relatively small part of their collection (ca. 15%) in 100 years, achieving similar results as when changing the environmental conditions to 16°C and 45% RH, if the selection criteria for deacidification are pH lower than 5 and records with DP lower than 300 are excluded. If the selection criteria are pH lower than 6, then the percentage to be deacidified rises to 35%. To obtain the same level of effectiveness as storage conditions of 16°C and 40% RH, the percentage of the collection that need to be treated rises from 45% for mixed collections to 70% for acidic collections. Table 6 shows an overview of the simulations conducted comparing the effect of different environmental conditions and deacidification, when records with pH lower than 6 are deacidified.

Preservation planning is generally driven by the available budget within the operational planning of 3–5 years (Bell, Cassar, and Strlič 2018). However, to save financial resources in the long-term, institutions that choose deacidification as a conservation strategy need to keep in mind that the most efficient strategy is to deacidify as much as possible and as soon as possible. Through simulations, we could examine the effect of preservation measures over time, while degradation of the collection takes place. We calculated that if an institution opts for a lower rate of deacidification, then deacidification treatment needs to be carried out longer period to obtain the same results, and consequently a higher percentage of the collection will be deacidified at a higher cost.

This study has shown the potential of agent-based simulation when the individual characteristics of the collection are a determinant factor. The use of simulations also allows testing what-if scenarios taking into account the changes that occur over time, such as degradation processes. Moreover, the level of detail of simulation is high, as any single element of the model can be modified during the runs. Although it has not been further explored in this study, combinations of preservation measures can be done and uncertainty can be introduced by using probability distributions, for example, to capture the uncertainty of the effectiveness of deacidification regarding the pH value after treatment. For this study, datasets were generated representing typical paper collections. However, any collection with its own characteristics can be introduced in our model. The model can also be further developed to include other aspects of

Table 6. Comparison of environmental strategies versus deacidification for acidic (L.1, C.1), modern (C.2) and mixed (C.3) collections after a time horizon of 500 years. First column shows different environmental strategies. Second column shows the percentage of the collection that should be deacidified to get the same results as the environmental strategies. Records with a pH value lower than 6 were selected for deacidification. The duration of the deacidification treatment was 100 years.

Storage conditions	Collection deacidified (%)	Unfit for purpose (%)
Library collection (L.1)		
18°C – 50%	–	95
16°C – 45%	30	77
16°C – 40%	45	68
10°C – 45%	100	39
5°C – 40%	–	20
Acidic archival collection (C.1)		
18°C – 50%	–	62
16°C – 45%	50	39
16°C – 40%	70	31
10°C – 45%	100	17
5°C – 40%	–	13
Modern archival collection (C.2)		
18°C – 50%	–	38
16°C – 45%	45	17
16°C – 40%	60	12
10°C – 45%	71	6
5°C – 40%	–	4
Mixed archival collection (C.3)		
18°C – 50%	–	33
16°C – 45%	35	19
16°C – 40%	45	16
10°C – 45%	–	8
5°C – 40%	–	7

preservation management, such as costs and access. Agent-based simulation has the potential to become a tool to be used to examine current strategies as well as to develop new ones.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on request.

References

Ahn, K., U. Henniges, A. Blüher, G. Banik, and A. Potthast. 2011. "Sustainability of Mass Deacidification. Part I: Concept, Selection of Sample Books and PH-Determination." *Restaurator* 32 (3): 193–222. doi:10.1515/rest.2011.010.

Bajzíková, M., J. Hanus, and V. Bukovský. 2008. "*Characterisation of the Slovak National Library Collections*." *Durability of paper and Writing 2: Book of Abstracts: 2nd International Symposium and Workshops*, Ljubljana, Slovenia, July 5–7, 2008, 51–52.

Balazic, A., S. Habicht, M. Smodis, J. Kolar, and M. Strlic. 2007. "Expending the Useful Life of Paper. Evaluation of the Effect of Various Preservation Actions." In *Museum Microclimates*, edited by T. Padfield, and K. Borchersen, 39–41. Copenhagen: National Museum of Denmark. http://www.conservationphysics.org/mm/balazic/balazic.pdf.

Bell, N., M. Cassar, and M. Strlič. 2018. "Evidence for Informed Preservation Planning and Advocacy. A Synoptic View." *Studies in Conservation* 63 (sup1): 8–14. doi:10.1080/00393630.2018.1475099.

Duran-Casablancas, C., J. Grau_Bové, T. Fearn, and M. Strlič. 2019. "Accumulation of Wear and Tear in Archival and Library Collections. Part II: An Epidemiological Study." *Heritage Science* 7 (11), doi:10.1186/s40494-019-0253-2.

Grossenbacher, G. 2006. "Paper Deacidification as a Measure for Preserving Originals." In *Save Paper! Mass Deacidification: Today's Experiences -Tomorrow's Perspectives*, edited by Agnes Blüher, and G. Grossenbacher, 7–20. Bern: Swiss National Library.

Ligterink, F., and G. Di Pietro. 2018. "The Limited Impact of Acetic Acid in Archives and Libraries." *Heritage Science* 6 (1), doi:10.1186/s40494-018-0225-y.

Macal, C. M., and Michael J North. 2014. "Introductory Tutorial. Agent-Based Modeling and Simulation." In *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 6–20. Piscataway, New Jersey: Institute of Electrica and Electronics Engineers, Inc.

Porck, Henk J. 2006. "The Bookkeeper Process and Its Application at the National Library of the Netherlands." In *Save Paper! Mass Deacidification: Today's Experiences -Tomorrow's Perspectives*, edited by Agnes Blüher, and G. Grossenbacher, 37–42. Bern: Swiss National Library.

Schieritz, N., and P. Milling. 2003. "Modeling the Forest or Modeling the Trees: A Comparison of System Dynamics and Agent-Based Simulation." In *Proceedings of the 21st International Conference of the System Dynamics Society: July 20 - 24, 2003, New York City, USA*, edited by R. Eberlein, V. Diker, R. Langer, and J. Rowe.

Shenton, H. 2006. "Strategies for Mass Preservation Treatment." In *Save Paper! Mass Deacidification: Today's Experiences -Tomorrow's Perspectives*, edited by Agnes Blüher, and G. Grossenbacher, 63–74. Bern: Swiss National Library.

Strlič, M., C. M. Grossi, C. Dillon, N. Bell, K. Fouseki, P. Brimblecombe, E. Menart, et al. 2015a. "Damage Function for Historic Paper. Part II: Wear and Tear." *Heritage Science* 3 (1): 36. doi:10.1186/s40494-015-0065-y.

Strlič, M., C. M. Grossi, C. Dillon, N. Bell, K. Fouseki, P. Brimblecombe, E. Menart, et al. 2015b. "Damage Function for Historic Paper. Part III: Isochrones and Demography of Collections." *Heritage Science* 3 (1): 40. doi:10.1186/s40494-015-0069-7.

Strlič, M., J. Kolar, and D. Lichtblau. 2007. "The SurveNIR Project—a Dedicated Near Infrared Instrument for Paper Characterization." In *Museum Microclimates*, edited by T. Padfield, and K. Borchersen,, 81–84. Copenhagen: National Museum of Denmark. http://www.conservationphysics.org/mm/musmic/musmic150.pdf.

Tétreault, J., P. Bégin, S. Paris-Lacombe, and A. L. Dupont. 2019. "Modelling Considerations for the Degradation of Cellulosic Paper." *Cellulose* 26 (3): 2013–2033. doi:10.1007/s10570-018-2156-x.

Vinther Hansen, B., and M. Vest. 2008. "*The Lifetime of Acid Paper in the Collection of the Royal Library*." Durability of paper and Writing 2: Book of Abstracts: 2nd International Symposium and Workshops. Ljubljana, Slovenia, July 5-7, 2008, edited by M. Strlic and J. Kolar, 38–39. Ljubjana: Faculty of Chemistry and Chemical Technology.

Weimer, Christopher W, J. O. Miller, and Raymond R Hill. 2016. "*Agent-Based Modeling: An Introduction and Primer*." Proceedings of the 2016 Winter simulation Conference, edited by T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, 65–79.

Zervos, S. 2010. "Natural Accelerated Ageing of Cellulose and Paper: A Literature Review." In *Cellulose: Structure and Properties, Derivatives and Industrial Uses*, edited by A. Lejeune and T. Deprez, 155–204. New York: Nova Science Publishers, Inc.

Zou, X., T. Uesaka, and N. Gurnagul. 1996. "Prediction of Paper Permanence by Accelerated Aging. Part I: Kinetic Analysis of the Aging Process." *Cellulose* 3: 243–267.