

DOI: 10.37943/ZCHB4846**Dina Kantayeva**

PhD student, School of Software Engineering
d.kantayeva@astanait.edu.kz, orcid.org/0000-0002-4097-5078
Astana IT University, Kazakhstan

Ilyas Kazambayev

PhD Student, Director, Industry 4.0 Scientific Innovation Center
i.kazambayev@astanait.edu.kz, orcid.org/0000-0003-0850-7490
Astana IT University, Kazakhstan

Lalita Kirichenko

Master's Degree, Researcher, Department of Scientific Programs
lalita17021996@gmail.com, orcid.org/0000-0001-7069-5395
Kazakh National University of Sports, Kazakhstan

Daniyar Dauletiya

Master's Degree, Head of the FabLab Research and Innovation Laboratory
d.dauletiya@astanait.edu.kz, orcid.org/0000-0002-3205-7453
Astana IT University, Kazakhstan

**A MODULE FOR ASSESSING AND FORECASTING THE CONDITION OF
HISTORICAL ARTIFACTS AND DOCUMENTS**

Abstract: Traditionally, preventive conservation of paper archives relies on recording threshold microclimate values in the storage facility or on periodic inspection of the materials. Neither approach gives an updated forecast of when each object will next require conservation. This article addresses that gap by proposing a condition-assessment and forecasting module for a smart, IoT-enabled archival storage facility. The module combines two mechanisms of paper degradation into a single preservation index for each object: a chemical dose-response function describing cellulose breakdown under temperature, relative humidity and acidity, and a mechanical function describing damage accumulated through document handling. From this index, the module forecasts the remaining time until the usability threshold is reached and issues a notification once that time falls below a specified planning horizon. Unlike existing approaches, applied either at the storage level (preservation index / time-weighted preservation index, commercial monitoring panels) or as a static, one-time calculation for an entire collection (damage-function isochrones), the proposed architecture recalculates the forecast continuously from real-time sensor data for each individual object. The computational core of the model was tested under accelerated-ageing conditions (ISO 5630-3) and reproduced the expected degradation periods, confirming correct implementation of the underlying kinetic equation, and was further validated against a real 12-year climate record and across several document profiles, with a sensitivity analysis of the mechanical parameters. The mechanical component and the composite Health Index remain validated only theoretically against real telemetry and have not yet been compared with an expert conservator assessment. The proposed module opens practical opportunities for archival equipment that not only maintains specified climatic conditions but also actively supports institutions in planning conservation work.

Keywords: preventive conservation; condition assessment; degradation modeling; heritage documents; Internet of Things; dose-response function; wear-out function; remaining useful life; Smart Archival Box.

Introduction (Literary review)

The purpose of the module proposed in this paper is to show the current condition of each document or artifact in storage, and how long it will be before it requires a repeat conservation

intervention. This task does not belong to the field of indoor microclimate forecasting, but to the field of damage functions and lifetime prediction in heritage science.

Table 1. Comparison of existing methods for condition assessment and forecasting of conservation timing

Method	What it does	Advantages	Limitations
Preservation Index (PI) / Time-Weighted Preservation Index (TWPI) [1]	Converts measured T and RH into an expected material lifetime (years) via the Arrhenius equation; TWPI time-weights the indicator over the real, fluctuating climate	Translates T/RH directly into a 'years remaining' indicator; established commercial software exists	Coefficients originally calibrated on a model reaction (cellulose acetate hydrolysis), not on paper; can produce implausible estimates; does not account for the individual DP/pH of a specific document
Damage function for historic paper. Part I: Fitness for use [2]	Experimentally determines what makes a paper document unfit for use — primarily loss of text, rather than discolouration or minor tears	Introduces, for the first time, an empirically grounded fitness-for-use threshold rather than an arbitrary one	The threshold is specific to reading-room access; does not address objects already assigned high historical/cultural value
Damage function for historic paper. Part II: Wear and tear [3]; extended by Vibert et al. [4] and Parsa Sadr et al. [5]	Builds a wear-out function describing the accumulation of text loss as a function of degree of polymerisation (DP) and the number of handling events	For the first time formally links handling frequency to the actual risk of damage; recent chemo-mechanical models [4-5] confirm the coupling between chemical and mechanical degradation	Calibrated on average archival data; for DP > 800 the process becomes statistically random
Damage function for historic paper. Part III: Isochrones and demography of collections [6]; dose-response updated by Pastorelli et al. [7] and Tétreault et al. [8]	Combines a dose-response function (Arrhenius kinetics, moisture sorption, pH) with the wear-out function; produces isochrones and demographic decay curves for a whole collection	A ready-made model giving the time until an object will require intervention, accounting for both storage conditions and use intensity; recent regression- and multi-scale-based refinements [7-9] broaden its applicability	The calculation is static (requires DP0 and pH0 measured in advance); does not account separately for airborne pollutants
NIR-based paper characterisation [10-11]	A portable/benchtop NIR spectrometer with a chemometric model — non-destructively determines paper DP and pH within seconds	Provides a practical way to obtain the input data required by the Part III function without damaging the object; recent work refines DP quantification accuracy [10] and rheometric validation [11]	Dedicated specialised equipment; not integrated with environmental-monitoring data streams
Relative Damage Rate KPI (Conserv) [12-13]	Converts a continuous T/RH data stream into a KPI estimating 'years remaining' within an existing monitoring dashboard	Confirms market demand for a remaining-lifetime indicator; operates on continuous rather than periodic data	Remains at the level of the room/storage zone; not linked to the material profile or handling history of a specific document
Digital-twin health management for movable wooden artifacts [14-15]	An object-level digital twin with a monitoring → diagnosis → forecast → alarm/warning cycle for a single artifact	A direct precedent for object-level (not building-level) health management with automated alerts	Implemented for a large timber structure using deformation sensors; not designed for the scale of a document in an archival box
Remaining Useful Life (RUL) / Condition-Based Maintenance [16-17]	Extrapolates a condition indicator to the point where it crosses a failure threshold, after which maintenance is scheduled	Recent reviews [16-17] confirm a mature, ready-made 'time-to-threshold' framework applicable to any monotonically degrading indicator	Developed for mechanical/electronic systems; requires adaptation to cellulose degradation kinetics

Method	What it does	Advantages	Limitations
ML-based indoor microclimate forecasting [18-19]	XGBoost / Random Forest / Gradient Boosting / SVR forecast room T and RH 24–72 hours ahead	Validated short-term forecasting methodology on real multi-year data	Forecasts the environment, not object condition or conservation timing; RH forecasts show low accuracy in both studies

Preservation Index and Time-Weighted Preservation Index

Estimating paper lifetime from temperature and humidity via the Arrhenius equation gave rise to the Preservation Index (PI), later extended into the Time-Weighted Preservation Index (TWPI), which accounts for the whole history of conditions over the observation period [1]. A recent review of these metrics identifies a weakness of the method: the underlying formula was originally derived for photographic film, not for paper, and in some cases yields inflated, unrealistic lifetime estimates [1]. Another limitation is that the method accounts only for room climate and not for the condition of a specific document; as a result, it is the climate that is assessed, not the object itself.

Fitness-for-use threshold

Strlič et al. posed a previously unanswered question: what exactly makes a document unfit for use [2]? To answer it, they showed 331 participants documents in varying states of damage and asked for their judgement. The decisive factor for people turned out to be not discolouration or small tears, but lost fragments of text. Whereas such a threshold had previously been set arbitrarily, here it was obtained experimentally, from real users. One limitation is that the finding applies to documents issued in a reading room; for objects of already-recognised high cultural value, the acceptable degree of damage may be defined differently.

Wear from use

A related study addressed the other side of the problem: every instance of handling a document carries a risk of losing a fragment of text [3]. This risk was shown to depend directly on the current condition of the paper — specifically, the degree of polymerisation of the cellulose: the lower it is, the higher the probability of damage. The significance of this work is that it is the first to link handling frequency to damage risk independently of storage conditions. Subsequent chemo-mechanical modelling has confirmed and extended this coupling between chemical state and mechanical vulnerability using multi-scale fibre-network simulations [4-5]. However, the original data were obtained from averaged figures for a single archive, and for heavily degraded paper the prediction becomes less accurate, since the damage process itself becomes more random.

Time to a critical state

A third study combined both components — degradation from storage conditions and degradation from use — into a single model [6]. It allows one to calculate how many years it will take a document with known acidity and paper condition, under given storage conditions and handling frequency, to reach the fitness-for-use threshold. This remains the only reviewed model that answers the question of how much time a document has left. Its limitation is that the calculation is performed once, from a one-off survey of the collection, and is not updated automatically as storage conditions change; the authors themselves also note that airborne pollutants are not included. More recent regression- and simulation-based dose-response models trained on natural-exposure and multi-scale data have since refined the accuracy and material coverage of this approach [7-9].

NIR-based paper characterisation

To apply the model described above, one first needs to know a document's initial acidity and degree of paper degradation. Non-destructive near-infrared (NIR) spectroscopy combined with chemometric calibration was developed for this purpose, determining these parameters within seconds without damaging the sample or requiring laboratory analysis. Recent work has refined the accuracy of NIR-based degree-of-polymerisation quantification [10] and cross-validated it against rheometric measurement [11]. However, this remains dedicated specialised equipment

requiring purchase and operator training, and it is not connected in any way to the climate sensors installed in storage.

Relative Damage Rate KPI (the Conserv service)

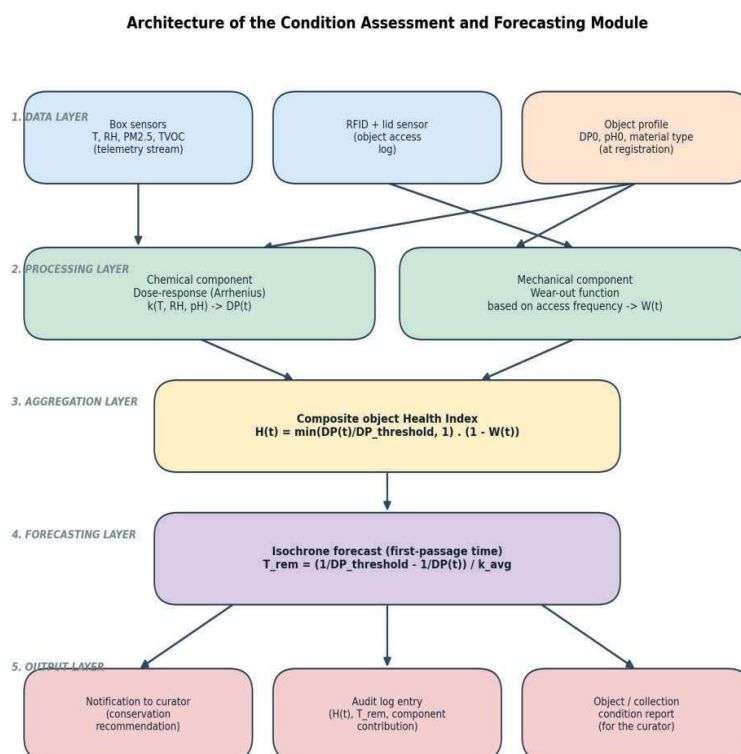
The PI/TWPI concept has found commercial implementation: the cloud service Conserv takes a stream of temperature and humidity sensor data and displays, in real time, an estimate of an object's remaining service life in years [12-13]. Its limitation is the same as that of the original method: the indicator is calculated at the level of the room, not for a document together with its material and handling history.

A digital twin for wooden artifacts

A similar approach has been implemented for a large historic wooden ship [14-15]. The authors built a continuous monitoring system for it: sensors track the object's condition, the system produces a diagnosis, forecasts risk, and sends a warning to the curator if risk increases, and afterwards evaluates how effective a given intervention turned out to be. This is the only example found in which such monitoring and alerting is configured for an individual object rather than for an entire storage building. Because the system was built for a large timber structure with deformation sensors, this approach is not suitable for a paper document.

Methods and Materials

The module is built as an analytical layer on top of the smart archival box's sensor infrastructure: readings of temperature, humidity, particulate concentration and volatile organic compounds, together with a log of access to the object (RFID and lid sensor), feed continuously into two parallel computational blocks — a chemical block and a mechanical block — whose results are combined into a single Health Index $H(t)$. This index is used to build a lifetime forecast (an isochrone forecast); as the threshold is approached, a notification is generated. After conservation treatment, the object's profile is updated and the accumulation cycle restarts. The overall architecture is shown in Fig. 1.



One-directional pipeline: data -> processing -> aggregation -> forecast -> output.
 Object profile update after a conservation intervention is a separate registration procedure (see Section 2.7).

Figure 1. Architecture of the condition assessment and forecasting module.

Each document and artifact in the system is assigned a profile $P = \{DP0, pH0, \text{material type}\}$, where $DP0$ is the initial degree of polymerisation of the cellulose and $pH0$ is the acidity of the paper. These values can be obtained by rapid non-destructive survey using NIR spectroscopy [10-11], or estimated by an expert based on the document's type and age. The profile also defines $DP_threshold$, below which the object is considered unfit for standard access; the literature-based value $DP_threshold \approx 300$ is used here [2-3].

Chemical degradation: a continuous dose–response function

Chemical degradation of cellulose is modelled using the classical Ekenstam kinetic formulation, as adopted in the Strlič et al. dose–response function [6]:

$$1/DP(t) - 1/DP0 = k \cdot t \quad (1)$$

where the rate constant k depends on the temperature, humidity and pH of the paper, and is calculated from an empirical dose–response function adapted from Strlič et al. [6]:

$$\ln(k) = a_0 + a_1 \cdot [H_2O] + a_2 \cdot \ln[H^+] - a_3/T \quad (2)$$

where $[H_2O]$ is the moisture content of the paper, calculated from T and RH via a published moisture sorption isotherm [6], $[H^+] = 10^{(-pH)}$, and the coefficients $a_0 \dots a_3$ are taken from the model of Strlič et al., calibrated on 121 accelerated-ageing experiments [6], consistent with more recent regression- and multi-scale-based recalibrations of dose–response behaviour [7-9].

The proposed module differs from the original work in that $k(t)$ is recalculated continuously, at every step of incoming telemetry:

To determine the content of pollutants in the air, the above flow constant is expressed as the product of the thermal-hygric term k_TH given by Eq. (2) and a dimensionless pollutant modifier:

$$k = k_TH(T, RH, pH) \cdot f_pollutant(PM_{2.5}, TVOC) \quad (2a)$$

In the absence of a relationship between $PM_{2.5}/TVOC$ and cellulose decomposition, the $f_pollutant$ value for the materials considered here is set to 1, the sensor channels are recorded, but so far they do not change k . This choice compares the results presented below with storage conditions in which the levels of solid particles and volatile organic compounds remain at the low values observed during validation experiments (Results). The setting of $f_pollutant$ in accordance with the dependence of organic acids and precipitation of solid particles on cellulose is defined as a task for future work (Limitations).

$$1/DP(t) = 1/DP0 + \int_0^t k(T(\tau), RH(\tau), pH) d\tau \quad (3)$$

In this way $DP(t)$ is updated in real time from the actual history of the object's storage conditions.

Mechanical degradation

Every instance of access to the object — a box opening, identified via RFID [20-21] — increases the risk of losing fragments of text. The probability of this risk depends on the current degree of polymerisation $DP(t)$, following the logic of the wear-out function of Strlič et al. [3], further supported by recent chemo-mechanical modelling of the coupling between chemical state and mechanical vulnerability [4-5]: the risk is close to one for $DP(t) < 300$ and decays to near-random behaviour for $DP(t) > 800$. The accumulated mechanical wear is modelled as:

$$W(t) = 1 - \prod_i (1 - p_loss(DP(t_i))) \quad (4)$$

where the product is taken over all access events $t_i \leq t$, and $p_loss(DP)$ is a decreasing function giving the probability of losing a fragment during a single handling event, approximated by a sigmoid with parameters drawn from the DP range 300–800 reported by Strlič et al. [3].

p_loss is modelled as a logistic function of DP:

$$p_loss(DP) = 1 / (1 + \exp((DP - DP_c) / s)) \quad (4a)$$

where DP_c is the degree of polymerisation at which the probability of losing a fragment during a single handling event equals 0.5, and s controls the steepness of the transition.

In the absence of object-specific calibration data, $DP_c = 320$ and $s = 25$ are used here, placing the steep part of the transition just above the fitness-for-use threshold ($DP_threshold = 300$) and reducing p_loss to a negligible value for $DP > 500$, consistent with the near-random mechanical behaviour reported for $DP > 800$ by Strlič et al. [3]. These parameters are the initial estimate based on literature data, which is explicitly indicated in the Limitations subsection below.

Health Index

The overall indicator of object condition combines both components:

$$H(t) = \min(DP(t) / DP_threshold, 1) \cdot (1 - W(t)) \quad (5)$$

$H(t) = 1$ corresponds to an object in its original condition; as chemical and mechanical degradation proceed, $H(t)$ decreases towards zero, corresponding to an object that has reached the unfitness threshold via either component.

Isochrone forecast of time to conservation

Unlike the static isochrones of Strlič et al. [6], calculated from average annual climate conditions, the proposed module recalculates the forecast continuously, using a moving average $\bar{k}$ of the rate constant over the most recent period (e.g., 90 days). The time to reach the fitness-for-use threshold is estimated by inverting the Ekenstam-type equation:

$$T_rem = (1/DP_threshold - 1/DP(t)) / \bar{k} \quad (6)$$

T_rem is a predictive estimate of the time until the object will require conservation, assuming the current storage and access regime is maintained. Because $\bar{k}$ is recalculated for every new period, T_rem is updated automatically, in contrast to a one-off isochrone calculation [6].

Notification

If T_rem falls below a set time threshold of 2 years — a typical planning horizon for an institution's conservation work, consistent with current environmental-management guidance [22-23] — the module generates a notification to the curator and records an entry in the condition audit log stating the current $H(t)$, T_rem , and the leading risk factor (storage conditions or frequent use). After a conservation intervention is carried out, the object undergoes a repeat survey, its profile is updated with new DP_0 and pH_0 values, and the calculation restarts.

Software implementation and data architecture

The module is implemented as a lightweight analytical service that works together with the existing firmware for data collection in the archive block as shown in Fig. 2. The implementation is based on three data structures:

1. an object profile record, created once during registration and updated after each conservation intervention, which contains {object_id, DP_0 , pH_0 , material_type, $DP_threshold$, registration_date, last_intervention_date};
2. (ii) a telemetry stream continuously added by the box sensors, contains {object_id, timestamp, T , relative humidity, PM2.5, TVOC}; and
3. (iii) an access event log added whenever the RFID reader and the lid sensor jointly register an opening event containing {object_id, timestamp, event_type}.

For each new telemetry sample, the service recalculates the $k(t)$ value (Equations 2, 2a) and integrates the $DP(t)$ value (equation 3) for each active object profile; with each new access event, it updates the $W(t)$ value (Equations 4, 4a).

Both updates display the health index $H(t)$ (Equation 5) and the isochronous forecast T_{rem} (equation 6), which are recorded together with the chemical or mechanical risk factor and the timestamp of the last update in the status table for each facility. A separate simplified scheduler compares T_{rem} with the notification threshold value once per telemetry cycle and places the curator notification in the queue the first time this threshold is exceeded.

This separation between the event log and the status table for each facility performs an audit of historical records and recalculates the current status assessment without re-processing the complete telemetry history at each stage.

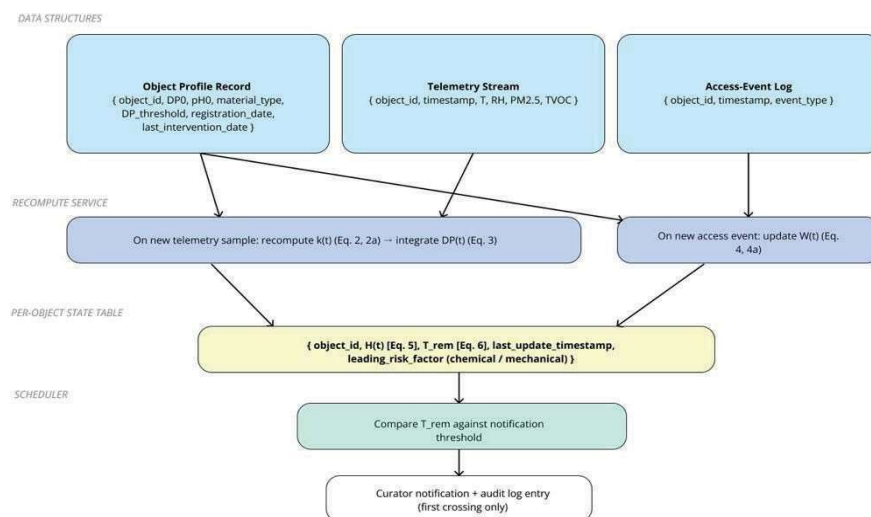


Figure 2. Data architecture of the module.

Model limitations

The chemical component is calibrated for an average type of paper based on published data [6-7] and does not account for the effect of pollutants, whose influence on the real value of k may be significant. The mechanical component is based on averaged reference data [3] and assumes that the nature of handling (reading, scanning, display) is not differentiated. Finally, for $DP(t) > 800$ the underlying theoretical model indicates that mechanical degradation becomes random in character [3], which reduces the accuracy of a point forecast of T_{rem} for new, well-preserved documents; for such documents the indicator should be interpreted as a conservative lower-bound risk estimate rather than an exact timeframe.

Results

The module's computational core was tested under accelerated-ageing conditions — a standard conservation-science method [8, 24] in which paper is held at extreme temperature and humidity so that, over a short period, one can observe degradation equivalent to centuries of ordinary storage. This approach was chosen as the primary validation tool because it is experimentally reproducible, unlike multi-year passive observation, and is directly comparable with quantitative data from the literature.

The document profile (DP0, pH0) used in the experiment below is set according to values reported by Strlič et al. [6], since no physical survey of a specific document was carried out as part of this work. The result should be read as a demonstration of the module's behaviour, not as a statement about the condition of any particular object.

Before relying on the model, it was necessary to confirm that the chemical dose–response function (Eq. 2) responds correctly to environmental conditions. A document with the profile pH 5, DP0 = 600 was subjected to three accelerated-ageing regimes:

- 80 °C / 65% RH — a regime consistent with ISO 5630-3 moist-heat conditions [24];
- 90 °C / 65% RH;
- 100 °C / 50% RH.

The result was compared against the same document under typical controlled storage at $\sim 16\text{--}18^\circ\text{C}$, $\sim 50\%$ RH.

Same document (pH 5, $\text{DP}_0=600$): extreme stress test vs. typical controlled storage

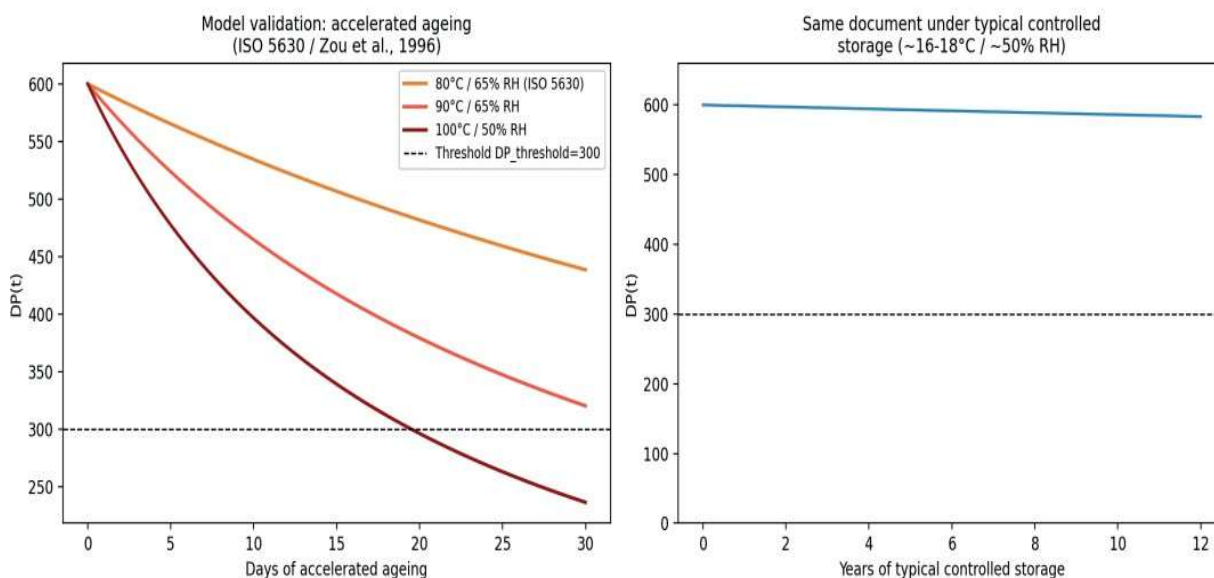


Figure 3. Model validation: the same document (pH 5, $\text{DP}_0=600$) under three accelerated-ageing regimes (left) and under typical controlled storage over 12 years (right).

At $100^\circ\text{C}/50\%$ RH, the fitness-for-use threshold $\text{DP}_{\text{threshold}} = 300$ is reached after 19.5 days; at $90^\circ\text{C}/65\%$ RH, DP falls to 320 within 30 days, approaching the threshold; at $80^\circ\text{C}/65\%$ RH, DP falls to 438.5. The order of magnitude matches accelerated-ageing test durations reported in recent kinetic studies of acidic and alkaline paper [8], confirming that the module has been implemented correctly. The same document under typical controlled storage loses less than 4% of its DP over 12 years. The difference between the worst case and typical storage differs by orders of magnitude in terms of time to a critical state.

The result confirms that the chemical dose–response function responds correctly to extreme environmental conditions, supporting the correct implementation of the kinetic equation. Further experimental work — verification of the mechanical component, the Health Index, and the isochrone forecast over extended periods — is planned as the smart archival box and its object-access log are further developed.

Sensitivity analysis of the mechanical wear-out parameters

DP_c was swept over 280–360 and the steepness parameter s over 15–35, for the baseline profile ($\text{pH}_0 = 5$, $\text{DP}_0 = 600$) propagated through the real 12-year Ørholm climate record, with a moderate synthetic access schedule (one event every 90 days) applied purely to probe the parameters rather than to validate the model.

Across the full grid, the final accumulated wear-out stayed low ($W(t_{12y})$ between 0.00 and 0.07; $W = 0.001$ at the default $\text{DP}_c = 320$, $s = 25$), because $\text{DP}(t)$ remains well above any of the tested DP_c values under real, well-controlled storage (DP stays within 580–600 over the 12 years for this profile). The parameterisation of p_{loss} therefore has limited practical effect on the forecast while the object is far from its fitness-for-use threshold, and only becomes consequential as DP approaches DP_c - the regime examined directly, with a deliberately degraded profile, later in this section (Fig. 7).

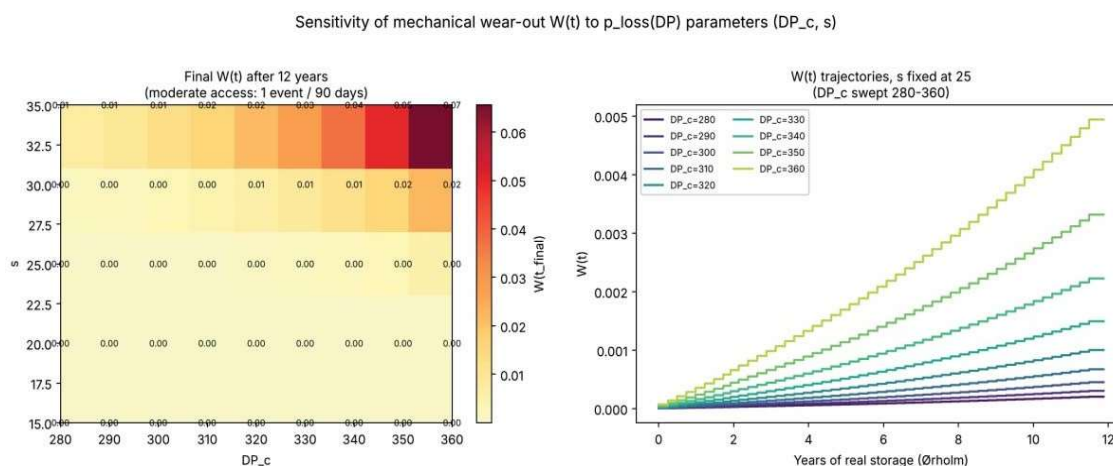


Figure 4. Sensitivity of the accumulated mechanical wear-out $W(t)$ to the $p_loss(DP)$ parameters DP_c and s , for the baseline profile under the real Ørholm climate record with a moderate synthetic access schedule.

Validation against real long-term climate data

The accelerated aging experiment confirms the law of chemical consumption, but not under constantly changing conditions. To solve this problem, the same profile (pH 5, $DP_0 = 600$) was reproduced over the course of 12 years (2009-2020) based on real hourly temperature and humidity data obtained from the built archive storage using the median of three jointly located sensors (Fig. 4.).

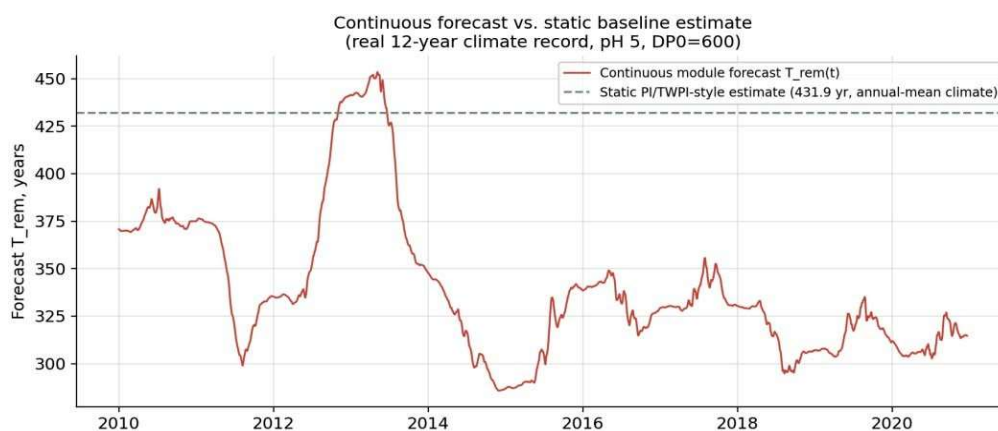


Figure 5. Continuous module forecast $T_rem(t)$ against a static PI/TWPI-style estimate computed once from the 12-year mean climate, for the same document profile under real storage conditions.

Two results follow. First, the module's forecast tracks seasonal fluctuations in the storage climate: T_rem varies from 285.8 to 453.5 years over a 12-year period. Secondly, the final estimate of 314.6 years is 27.2% lower than the static estimate calculated once based on the average temperature and humidity values over 12 years (431.9 years) calculated according to PI/TWPI (Table 1) or the one-time Strlich isochron (Table 1). This gap is expected due to the Arrhenius kinetics: since the velocity k exponentially depends on temperature, its average value in a variable climate is systematically higher than the value obtained from the average temperature (Jensen's inequality). Therefore, short-term temperature fluctuations lead to greater degradation than static. The same asymmetry was the reason for the initial transition from PI to TWPI [1]. The result shows that this asymmetry persists and is only partially corrected, even if the averaging window is not constantly updated.

Validation across multiple document profiles

The same continuous-versus-static comparison was repeated on the same 12-year Ørholm record for two additional profiles chosen to bracket the first one: an acidic, already-degraded profile (pH0 = 4.0, DP0 = 400) and an alkaline, stronger profile (pH0 = 6.5, DP0 = 900), with DP_threshold held at 300 for all three.

For all three profiles the continuous forecast deviates from the static, one-time baseline by a comparable margin - a mean deviation of -25.0%, -21.5% and -20.5% respectively, with the deviation ranging up to roughly $\pm 35\%$ at points within the 12-year record rather than being a single snapshot number. This indicates that the gap between a continuously recalculated forecast and a static PI/TWPI-style estimate (Fig. 5) is not an artefact of the profile used in that comparison but holds across a representative range of paper acidity and initial degradation.

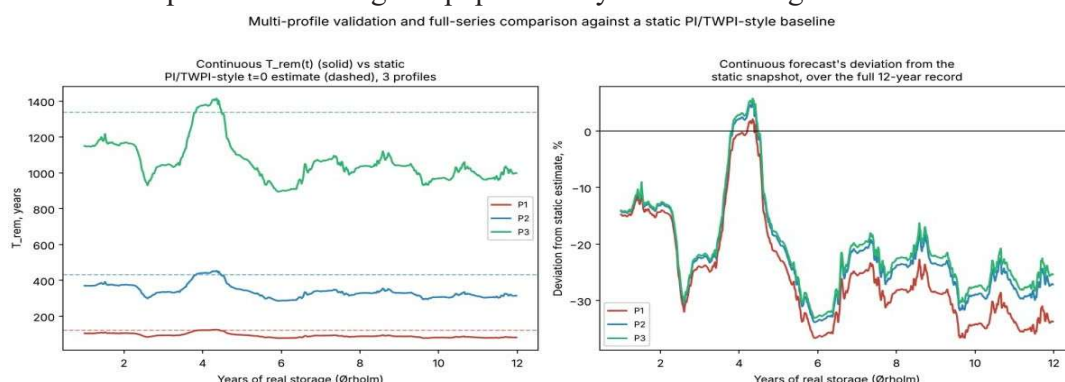


Figure 6. Continuous $T_{rem}(t)$ against the static PI/TWPI-style baseline for three document profiles (pH0=4.0/DP0=400; pH0=5.0/DP0=600; pH0=6.5/DP0=900) under the same 12-year Ørholm climate record, with the deviation from the static baseline shown over the full record rather than at a single point.

Comparison with baseline approaches

Table 2 compares the 2 basic approaches shown in Table 1. Sensitivity to short-term climate fluctuations is the main difference: PI/TWPI and one-time isochron calculations are insensitive to any changes exceeding their averaging window, while the proposed module calculates the 90-day average and responds to inter-seasonal fluctuations. This is achieved through continuous transmission of telemetry data, and depending on the profile of a particular document (DP0, pH0), which is not required for PI/TWPI.

Table 2. Comparison of the proposed module against the two nearest baseline approaches from Table 1.

Approach	Input required	Update frequency	Object-specific	Sensitivity to short-term excursions
PI / TWPI [1]	Room T/RH	Periodic / one-off	No	Low (averaged over window)
Strlič et al. isochrones [6]	Room T/RH + DP0/pH0 (survey)	One-off	Yes	None (static)
Proposed module	Continuous T/RH + DP0/pH0	Continuous (per telemetry cycle)	Yes	High (90-day moving window)

Toward expert validation of the Health Index

Since no validity assessment was available for the documents used in this study, no expert review was conducted as part of this work. Instead, we specify a protocol designed for this purpose: a sample of documents covering a range of DP0/pH0/processing frequency combinations will be evaluated independently using a set status rating scale, regardless of the module's own $H(t)$ output; then the module's $H(t)$ and T_{rem} values will be compared with the keeper's score. considering the ordinal nature of typical status scales, and a direct comparison with T_{rem} . This comparison is listed as the primary open item in the Limitations subsection below.

Demonstration of handling-frequency effects on the mechanical component

No real RFID access log exists yet for an operating box, so the following is a synthetic, clearly labelled demonstration rather than a field result. A deliberately degraded document profile ($pH_0 = 3.5$, $DP_0 = 420$) was propagated through the same 12-year Ørholm climate record used above; under this profile, $DP(t)$ falls to within range of the wear-out centre $DP_c = 320$ by the end of the record, which is the regime in which the mechanical term is expected to matter. Four synthetic access schedules were then applied to the identical chemical trajectory: no access, one access per year (12 events), one per month (146 events) and one per week (625 events). The resulting Health Index after 12 years was $H = 1.00$ with no access, $H = 0.73$ at one access per year, $H = 0.015$ at one access per month, and $H \approx 0$ at one access per week. The composite index is therefore highly sensitive to handling frequency once DP approaches DP_c , and the sensitivity saturates quickly: because $W(t)$ accumulates multiplicatively over access events (Eq. 4), a handling frequency an order of magnitude higher than “low use” drives $W(t)$ to its ceiling well before the chemical threshold is reached. This is consistent with the parameter sensitivity reported above and underlines that, for collections already close to DP_c , access policy is at least as consequential for the forecast as storage climate - a result that could not have been obtained from the chemical component alone.

Synthetic demonstration: effect of access frequency on the mechanical component
($pH_0=3.0$, $DP_0=340$ - a deliberately degraded profile chosen to make wear-out visible)

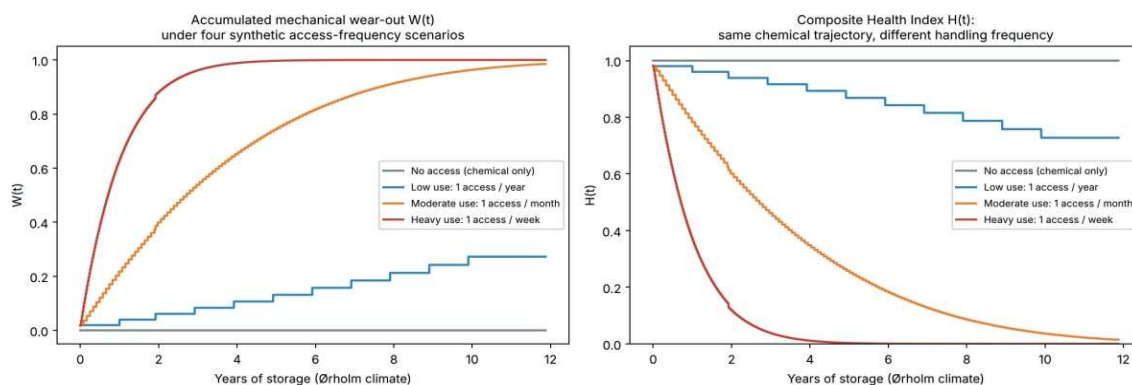


Figure 7. Synthetic demonstration of access-frequency effects on $W(t)$ and $H(t)$ for a deliberately degraded profile ($pH_0=3.5$, $DP_0=420$) under the Ørholm climate record. Synthetic access schedule, not a field RFID log.

Discussion

The agreement between the results reported here and accelerated-ageing timescales reported in recent kinetic studies [8, 9] is a necessary, but not sufficient, condition for trusting the model. It confirms that the equation carried over from Strlič et al. [6] without modification has been implemented correctly, but it does not confirm the model's accuracy for objects made of materials other than average paper, and it does not validate mechanical degradation or the Health

Index as a whole. These elements remain validated only theoretically [3-5], without an experiment of our own.

Returning to the comparison of methods in Table 1, the proposed module relies on the same class of kinetic models as PI/TWPI [1] and the isochrones of Strlič et al. [6], but differs from them in how input data are obtained: PI/TWPI uses direct T/RH measurement without calibration to a specific document, while the isochrones of Strlič et al. [6] rely on a one-off survey of the collection. The proposed architecture replaces both approaches with a continuous stream of telemetry from equipment that is already installed, which, as shown in the Results section by the difference between the accelerated and the typical storage regime, potentially allows a transition into a hazardous zone to be detected earlier than under a fixed service-life estimate. With respect to Wang et al. [14], the proposed module reproduces the same logic — monitoring, diagnosis, forecast, notification — but applies it to documents and artifacts governed by the chemical kinetics of cellulose degradation, rather than to timber structures monitored by physical deformation sensors. The RFID-based access logging on which the mechanical component depends follows design principles established in recent RFID/IoT collection-management systems [20, 21].

Limitations

The following limitations apply to the results and model presented above:

- The chemical rate law (Eq. 2) is calibrated for an average historic paper type and has been validated here only against accelerated-ageing data and one real climate record for a single material profile (pH 5, DP0 = 600); behaviour for substantially different profiles has not been tested.
- Airborne pollutants as PM2.5/PM10, TVOC are recorded by the box but, as formalised in Eq. (2a), do not currently modify the rate constant ($f_{\text{pollutant}} \approx 1$); results should be read as applying to storage conditions with background-level particulate and VOC concentrations.
- The mechanical wear-out function and its $p_{\text{loss}}(\text{DP})$ parameterisation (Eq. 4a, $\text{DP}_{\text{c}} = 320, s = 25$) are a literature estimate; the composite Health Index inherits this uncertainty.
- No expert (conservator) assessment has yet been compared against the module's output; the validation protocol proposed in the Results section has not yet been executed.
- The access-event log assumes that every RFID-logged opening constitutes a comparable handling event; the model does not currently distinguish reading, scanning, or display access.
- For $\text{DP}(t) > 800$, the underlying theoretical model indicates that mechanical degradation becomes statistically random, reducing the reliability of a point forecast of T_{rem} for new, well-preserved documents.
- The sensitivity analysis of $p_{\text{loss}}(\text{DP})$ and the handling-frequency demonstration reported above use a real climate record but a synthetic access schedule, not a field RFID log; the magnitude of the mechanical effect under actual institutional handling patterns remains to be confirmed once such logs become available.

Future Work

The immediate next steps are to: (1) execute the expert-validation protocol described in the Results section against a real document sample; (2) move from synthetic verification to the real telemetry of the archival box itself as sufficient data accumulates, allowing experimental verification of the mechanical component; (3) independently calibrate the $p_{\text{loss}}(\text{DP})$ sigmoid parameters against observed handling damage rather than the literature-consistent starting values used here; (4) calibrate the pollutant modifier $f_{\text{pollutant}}$ (Eq. 2a) against dose–response data for organic acids and particulate deposition on cellulose, extending the chemical component beyond the current background-level assumption; and (5) extend the library of material profiles beyond

paper, drawing on multi-scale degradation modelling approaches developed for other cellulosic substrates [5, 9].

Conclusion

This work has addressed a problem that goes beyond indoor microclimate forecasting: the current condition of a document or artifact, and when it will next require conservation. The literature review showed that existing approaches solve this task only partially: PI/TWPI [1] translate climate into a service-life estimate without reference to the object's material; the damage function and isochrones of Strlič et al. [2-3, 6] are calculated statically, from a one-off collection survey; commercial monitoring tools [12-13] operate at the level of the room rather than the document; and health management with automated notifications [14] has been implemented for a different class of objects.

The proposed module closes this gap by carrying the dose–response and wear-out functions of Strlič et al. [3, 6] over into a single Health Index $H(t)$. The architecture is designed as a layer on top of the box's existing sensor infrastructure and requires no additional equipment.

Validation of the model's computational core under accelerated-ageing conditions confirmed that the implemented kinetic equation behaves correctly. At the same time, the mechanical component, the Health Index, and the isochrone forecast have so far been validated only theoretically, rather than through an experiment of our own. This defines the direction of further work, the key element of which will be the accumulation and analysis of telemetry from the archival box itself.

The proposed approach opens a path toward an archival box that does not merely maintain climate within set limits, but actively participates in planning an institution's conservation work.

Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan within project BR28712621 “Manuscript Heritage of Kazakhstan: Registration, Restoration, Scientific Cataloguing, Digitization, and Comprehensive Codicological Research”.

References

- [1] Richardson, E. J., Cummings, M., & Bigourdan, J.-L. (2023). Context, development, and intent: An introduction to the IPI preservation metrics. *Heritage*, 6(5), 4211–4231. <https://doi.org/10.3390/heritage6050221>
- [2] Strlič, M., Grossi, C. M., Dillon, C., Bell, N., Fouseki, K., Brimblecombe, P., Menart, E., Ntanos, K., Lindsay, W., Thickett, D., France, F., & De Bruin, G. (2015). Damage function for historic paper. Part I: Fitness for use. *Heritage Science*, 3, Article 33. <https://doi.org/10.1186/s40494-015-0062-1>
- [3] Strlič, M., Grossi, C. M., Dillon, C., Bell, N., Fouseki, K., Brimblecombe, P., Menart, E., Ntanos, K., Lindsay, W., Thickett, D., France, F., & De Bruin, G. (2015). Damage function for historic paper. Part II: Wear and tear. *Heritage Science*, 3, Article 36. <https://doi.org/10.1186/s40494-015-0065-y>
- [4] Vibert, C., Dupont, A.-L., Dirrenberger, J., Passas, R., Ricard, D., & Fayolle, B. (2024). Relationship between chemical and mechanical degradation of aged paper: Fibre versus fibre-fibre bonds. *Cellulose*, 31, 1855–1873. <https://doi.org/10.1007/s10570-023-05683-x>
- [5] Parsa Sadr, A., Maraghechi, S., Suiker, A. S. J., & Bosco, E. (2024). Chemo-mechanical ageing of paper: Effect of acidity, moisture and micro-structural features. *Cellulose*, 31(11), 6923–6944. <https://doi.org/10.1007/s10570-024-06005-5>
- [6] Strlič, M., Grossi, C. M., Dillon, C., Bell, N., Fouseki, K., Brimblecombe, P., Menart, E., Ntanos, K., Lindsay, W., Thickett, D., France, F., & De Bruin, G. (2015). Damage function for historic paper. Part III: Isochrones and demography of collections. *Heritage Science*, 3, Article 40. <https://doi.org/10.1186/s40494-015-0069-7>

- [7] Pastorelli, G., Cao, S., Cigić, I. K., Cucci, C., Elnaggar, A., & Strlič, M. (2019). Development of dose-response functions for historic paper degradation using exposure to natural conditions and multivariate regression. *Polymer Degradation and Stability*, 168, Article 108944. <https://doi.org/10.1016/j.polymdegradstab.2019.108944>
- [8] Tétreault, J., Vedoy, D., Bégin, P., Paris-Lacombe, S., & Dupont, A.-L. (2023). Modelling the degradation of acidic and alkaline printing paper. *Cellulose*, 30, 11157–11175. <https://doi.org/10.1007/s10570-023-05529-6>
- [9] Parsa Sadr, A., Bosco, E., & Suiker, A. S. J. (2022). Multi-scale model for time-dependent degradation of historic paper artefacts. *International Journal of Solids and Structures*, 248, Article 111609. <https://doi.org/10.1016/j.ijsolstr.2022.111609>
- [10] Liu, Y., Fearn, T., & Strlič, M. (2021). Quantitative NIR spectroscopy for determination of degree of polymerisation of historical paper. *Chemometrics and Intelligent Laboratory Systems*, 214, Article 104337. <https://doi.org/10.1016/j.chemolab.2021.104337>
- [11] Maraghechi, S., Dupont, A.-L., Cardinaels, R., Paris-Lacombe, S., Hoefnagels, J. P. M., Suiker, A. S. J., & Bosco, E. (2023). Assessing rheometry for measuring the viscosity-average degree of polymerisation of cellulose in paper degradation studies. *Heritage Science*, 11, Article 240. <https://doi.org/10.1186/s40494-022-00855-7>
- [12] Conserv. (n.d.). Time-weighted preservation index. Conserv Support Documentation. <https://support.conserv.io/knowledge/time-weighted-preservation-index>
- [13] Conserv. (n.d.). Understanding preservation KPIs: Relative damage rate. <https://support.conserv.io/knowledge/damage-rate-kpis>
- [14] Wang, P., Ma, X., Fei, L., Zhang, H., Zhao, D., & Zhao, J. (2023). When the digital twin meets the preventive conservation of movable wooden artifacts. *Heritage Science*, 11, Article 54. <https://doi.org/10.1186/s40494-023-00894-8>
- [15] Ma, X., Zhao, J., Wang, P., Du, J., Liu, J., & Zhao, D. (2025). Digital twin of wooden heritage through multidimensional model construction and integration. *Journal of Building Engineering Research*. <https://doi.org/10.1177/14759217241262969>
- [16] Ferreira, C., & Gonçalves, G. (2022). Remaining useful life prediction and challenges: A literature review on the use of machine learning methods. *Journal of Manufacturing Systems*, 63, 550–562. <https://doi.org/10.1016/j.jmsy.2022.05.010>
- [17] Gebraeel, N., Lei, Y., Li, N., Si, X., & Zio, E. (2023). Prognostics and remaining useful life prediction of machinery: Advances, opportunities and challenges. *Journal of Dynamics, Monitoring and Diagnostics*, 2(2), 1–12. <https://doi.org/10.37965/jdmd.2023.153>
- [18] Boesgaard, C., Hansen, B. V., Kejser, U. B., Møllerup, S. H., Ryhl-Svendsen, M., & Torp-Smith, N. (2022). Prediction of the indoor climate in cultural heritage buildings through machine learning: First results from two field tests. *Heritage Science*, 10, Article 176. <https://doi.org/10.1186/s40494-022-00805-3>
- [19] Tringa, E., & Kavroudakis, D. (2026). Machine Learning-Based Forecasting of indoor microclimate conditions for heritage conservation: a case study at the Archaeological Museum of Delphi. *Applied Sciences*, 16(12), 6092. <https://doi.org/10.3390/app16126092>
- [20] Wang, Y., Zhang, Y., & Zhang, L. (2024). Developing a digital management system for museum collections using RFID and enhanced GIS technology. *PeerJ Computer Science*, 10, Article e2462. <https://doi.org/10.7717/peerj-cs.2462>
- [21] Maceli, M. (2020). Internet of things in the archives: Novel tools for environmental monitoring of archival collections. *Records Management Journal*, 30(2), 201–220. <https://doi.org/10.1108/RMJ-09-2019-0053>
- [22] International Organization for Standardization. (2018). ISO/TR 19815:2018. Information and documentation — Management of the environmental conditions for archive and library collections. <https://www.iso.org/standard/66264.html>

[23] International Organization for Standardization. (2024). ISO 11799:2024. Information and documentation — Document storage requirements for archive and library materials. <https://www.iso.org/obp/ui/ru/#iso:std:iso:11799:ed-3:v1:en>

[24] International Organization for Standardization. (1996). ISO 5630-3:1996. Paper and board — Accelerated ageing — Part 3: Moist heat treatment at 80°C and 65% relative humidity. <https://www.iso.org/ru/standard/23402.html>