Improvement options for archive boxes in tropical climates

M. Meinders, E.R.P. Keijsers, I.W. Smeding-Zuurendonk

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Authors: M. Meinders, E.R.P. Keijsers, I.W. Smeding-Zuurendonk

Institute: Wageningen Food & Biobased Research

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PO box 17, 6700 AA Wageningen, The Netherlands, T + 31 (0)317 48 00 84, E info.wfbr@wur.nl, www.wur.eu/wfbr.

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Summary

Preserving archives in countries like India, Indonesia, Sri Lanka, Brazil, and Suriname is challenging because of tropical climate conditions (high relative humidity (RH) and high temperature (T)), especially in combination with often non-reliable climate control systems. Variable (and fast-changing) climate conditions in combination with high RH pose a serious threat to archival records. The National Archives of the Netherlands (NAN) cooperates with local archive institutions to preserve the archives originating from the Dutch presence in these countries. This project aims to investigate the packaging concept of archive boxes and to come up with possible solutions to protect archived documents better against (fast-changing) variable climate conditions and insect intrusion, thereby also taking into account other requirements such as the economy (low price), the possibility for local production (less transportation), sustainability, and lifespan. For good preservation the RH (or water activity) inside the box and of the archived material must be below 60%.

The starting point of this project was the wish to create a packaging (archive box) that protects its content against varying climatic environmental conditions. A hypothesis was that this could be obtained by suitable packaging material and coating with optimal moisture permeability in combination with an absorber. This could result in a lower RH and lower RH variability inside the packaging upon changes in environmental conditions.

Wageningen Food and Biobased Research (WFBR) performed a study of possible solutions, including an investigation into the state-of-the-art knowledge on the moisture migration phenomena relevant to the archive box. Based on these results, WFBR developed a quantitative physical model describing moisture transport through and inside an archive box, to get insight into the key factors that control water migration and moisture content of the archived materials and to test the starting hypotheses. With this model, the effects of different packaging options, including coating and usage of moisture absorbers, were evaluated in relation to (changes in) environmental RH and T.

WFBR found that the application of polymer coatings on cardboard archival boxes will indeed decrease the water vapour flux between the inside and outside environment of the box, but that it will only be effective on a time scale of hours to days and not on the desired longer time scale of months. Other materials are needed for boxes that need to withstand moisture migration on a time scale of months, such as metals or plastics that do not comply with additional requirements (i.e. cost-effectiveness and/or the possibility of local production). Furthermore, the outflux of water from the box is also decreased when a coating is applied in cases of high humidity inside the box, due to e.g. adding a moist paper to the box or due to a malfunctioning of the climate control system for a period longer than a few days. The result is, therefore, counter-effective: when the coating on an archival box is improved to decrease water vapour permeability, upon a temporary increase of the humidity in the storage room the archival content of that box will be subjected to high humidity during a longer time period.

Concerning the role of absorbers, it is concluded that the effect of common absorbers is very limited. This because they are already saturated at RHs around 50%, which are common RHs in tropical archival storage rooms. Therefore, their buffering capacity is limited when the environmental RHs increase above 50%. Ideally, a special absorber is needed that does not absorb at storage room humidities (below about 55%) but absorbs at higher RHs that may occur either during transport or during defects in the climate control of a storage room. However, these are specific and expensive and do not match the boundary conditions set in this project.

In general, the archives of the NAN experience different types of problems due to the tropical climate, which require different types of solutions. No single archive box or material can solve all of these problems simultaneously, because the effect of a certain adaptation on the moisture exposure of the archived documents, like the application of a coating or absorber, depends on the details and timescale of the experienced problem. So, because tropical archives experience different types of problems of different durations, no general advice for the construction of an archive box can be given to minimise the exposure of the archived materials to high humidities. However, recommendations depending on the situation and

duration can be and are given. These include changing the currently used corrugated cardboard to solid board and closing gaps in the box to minimise insect intrusion as well as stabilizing the storage conditions and improving the handling protocols.

1 Introduction

The National Archives of the Netherlands (NAN) has asked Wageningen Food and Biobased Research to provide advice for a new packaging concept to store and protect archived documents in tropical areas. This report describes the outcome of the project.

Client and international team
The National Archives of The Netherlands (NAN) holds over 3.5 million records of national significance, created by the central government, organisations and individuals. Records related to the colonial and trading history of The Netherlands in the period from 1600 to 1975, are stored both in the Netherlands and in countries like India, Indonesia, Sri Lanka, Brazil, the Caribbean and Suriname and are property of these countries. Conservation of these archives that give insights into the shared colonial history are an important task of NAN and partner countries. Therefore, NAN cooperates with local archive institutions to preserve these archives.

The National Archives of the Netherlands (NAN) cooperates within the International Heritage Cooperation Programme with (among other countries) Australia, Brazil, India, Indonesia, Japan, Russia (on hold), Sri Lanka, Suriname, United States and South Africa. A worldwide heritage community, in which professionals connect, learn from each other and develop knowledge together towards finding solutions to shared challenges.

Background
Partnering archive institutes (e.g. in Indonesia, India, Sri Lanka and Suriname) have to deal with strong and sometimes rapid fluctuations in climatic conditions and high relative humidities. Changing conditions and high relative humidity pose a serious threat to archival records. An archival storage box is meant to reduce the effect of these threats and ideally should reduce or eliminate the effect of changing conditions when the climatised rooms are not working or archival records are temporarily taken out of the climatised rooms.

To anticipate on the current storage conditions and handling procedures at partner archives in tropical areas, NAN sent out a survey prior to this project to further refine the requirements for the new archive boxes.

The existing corrugated board-based archive box (Figure 1) is a good starting point for further improvements.

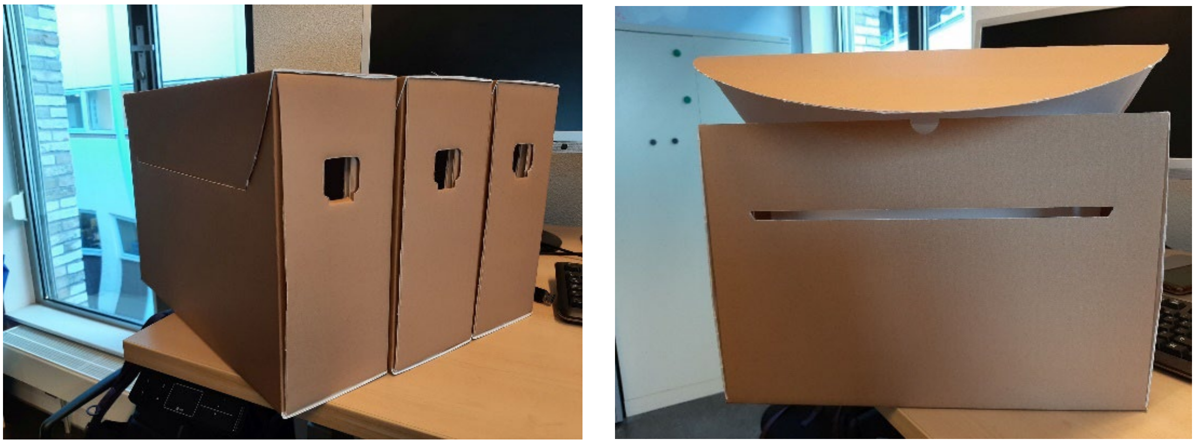

Figure 1 Corrugated board-based archive boxes.

Objective and scope
The objective of this study is to design an archive box that is optimised to protect archived records under tropical circumstances: i.e. high temperatures and humidities as well as large variations therein. The aim is to give insights in methods and materials that can be used to improve the climate (humidity) within archive

boxes. To well preserve archive documents, relative humidity inside the box should ideally be between 35% and 60%.
Besides this most important requirement, there are many other desired properties for the box, like:

- Insect-proof;
- Easy to be handled and transported (not too heavy);
- No impact of the packaging on the items (and ink) stored in the box;
- Locally produced (less transportation);
- As sustainable as possible;
- Protect against (local) vermin and fungi;
- Lifetime of at least 10-15 years, ideally 30 years;
- Two box sizes (standard size and folio size);
- Maintenance free (other than dusting);
- Low local production costs to increase the chance of purchase and thus use of the archive box.

The aim is that the final archive box meets as many desired properties as possible.

Project approach
To achieve this goal, the following project approach has been proposed. First of all, NAN will run a survey at their international partners in tropical countries to understand the main issues and challenges in these archives. As a next step the project, background information and survey results will be extensively discussed between WFBR and NAN; this will result in a mutual approach for the next steps. WFBR will perform a literature review on materials that could potentially be suitable for this application and requirements. A model will be set up to simulate the moisture transport in an archive box, depending on different scenarios. Outcomes will be discussed with NAN and results reported in a written report.

2 State-of-the-art / literature review

An investigation into the state-of-the-art knowledge on the moisture content of and moisture migration between the different components of an archive box system, including archived documents, possible absorbers, box, and coatings, is performed at the start of the project. This was performed by means of a literature review and discussions with experts. The focus was on moisture sorption and transport phenomena of paper-like cellulose-based materials, polymer coatings, and absorbers.

2.1 Moisture sorption and transport

Moisture sorption and transport through polymers and paper (including card-board and other cellulose-based materials) is complex. Paper can be viewed as a porous system containing solid particles (like cellulose fibres, fillers, chemical additives), air pockets (gas phase), and when wet, also water pockets (liquid phase). Moisture sorption and migration therefore includes processes within and between solid, liquid, and gas phases. Various scientific papers on these processes have been published (see e.g. references [1] [2] [3] [4] [5] [6] [7] [8]. A short summary is given here.

In general, moisture transport in materials is described using Fick's law of diffusion

$$\frac{\partial c_w}{\partial t} = \frac{\partial}{dx} D \frac{\partial c_w}{\partial x} \qquad (1)$$

where c_w [kg/m^3] is the water concentration, D [m^2/s] is the diffusion constant or diffusivity, t [s] is time and x [m] is the spatial coordinate. In general x is three dimensional, but to keep it simple here, we will take x to be one dimensional. The water activity a_w, and not the water concentration, is a good measure for the driving force of water migration, because it also takes the interactions between the water and material into account. One can rewrite equation 1 in terms of the water activity, as follows,

$$\frac{\partial a_w}{\partial t}\frac{\partial c_w}{\partial a_w} = \frac{\partial}{dx} D \frac{\partial c_w}{\partial a_w}\frac{\partial a_w}{\partial x} \qquad (2)$$

where $\partial c_w/\partial a_w$ is the derivative of the material's sorption isotherm (see also below). For complex porous materials like paper, the total moisture migration includes those of the various present materials and solid, liquid, and gas phases. Furthermore, the corresponding diffusion coefficients depend on temperature, water content, and specific material properties. Under certain assumptions, like local equilibrium between the different phases, equation 2 can be rewritten in terms of an effective diffusion constant. This gives

$$\frac{\partial a_w}{\partial t} = \frac{\partial}{dx} D_e \frac{\partial a_w}{\partial x} \qquad (3)$$

with D_e being the effective moisture diffusion constant, which depends on the material, a_w (and thus x) and temperature T.

Water vapour diffusivities and permeabilities
For packaging materials and coatings, one is often interested in the barrier properties. The water migration is then described in terms of the water vapour permeability (WVP) or moisture vapour permeability (MVP) K_v [s]. It is defined via a stationary water flux J [kg/m^{2}s], referred to as the water vapour transmission rate (WVTR], across an area A of barrier with thickness d (see Figure 2), as follows:

$$J = -K_v \frac{\partial P_v}{\partial x} \qquad (4)$$

with $\frac{\partial P_v}{\partial x} \approx \frac{P_{v2}-P_{v1}}{d}$ corresponding to the difference in water vapour pressures on both sides of the barrier. From $P_v = P_{v,sat}\frac{RH}{100\%} = P_{v,sat}\,a_w$, the relation between the diffusion coefficient *D* and water vapour permeability K_v follows: $D = K_v\,P_{v,sat}\frac{\partial a_w}{\partial c_w}$, with $P_{v,sat}$ being the water vapour saturation pressure.

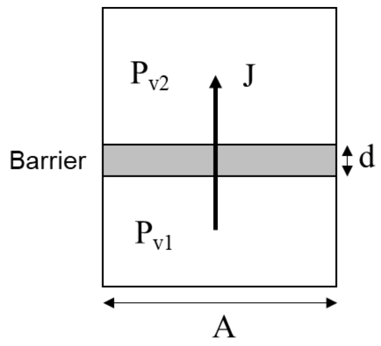

Figure 2: ***Schematic view of the water flux J (water vapour transmission rate) across a barrier of thickness d and area A, due to a difference in water vapour pressures P_{v1} and P_{v2} on both sides of the barrier.***

Various values can be found in the literature for the effective diffusion coefficient D_e of water in paperlike materials. They range from about 10^{-10} to 10^{-6} m^2/s, depending on various parameters including the type of paper, water content, and temperature. For the temperature and water activity range relevant for the archive box (20 °C - 40 °C and 0.3-0.9, respectively), effective diffusion coefficients of paper sheets and historical based cellulose materials are found to be in the range of 10^{-7} m^2/s and 10^{-6} m^2/s [3] [4] [5] [6] [9].

Polymeric coatings applied to paper or cardboard can be used to control or decrease the water vapour permeability. The WVP is conveniently measured according to ASTM E96 [10], at a fixed temperature and fixed gradient of humidity. The materials with the lowest WVP values are poly-olefines (including poly-esters (PE) and poly-propylene (PP)). Materials with more polar moieties (such as polyesters with ester groups or polyamides with amide groups) will have a higher WVP, while hydrophilic materials like poly vinyl alcohol and starch films have even higher WVPs. Expressed in the diffusion coefficient, they are for the relevant environmental conditions between about 10^{-11} m^2/s for the hydrophobic polymers and about 10^{-8} m^2/s for the more hydrophilic polymers [11].

Water vapour sorption

An important parameter in the description of water vapour transport and sorption phenomena is the water sorption isotherm. It describes the relation between the water content c_w [kg/m^3] and water activity a_w [-] of the material at constant temperature. The sorption of water vapour is measured by conditioning the material in a cabinet with well-regulated temperature and relative humidity, while measuring the weight with respect to that of the dry material as a function of RH = a_w100%. For most materials the amount of sorbed water is significantly lower when going from the dry state to the wet state and vice versa. This results in an adsorption and desorption isotherm. This hysteresis is more pronounced for hydrophilic materials. For many materials the moisture absorption and desorption are even reversible.

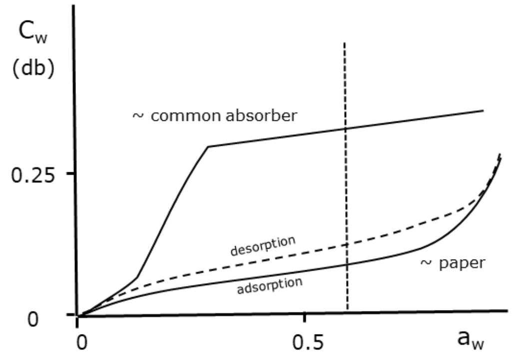

Figure 3 Typical example of adsorption and desorption isotherm (water content c_w versus water activity a_w) of a paper-like material (indicated) as well as an absorption isotherm of a common high moisture absorbing material. The vertical dashed line indicates a_w=0.6.

Hydrophilic porous materials can absorb most moisture at a certain RH. Good moisture absorbers are silica gel, zeolites, fluffy cellulose and dried starch. A typical example is shown in Figure 3. For example, trays made from moulded fibres can take up 15-25% mass weight of moisture from the air, depending on the quality of the fibres, the production process and humidity [12]. Normal paper absorbs less moisture from the air, typically less than 10% at humidity levels not exceeding RH=90% [13] [14]. Paper and cotton are also great water absorbers. Materials with the highest absorption coefficients are so-called super-absorbing polymers (SAP), also known as hydrogels. These are modified polyacrylate salts, meaning that co-polymers such as acrylamide, hydroxyethyl methacrylate, vinyl acetate, maleic acid anhydride and crosslinkers are present. Without cross-linkers these polymers would simply dissolve in water. SAPs are used in diapers, nappies etc. Both carboxymethylcellulose (CMC) derivatives and modified starches have been used as biobased SAPs for compostable diapers [15].

3 Method

3.1 Survey

In the framework of this project, the National Archives of the Netherlands has performed a survey among their international partners, asking what the main issues are in the current archives. Survey questions are listed in Annex 1. Responses were obtained from Indonesia (2x), Brazil, Suriname and South Africa. Outcomes are discussed in section 4.2.

3.2 Modelling

The modelling focuses on the expected change in moisture level inside the books/paper stored in an archive box under varying relative humidities of the environment. Effects of the water vapour permeability of the box as well as the presence of absorbers are considered.

3.2.1 Diffusion model

A one-dimensional Fickian diffusion model is used to estimate the water migration in an archive box as well as in paper sheets and/or books inside the box, under various environmental circumstances as varying relative humidity (RH) and temperature (T). A schematic drawing of the archive box is shown in Figure 4.

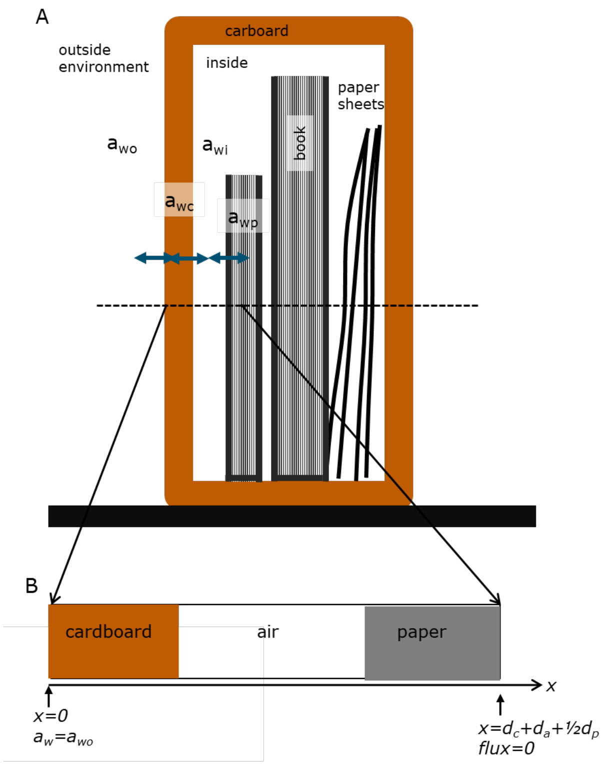

Figure 4: ***a two-dimensional schematic drawing of a cardboard archive box containing books and paper sheets. Water migration can occur between the air of the outside environment, cardboard, air of the inside environment, and books and paper sheets. The driving force for water migration is the water activity a_w. The bottom panel B shows the one-dimensional cross section used for the Fickian diffusion model.***

Various papers on water migration in air and paper have been published (see e.g. references [1] [2] [3] [4] [5] [6] [7] [8]. Water transport through paper is complex and includes migration through the solid and fluid phases. Here we will use a simplified Fickian diffusion model, as it gives very good insights in the fundamental water migration processes and time scales involved. See also section 2.1. In 1D the model reads

$$\frac{\partial a_w}{\partial t} = \frac{\partial}{dx} D_e \frac{\partial a_w}{\partial x} \qquad (5)$$

where a_w is the water activity, D_e is an effective diffusion coefficient, t is time, and x is the spatial coordinate. The water activity acts as the driving force for water migration, which in air is equal to the relative humidity RH/100% and which in the solid materials (like paper, cardboards, coatings, absorbers) is related to the moisture content via the moisture sorption isotherm. The effective diffusion coefficient D_e depends on temperature and water content as well as material properties including fibre density, fibre orientation, porosity, tortuosity, and moisture sorption isotherm. Given the effective diffusion coefficient $D_e(x, a_w)$ as function of x and a_w, equation 5 can be solved applying appropriate initial conditions and boundary conditions, yielding the water activity $a_w(t, x)$ as function of time t and position x.

The model describes the transport from water vapour into and out of the box by predicting change in the amount of water (represented by the water activity) at every position. Instead of a 3-dimensional model, the box is represented as a single line, with – from left to right – air, a cardboard layer, open space (air) and paper. (The other half of the box is not modelled, because it is assumed to be the same). The water vapour diffusion coefficient is the main parameter of the model.

3.2.2 Model parameters

The effective water vapour diffusion coefficient in air varies linearly between about 2.4 10^{-5} m^2/s and 2.7 10^{-5} m^2/s at temperatures between 20 °C and 40 °C, respectively [16].

The effective diffusion coefficient of water in paper-like materials varies with the used material. Various values can be found in the scientific literature, ranging from about 10^{-10} to 10^{-6} m^2/s. For the temperature and water activity range relevant for the archive box (20-40 °C and 0.2-0.9, respectively), effective diffusion coefficients of paper sheets are found to be in the range of 10^{-7} m^2/s and 10^{-6} m^2/s [3] [4] [5] [6], including historical based papers [9].

The effective diffusion coefficients of polymer coatings are between about 10^{-8} and 10^{-11} m^2/s for the relevant environmental conditions [11].

Good insights into the water migration dynamics through an archive box, coating, and to the papers and books inside can already be obtained by assuming effective diffusion coefficients that are independent of temperature and water activity. Therefore, we used a constant effective water diffusion coefficient in air, paper, and coating of 10^{-5}, 10^{-7}, and 10^{-9} m^2/s, respectively. If otherwise, it will be indicated.

3.2.3 Scenarios

To gain insight into the effect of changing humidity on the contents of the archive box, various scenarios have been modelled. Based on the objective and the results of the survey (see section 4.2) three general scenarios are considered in this report:

I. The climate control of the room containing the archive box fails, resulting in a change in climate conditions (high humidity) for a longer period of time.
II. Archival boxes are temporarily taken out of the climatised room, papers are removed from the box, boxed after use and returned to the climatised room.
III. The climate control of the room is temporarily out of order (5 or 24 hours) and turned back on afterwards.

The details of the scenarios are described in Chapter 4.

4 Results and discussion

4.1 Base material and design

The box currently used in most archives (especially in countries with a temperate climate) is made of corrugated board, see Figure 1 and Figure 6. Corrugated board is chosen as the main construction material as it is affordable, light-weight, strong and can be produced locally. Other materials like e.g. plastic or metal do not match these requirements because they are more expensive and heavier [25][26].

The current corrugated board, however, is sensitive to insect intrusions, because of the open construction. Therefore, we propose to use solid board as the base material for the new archive box. This can provide specific benefits with respect to pest/insect control.

The main differences between corrugated board and solid board (Figure 5) are [17] :

Solid board	Corrugated board
Increased puncture resistance	Higher fire risk
	Increased risk of water damage
	Possibility of pest infestation
More expensive (more weight per thickness of board)	Greater stability at same weight

Both corrugated and solid board can be recycled. Both products are produced all over the world.

The current archive box (see Figure 1) contains a hole to facilitate picking it up from a shelf. To prevent intrusion of insects, we propose to close the hole and work with closed boxes. For existing boxes, the hole can easily be closed using e.g. a sticker or tape. For new archive boxes, this can be taken into account in the design phase. For example, one can include a strip that facilitates lifting the box from the shelf.

Figure 5: ***Schematic depiction of solid board (l) and corrugated board (r).***

Figure 6: ***Left panel: A close-up of several pieces of corrugated cardboard[1].***
Right panel: An example of commercially available solid board[2].

[1] By Richard Wheeler (Zephyris) - Taken from http://en.wikipedia.org/wiki/File:Corrugated_Cardboard.JPG, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6534720
[2] https://www.smurfitkappa.com/nl/products-and-services/solid-board/graphic-board-brown

4.2 Main issues in archives in tropical countries

National Archives of the Netherlands has performed a survey asking what the main issues are in the current archives in tropical countries. Detailed replies from the various countries were analysed. A general conclusion is difficult to draw, as each archive has its own specific issues.

Some problems are common in several countries, like for example, problems with climate control due to outdated air conditioning equipment, poor maintenance, or frequent power outages. These appear to be a main worry. Examples of the survey results:

- Western Cape Archives and Records Service (South Africa): "*Ageing infrastructure (air-conditioning system), with budgetary constraints making replacement / repair difficult. […] Power cuts are increasingly an issue; our main power supply company has been engaging in periodic "load-shedding" when the power grid is constrained. These can happen at quite short notice. […] There are frequent issues, including with the sourcing of spare parts for the ageing system. About two years ago we had a complete breakdown of the system for a number of months before a new air-conditioning unit was able to be installed*."
- National Archives of the Republic of Indonesia: "*The main problem in the repository is that we never achieve the ideal temperature and humidity in spite of the utilisation of the Air Conditioner and the Humidifier. The main issue is Indonesia's tropical climate. Another problem is power outages caused by natural disasters. The back-up generator is only capable of supporting brief intervals of air-conditioner or humidifier use."*

A second main worry is the human aspect: occasional poor handling of the documents by staff and readers is an uncertain and certainly not unimportant aspect.

Other topics that were mentioned:

- In some countries also water/moisture damage is an issue.
- Insect infestation is only an issue in tropical climates.
- Most archives are sufficiently dark to avoid UV radiation issues, so this is not a major issue.

This information is used to define scenarios for the modelling.

4.3 Modelling

A model has been developed to simulate the water/moisture migration in the components of an archive box. The model is described in section 3.2. Various scenarios of changing environmental conditions were calculated, giving important insights into the effect of changing parameters like the application of coatings and absorbers and changes in environmental conditions (RH and T) on the moisture content (water activity) of the archived materials.

4.3.1 Characteristic diffusion times

The characteristic diffusion time $\tau = \frac{d^2}{D}$ indicates how long it takes for a substance to diffuse along a certain distance d. It can therefore be used to roughly estimate diffusion times. As an example, Figure 7 shows the uptake of a substance into a plane sheet due to diffusion as a function of the characteristic time. It is seen that a mass increase of half of the final value is reached after about 0.5τ. Thus diffusion into cardboard of 2 mm thickness with a $D_e=10^{-7}$ m^2/s takes about 40s, similar to the diffusion through air along a distance of 20 mm ($D_e=10^{-5}$ m^2/s). Diffusion of water with $D_e=10^{-7}$ m^2/s into a book of 10 cm thickness would take in the order of 10^5 s, or days, to reach about 93% (corresponding to τ=1) of the final water content.

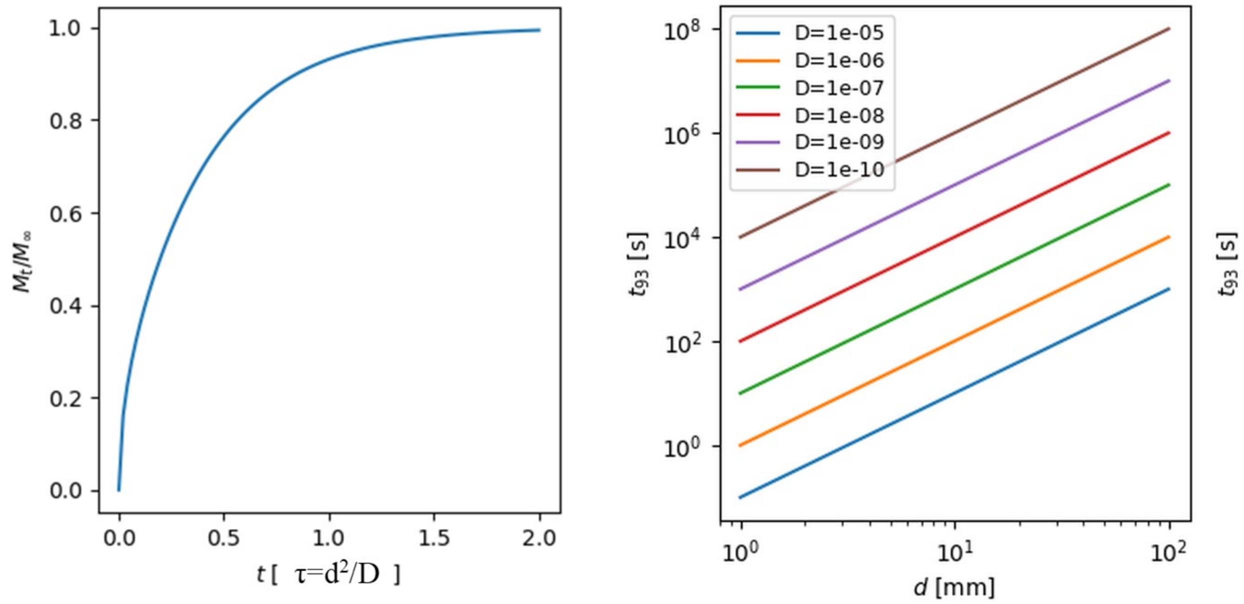

Figure 7** **Left panel: Mass increase due to water sorption of a material subjected to a sudden change in environmental RH at t=0, as a function of time expressed in units of the characteristic diffusion time. Right panel: Typical diffusion time t_{93} (the time that 93% of the final amount of water is absorbed, corresponding to τ=1) as function of the thickness of the paper (d [mm]) for multiple diffusion coefficients (D [m²/s]). Each separate line shows a different diffusion coefficient value.

The model can be used to estimate how long transportation of water vapour through a layer of material takes. The right panel of Figure 7 shows how much time it takes to reach approximately 93% of the saturation of a material of thickness *d* for different diffusion coefficients *D*. This time increases (double logarithmic) with the thickness of the material. The graphs show results for a material with thickness varying from 1 mm to 100 mm. Six lines are shown as examples for different diffusion coefficients. It can be seen that for a diffusion coefficient $D=10^{-6}$ [m²/s], it takes roughly 100 seconds for water vapour to penetrate a material of 10 mm thickness (orange line, $d=10^1$ mm, $t_{93} = 10^2$ s). Using a material with a diffusion coefficient of 10^{-8} [m²/s], it takes roughly 10 000 seconds for water vapour to penetrate a material of 10 mm thickness (red line, $d=10^1$ mm, $t_{93} = 10^4$ s). Furthermore, a 10 times increase in material thickness will result in a 100 times increase in diffusion time to transport vapour.

4.3.2 Scenario I: Long-term failing of the climate control

Standard archive box

As a first scenario, we studied the moisture migration in a standard cardboard box without coating. The box experiences a sudden change in relative humidity in the storage room – from 50% to 80% - to simulate a climate control that fails at a sudden moment. Figure 8 shows the model outcome for this scenario. The left graph shows the water activity (of the cardboard and paper) or relative humidity RH of the air (in the box) as a function of the cross-section of the box. It is noted that the water activity (a_w) of a material is equal to RH/100% when it is in equilibrium with an environment at RH. The relation between the moisture content and the water activity is the sorption isotherm. The various lines display the moisture profile at a specific moment, starting at t=0 seconds, up to t=200 seconds.
In the right panel of the figure, data for the same scenario is shown, but displayed in a different way. Here the RH/100% is displayed on the vertical axis and the time on the horizontal axis. The different lines correspond to different positions in the box, ranging from the blue line z=0 (outside border of the box) to the black line z=paper, corresponding to the middle of the document/paper.
The graphs clearly show that the characteristic time frame needed to reach an equilibrium situation, meaning the point where the humidity level inside the box of archived documents reaches the same level as the humidity outside the box, is only in the order of minutes. This means that within a few minutes the humidity levels inside and outside the box will be comparable. We noted that failure of the climate control can result in

a more gradual increase of the environmental (outside) RH. These results show that in the order of minutes, the RH inside the box is about equal to that of the environment.

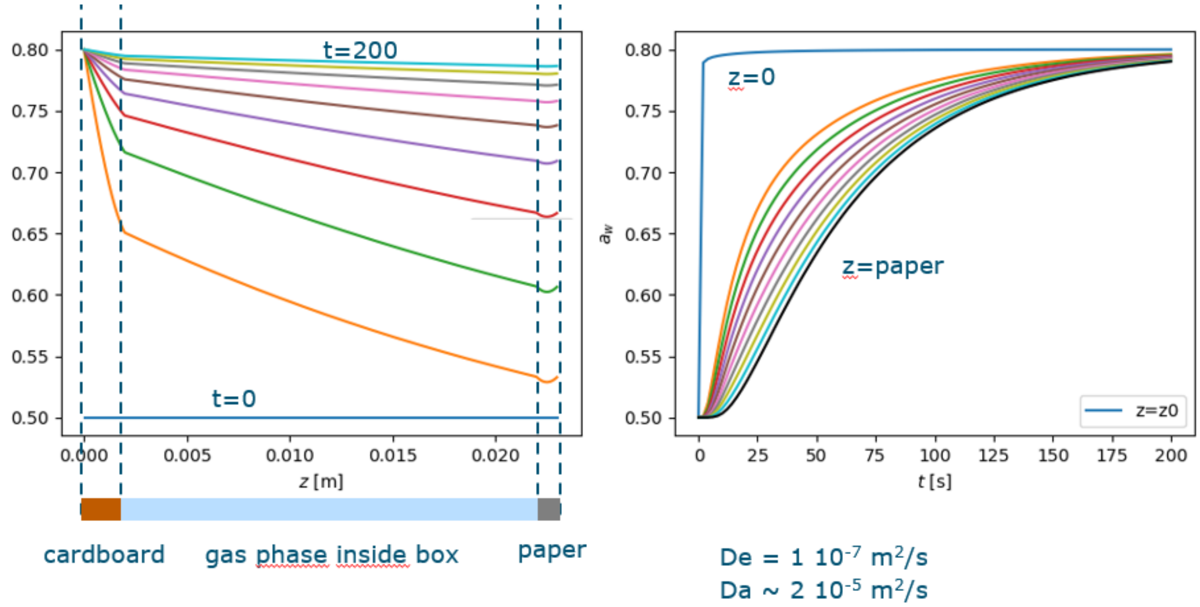

Figure 8 ***Left: a_w (related to the moisture content via the sorption isotherm) on the vertical axis (a_w=RH/100%) versus a cross-section of the box on the horizontal axis (2mm cardboard with D=10^{-7} m^2/s, 20mm air with D=2 10^{-5} m^2/s, 1 mm paper sheet with D=10^{-7} m^2/s). The various lines display the moisture profile at a specific moment, starting at t=0 seconds, up to t=200 seconds (as indicated in the graph). Right: water activity vs time [seconds]. The different lines show the location in the box, ranging from z=0 (outside boundary of the box) to the black line z=23mm, corresponding to the middle of the paper sheet. Scenario: relative humidity outside the box increases instantly from 50% to 80% at t=0.***

Effect of coating

As a next step, the effect of a coating is investigated and whether it can help to prevent this quick moisture transport into the box. Therefore, a coating layer of 0.1 mm thickness was added on the outside of the box. Furthermore, a thicker document was considered (a book or pile of papers of a total thickness of 2 cm, so that ½ of the thickness is 1 cm) as well as a thin boundary layer of air outside the box. A cross section of the non-coated and coated archive box is displayed in Figure 9.

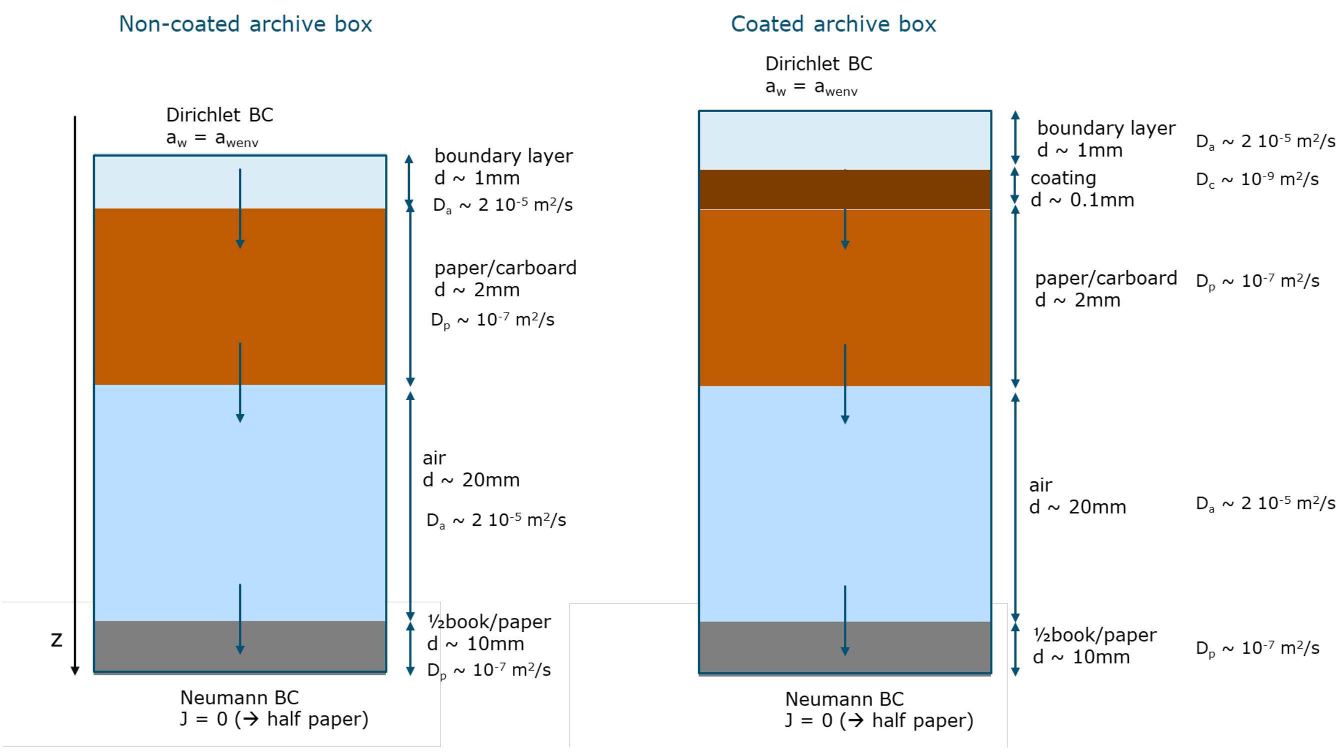

Figure 9 Cross section of the non-coated archive box (left) and coated archive box (right) showing the different layers and diffusion constants used in the model. Boundary conditions are also indicated.

In this study, the same scenario was used as before, so the relative humidity increases from 50% to 80% at t=0. Results are displayed in Figure 10.

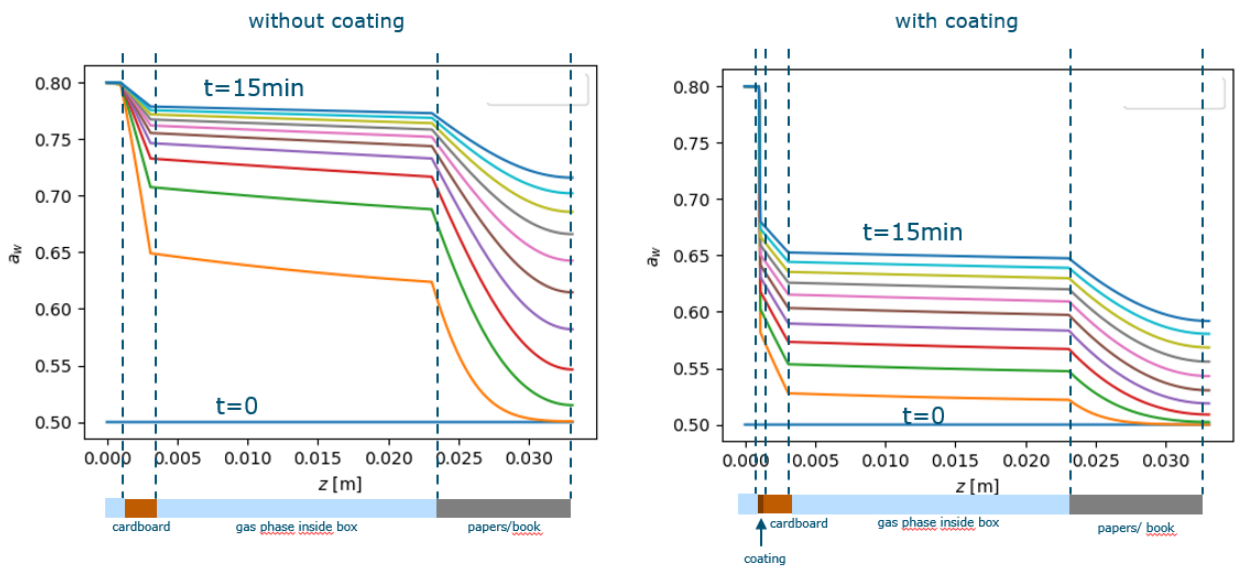

Figure 10 Both images show a_w (related to the moisture content via the sorption isotherm) on the vertical axis (a_w=RH/100%) versus a cross-section of the box on the horizontal axis. The various lines display the moisture profile at a specific moment, starting at t=0 seconds, up to t=200 seconds. Scenario: relative humidity outside the box increases instantly from 50% to 80%. The left graph shows the results of a box without a coating. The right graph shows the results of a box with coating.

When comparing the model results without and with coating on the box, we noticed that the coating delays the effect of the change in humidity. Fifteen minutes after the increase in RH, the moisture content in the box with coating is significantly lower compared to the moisture content in the box without coating. The bigger pile of papers also makes clear that the contents of the box (single papers, a folder with multiple papers, a book, a book with a leather cover) will influence how quickly the documents are affected by a change in environmental RH. Generally, also with a coated box, the moisture level in the box increases within minutes up to hours. This can also be estimated from the characteristic diffusion times. A coating with $D_c \sim 10^{-9}$ m^2/s and thickness d~0.1 mm thickness has a characteristic diffusion time of $\tau = d^2/D = 10$ s, which is about equal to that of cardboard with $D_p \sim 10^{-7}$ m^2/s and 10 times thicker. Thus, adding such a coating would result in characteristic diffusion times of about two times longer, and thus in the same order of magnitude.

4.3.3 Scenario II: Temporary removal of the papers out of the climatised room

Another scenario that has been investigated is what happens if an archive box is opened and a document from that box is read in a room with a high relative humidity. We assume the following steps in this scenario:

- Box stored in storage room (RH 50%) (t<0)
- Box transported at RH 80% during 15 minutes (0<t<0.25h)
- Paper taken outside box during 30 minutes and box closed again in reading room (RH 80%) (0.25h<t<0.75h)
- Paper put back in box and transported (RH 80% during 15 minutes) to storage room (0.75h<t<1h)
- Box stored in storage room (RH 50%) (t>1h)

Results of this scenario for a coated and non-coated archive box are displayed in Figure 11. It shows the average water activity of the document as a function of time. Diffusion coefficients and thicknesses are as discussed above.

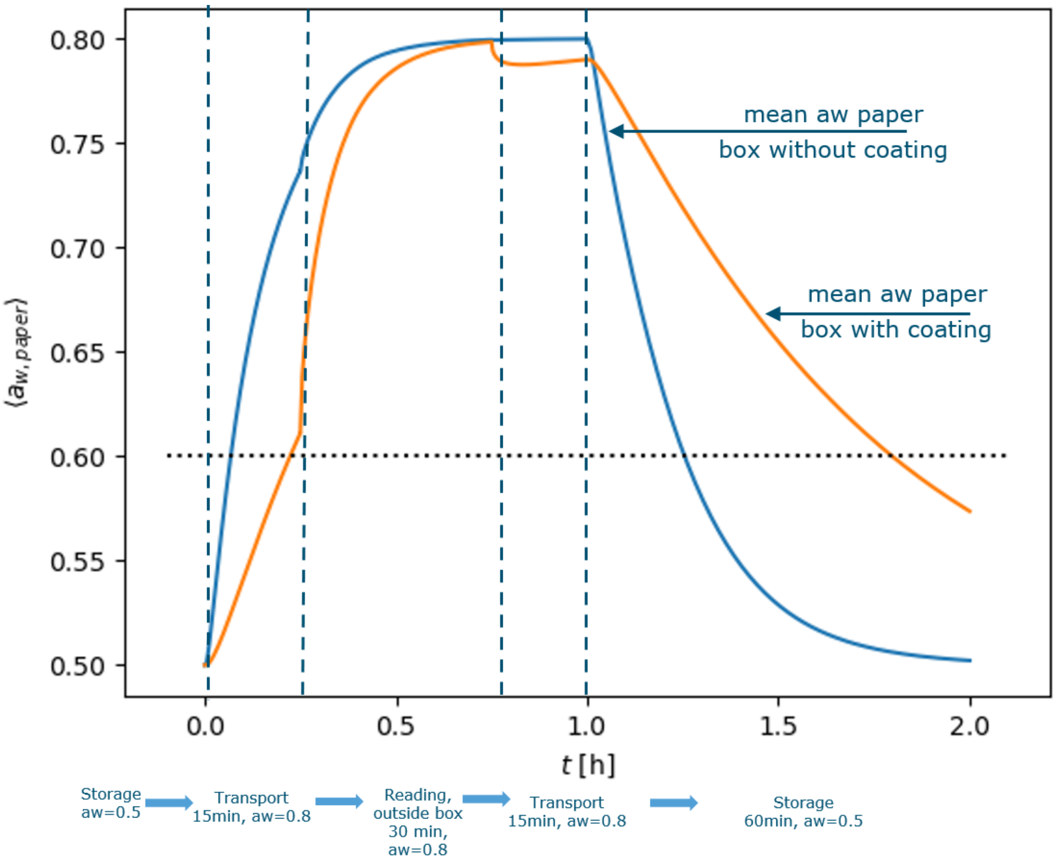

Figure 11 ***mean water activity of the paper versus time in hours. Blue line: box without a coating. Orange line: box with a coating.***

We observed that a coating slightly delays the increase of moisture in the paper documents during transport to the reading room. After removing the document from the archive box (which is closed afterwards) the water content in the documents quickly rises. During reading, the closed archive boxes are still exposed to a RH of 80%, resulting in the RH in the boxes gradually increasing. After putting the documents back in the coated archive box, we observed a small reduction in the average water activity of the documents (see orange line at t around 0.9h). This is caused by the fact that for the coated archive box the inside RH at that time is lower than 80%, the RH of the read paper. This is not observed for the non-coated archive box (see the blue line) because the inside RH has reached about 80% at that time. After placing the archive box back in the climate-controlled storage room we observed that the decrease in moisture of humid documents is actually slower in the coated box compared to that of the non-coated one. Furthermore, we observed that documents stored in the coated archive box have in this scenario a water activity larger than 0.6 for a longer period as compared to those stored in the non-coated box. This means that coating of the archive box can also have an adverse effect, because the coating slows the drying process.

4.3.4 Scenario III: Temporary failing of the climate system

Effect of coating
As a next scenario the effect of coating an archive box has been studied in case of a defect in the climate control system of the storage room. We assume that the default relative humidity in the storage room is 50%. When the air conditioning is out of order, we assume the relative humidity to be 80% for 24 hours, or as an alternative scenario, 70% during a period of 5 hours. Figure 12 shows the results of these calculations.

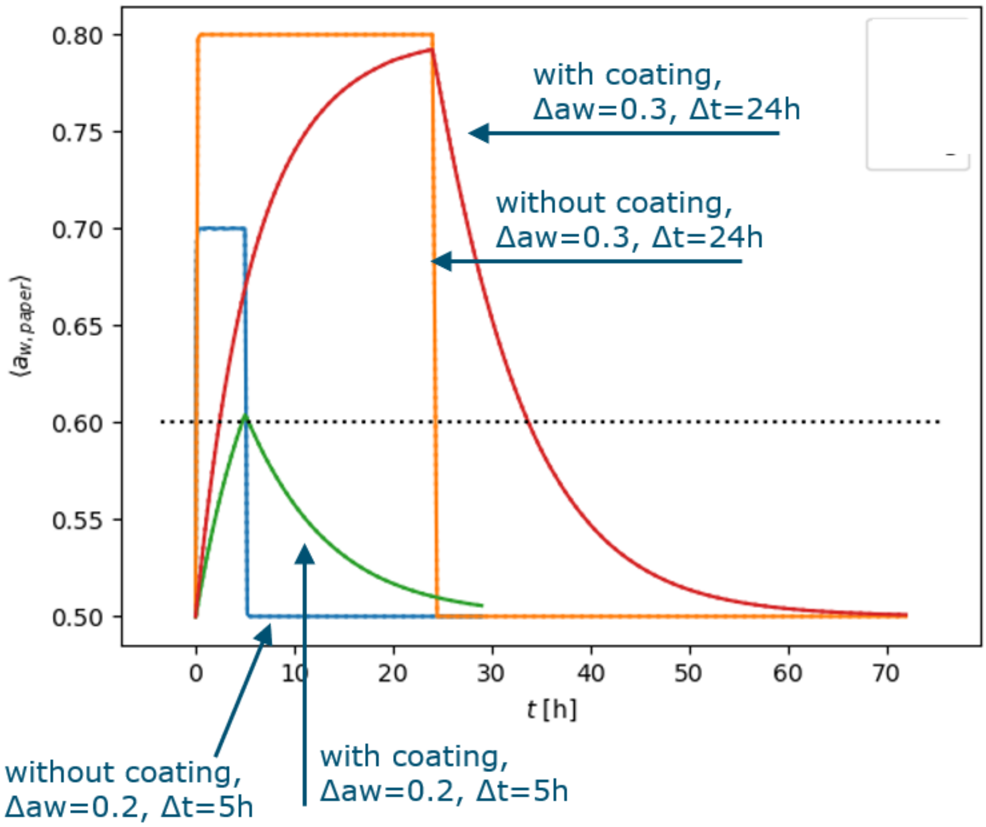

Figure 12: ***average water activity of the paper versus the time in hours. Orange and blue lines: box without a coating. Red and green lines: box with a coating. The orange and red lines assume that the high relative humidity of 80% lasts 24 hours. The blue and green lines assume that a high relative humidity of 70% lasts only 5 hours. The diffusion coefficient of paper equals D_{paper}=5 10^{-7} m2/s, and that of the coating equals $D_{coating}$= $10^{-4}D_{paper}$.***

Again, we see the behaviour that the coating slows the increase of humidity in the paper documents. However, the drying of the documents after fixing the climate control also takes longer compared to the non-coated box. So, for the situation where the climate control is defect for a long time (with respect to the characteristic diffusion times of the archive box), the content of the coated box stays wet for a longer time period compared to the content of the non-coated box, similar to what was observed above. However, for the scenario with a relative humidity of 70% during 5 hours, the documents did not reach the critical level of 60% humidity. This implies that a coating could help for short outages (smaller or equal than the characteristic diffusion time).

Effect of different types of coating
Different types of coatings exist that have different diffusivities. The lower the diffusivity of the coating, the slower moisture will be transported in and out of the archive box when there exists a different RH inside and outside the box. The effect of different coating diffusivities on the average water activity of documents inside the archive box is displayed in Figure 13, for a scenario where the climate control system is out of order during 12 hours, causing a relative humidity of 80% instead of 50%. Only a coating with thickness of 0.1mm and diffusivity of 10.000 times less compared to that of paper keeps the documents under the threshold value of 60% RH. It is noted that a similar effect can be obtained with a coating 10 times as thick and a diffusivity 100 times as high.

In summary, a coating will slow the moisture migration between the box and the environment. Thus, in the case of a malfunctioning of the climate control system resulting in an increase of the RH above 60% in the storage room for a short time (in the order of days), the coating will successfully decrease the exposure of the archived materials to high moisture. However, when the malfunctioning lasts longer, causing the RH in the box to rise above 60%, the coating has a negative effect, because it will take longer to decrease the RH in the box to the acceptable level below 60%. Thus, the effect of applying a coating on the exposure of archived materials (positive or negative) depends on the duration of the defect of the climate control system as well as on the type of coating (thickness and diffusion constant). The less permeable the coating is, the more difficult it is to get the contents of the box dry again. A coating can therefore also have an adverse effect. We can conclude that whether a coating is beneficial depends on the circumstances.

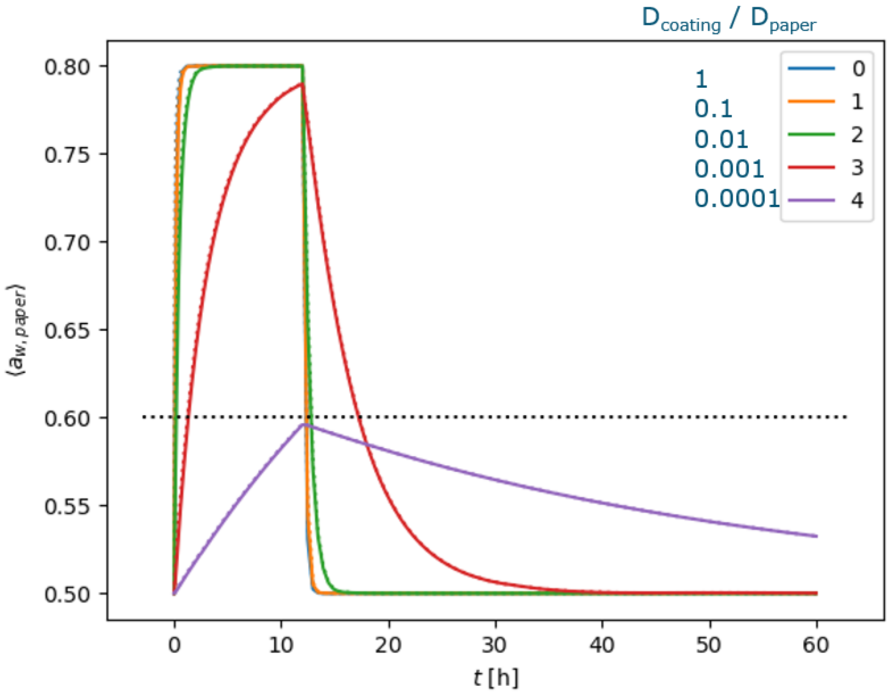

Figure 13:** **Moisture content of the paper versus the time in hours. Different colours show various types of (virtual) coatings with different diffusivity values. The colour of the lines indicate different ratios between the diffusivity of the coating and that of the cardboard (as indicated in the legend). Modelled scenario: climate control defect during 12 hours. RH 80% instead of 50%. The diffusion coefficient of paper equals $D_{paper}=10^{-7}$ m2/s, and those of the different coatings vary between $D_{coating}= D_{paper}$ and $D_{coating}=10^{-4}D_{paper}$., as indicated in the legend.

Effect of absorber

The effect of an absorber has been investigated by calculating the mean water activity of a document inside an archive box in which an absorber is placed. The absorber has properties similar to that of silica-gel (D_{sg}~10^{-9} m^2/s) and dimensions similar to that of the document. Calculations have been performed for a coated and non-coated archive box. A cross section of the coated box is shown in Figure 14. Figure 15 shows the average water activity of the document inside the archive box as a function of time (continuous lines) as well as that of the absorber (dotted lines) for four situations: 0) non-coated archive box, no absorber (blue line), 1) non-coated archive box, with absorber (orange line) 2) coated archive box, no absorber (green line) 3) coated archive box, with absorber (red line). It shows the results for a failure of the climate control system for 3h.

From the figures it can be estimated that the time that the document has mean water activity above 0.6 is about 3 h for all cases, except for situation 2 (coated, no absorber), where it is about 4h.

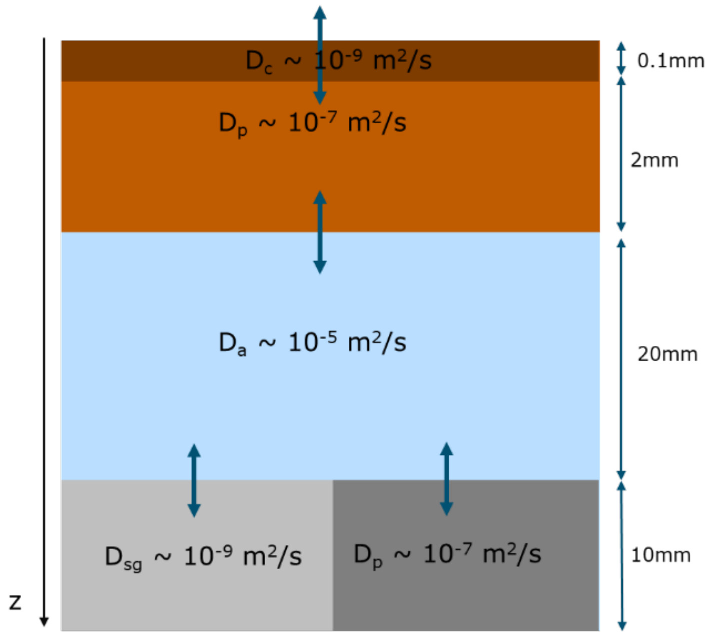

Figure 14: ***cross section of a coated box with absorber (light grey) and paper document (dark grey).***

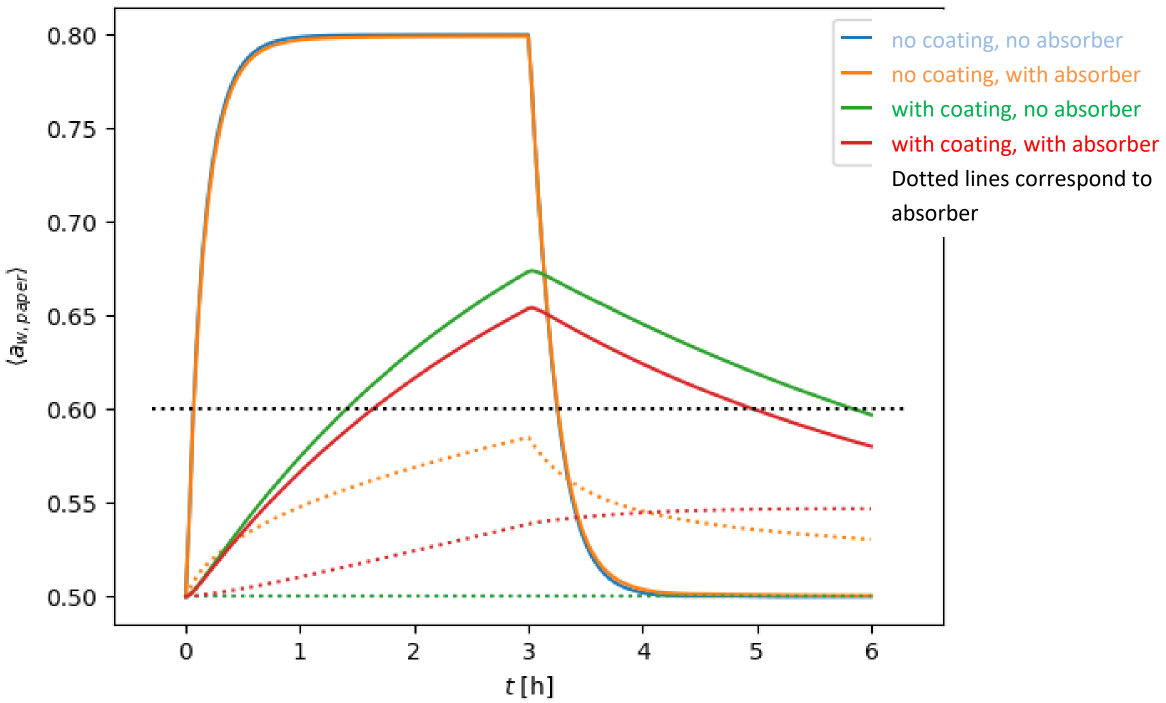

Figure 15: ***Average water activity of the paper document (continuous lines) and absorber (dotted lines) for four situations: 0) non-coated archive box, no absorber (blue line), 1) non-coated archive box, with absorber (orange line) 2) coated archive box, no absorber (green line) 3) coated archive box, with absorber (red line). The horizontal dotted lines represent a water activity of 0.50 (green) and 0.60 (black), respectively. Modelled scenario: climate control defect for 3 hours (left panel), resulting in an RH 80% during that period, instead of 50%.***

This study shows that the presence of an absorber can have a slightly positive effect to keep the water activity of archived documents lower in the case that the climate control of the storage room fails for only a short period (3h, short with regards to the characteristic diffusion time of the absorber) for a coated archive box. In other cases, like with a climate control defect of 30 hours (not shown here) the absorber has no significant effect.

Most common absorbers, like silica-gel, absorb most water at low relative humidities (see Figure 3), which make these absorbers not a suitable absorber for the archive box. This is because a common super-absorber is already saturated at RHs around 50% (about the RH of the archival storage room) meaning that the buffering capacity of the silica-gel is very limiting when increasing environmental RH above 50%. Ideally, a special absorber is used, which does not absorb at storage room humidities but absorbs at higher RHs that may occur either during transport or during defects in the climate control of a storage room. However, these are specific and expensive and do not match the boundary conditions set in this project. Model calculations have shown that the effect of an absorber is indeed expected to be limited.

4.3.5 Effect of temperature and water activity on diffusivities

In the calculations presented above the effect of various scenarios and archive box properties (in terms of diffusivities and thickness of the materials) on the water activity of archived paper documents were studied. The diffusivities were considered to be constant, and not dependent on water activity a_w and temperature T. In general, they do depend on a_w and T. However, including these effects could result in at most a factor of 10 difference in diffusivity in the relevant range of water activities (between about 0.2 and 0.9) and temperatures (between about 15ºC and 45ºC). This therefore does not change our conclusions.

4.3.6 Effect of possible condensation

The water vapour saturation pressure P_{vsat} depends on the temperature. For example, P_{vsat}=4.2kPa at T=30°C, while it is 2.3kPa at 20°C. Thus when an archive box in equilibrium with an environment having RH=80% and T=30°C is transported to a room with T=20°C, then about 0.8*4.2-2.3=1kPa of water vapour can condense. However, considering the amount of air in an archive box compared to the amount of water present in the documents and cardboard, condensation can be neglected.

4.4 Discussion

The goal of the project is to advise on the design of an archive box that is optimised to protect archived records under tropical circumstances: high temperatures and relative humidities as well as large variations therein. The relative humidity inside the box should be between 35% and 60% to protect the documents. A Fickian diffusion model has been developed and used to estimate the effect of different scenarios of varying environmental changes on the exposure of archived materials to moisture. In this section, the use of the model as proxy is discussed.

A model is a simplification of reality, but describes the relation between the key variables of a certain system. Here, the system contains the archive box, out- and inside environment (air) and inside archived documents. The key variables are their relative humidities (water activities) and time. The model can calculate these variables as a function of time, given a certain boundary condition, like the (time dependent) relative humidity of the environment (climate room). This is called a scenario. The key variable of interest is the water activity of the archived documents with time. This should be between 0.35 and 0.6. Models are used to quickly calculate and predict what could happen in a certain scenario. In order to determine whether the calculated results make sense, it is important that the model be checked and validated with practical measurements.
As discussed in section 3.2, the Fickian diffusion model has been proven to be a suitable quantitative model to describe and predict water migration in materials and systems like the archive box. The model contains an important parameter, the diffusion constant of the materials. Here we worked with a broad range of diffusion constants that are validated in the scientific literature, representing different types of paper (including historical cellulose-based materials), absorbers, and coatings, varying from permeable to more dense coatings.

A study of Schönbohm and co-workers to the fluctuation of moisture content in cardboard boxes shows time-scales similar to what we found in our study [18]. Furthermore, Derluyn *et al.* [19] performed a study on the sorption properties of paper and books. They studied moisture uptake rates of magazine and telephone books with different paper fractions (paper volume per total volume), and found typical $t_{50\%}$ absorption times in the order of a few days, which corresponds well to our findings. A similar study was performed by the National Cultural Heritage Agency (Rijksdienst voor het Cultureel Erfgoed – RCE) by doing measurements for the Royal Library (Koninklijke Bibliotheek). Piles of books were stored under specific climate conditions (RH and T), while their degree of moisture was measured over time. The study is – to our knowledge – not published. Through personal communication with RCE we obtained information on the set-up and preliminary results of their study, wherein we ascertained that RCE worked with diffusion coefficients that are in the same order of magnitude as those we used in our model. Differences in sorption time scales were noticed between the measurements from RCE and the results of our modelling study. However, these could be explained by the differences in the size of the documents used; in our study we worked with a paper-like document with thickness of 2 cm maximum, whereas RCE worked with a much thicker pile of books, with covers made of other materials (like leather).

From the calculations of various scenarios, important conclusions could be drawn about the time scales involved and the effect of coatings and absorbers. The developed and used model is one-dimensional and contains the essential physics of water-migration in the archive box, using validated diffusion coefficients for the materials, which are taken to be independent of RH and T. This because of simplicity and to get a better understanding of the time scales involved. The conclusions drawn hold for choices of different cardboards as base material for the box, as well as for coatings applied on the outside or inside of the box. Furthermore, the model could be extended to include temperature and water activity dependent diffusion constants. However, as discussed in 4.3.5, the influence is really limited and will not change the conclusions. The one-dimensional model can also be extended to a full, three-dimensional model. However, the order of magnitude of the moisture transport is clear based on the one-dimensional model. Extension to higher spatial dimensions will not change the order of magnitude of the results and conclusions drawn.

5 Conclusion and recommendations

The National Archives of The Netherlands (NAN) stores millions of records of national significance that need to be preserved carefully. NAN is working closely with partner institutions in tropical countries, where temperature and humidity are high and air conditioning systems are often not reliable. Wageningen Food and Biobased Research has been asked by The National Archives of the Netherlands to provide help to develop a new packaging concept to store archived documents in tropical areas.

The aim is to develop an archive box that meets as many desired properties as possible, with a focus on protection against varying climatic environmental conditions. The main aim is to limit the inside relative humidity of the box to values between 35% and 60%. Moreover, the box should minimise insect intrusion, have no negative impact on the items stored in the box, and the box must be locally produced, low-cost, and sustainable.

An investigation into the state-of-the-art knowledge on the moisture migration phenomena relevant for the archive box system has been performed. The archive box system includes archived documents, possible absorbers, cardboard box, and coatings. The focus was on moisture sorption and transport phenomena of paper-like cellulose-based materials, polymer coatings, and absorbers. Based on these results, a physical model has been developed and used to get insights in the effects of different solid board boxes, coatings and absorbers, under various scenarios of varying environmental humidity and temperature. A stand-alone cardboard box without a coating reacts very quickly to a change in environmental relative humidity. Typically, the RH level inside the box is equal to that outside the box within a few minutes. A coating can delay this to a few hours or days, depending on the type and thickness of the coating. However, a decrease in the moisture transport rate through the packaging material due to a coating can also have an adverse effect. This is in cases where the RH inside the box has reached a value larger than about 60% and larger than that of the environment. This may happen e.g. after adding a wet paper to the box, or after repairing a climate control system that was out of order for a few days. It is worth noting that a coating on the box makes it more difficult to remove moisture once there is moisture inside the box. This causes the documents inside the box to experience high humidity over a longer period of time than in a box without a coating, where the moisture dissipates more rapidly.

Application of polymer coatings on cardboard archival boxes will only be effective on a time scale of hours to days. For boxes that need to withstand moisture migration on a time scale of months, other materials are needed, like metals, that do not comply with additional requirements like cost-effectiveness and possibility of local production.

In general, the archives of the NAN experience different types of problems due to the tropical climate, which require different types of solutions. There is no archive box or material that can solve all of these problems at the same time. This because the effect of a certain adaptation, like application of a coating or absorber, on the moisture exposure of the archived documents depends on the details and time scale of the experienced problem. One example is that applying a coating could help to prevent exposure of the archived material to a high humidity when the problem involves a brief defect of the climate control of the storage room. However, the same coating will enhance the negative effect of exposure to high humidities when a moist document is put into an archive box or when the climate control is out of order for a longer time period, causing the water activity inside the archive box to exceed the upper limit of 60%. This is because the drying process is slower.

Furthermore, it is concluded that the effect of common absorbers is limited, because they are already saturated at RHs around 50%, which are common in tropical storage rooms. Therefore, their buffering capacity when the environmental RH increases above 50% is very limiting. Ideally, a special absorber is used that does not absorb at storage room humidities (below about 55%) but absorbs at higher RHs that may occur either during transport or during defects in the climate control of a storage room. However, these are specific and expensive and do not match the boundary conditions set in this project.

So, because tropical archives experience different types of problems of different durations, no general advice for the construction of an archive box can be given to minimise the exposure of the archived materials to high humidities. Different types of problems due to the tropical climate require different types of solutions. There is no archive box or material that can solve all of these problems at the same time. However, general recommendations and handling advice can be given depending on the situation and duration. In summary:

- Produce the archive box from solid board instead of corrugated board to minimise insect intrusion. Other materials like metal or plastic could also be used, but for these materials it is more difficult to comply with other requirements like cost efficiency and local production.
- Remove or close the hole in the current box design. This will minimise insect intrusion.
- Application of a coating to reduce the water vapour permeability of the box is in general not recommended. This because it can have positive but also adverse effects, depending on the situation, as explained above.
- The use of an absorber can be considered in specific cases. In general, the effect of a common absorber is limited or negligible because it will be saturated around 50% RH. In that case, specific and expensive absorbers are needed, which do not match the boundary conditions set in this project. However, dry absorbers could be used and added, for example, to archive boxes when they are exposed to high RH for a short time (shorter than days) to decrease the water activity of the archived materials. Another option is to use de-humidifiers in the repository, however, this has not been modelled.
- Stabilise the relative humidity conditions in the storage rooms and keep it below 60%. Invest in reliable climate control systems.
- Identify and select different handling and storage solutions, like a transport protocol, depending on the type of archived documents and the type of experienced problem. For example, a special transport box could be used, which is made from a material with low water permeability (e.g. plastic or metal like aluminium) during transport through not climatised spaces with high RH. This will limit the water migration to the archive box during high RH exposure for a short time, which can be important for brittle and sensitive historical documents to keep their humidity low when environmental humidity is changing.

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Annex 1 Survey questions

Survey Archive box for tropical conditions

Archive size and composition

1. What is the size of your archive holdings (in linear meters)?
2. What is the composition of your archive (period of time, main subjects, size in that time period)?

Storage method

3. What is your current storage method of archives in your repository (boxes, archive racks (of metal, wood), stacks of paper on the floor, use of folders, in bags, climate system (airco), insect prevention system, etc.)?
4. How is the climate maintained in the storage rooms (no active control, climate system, type of system, etc.)?
5. How is the temperature and relative humidity climate monitored in the storage rooms

Examination method

6. What is the procedure to examine documents?
7. How is the climate maintained in the examination rooms (no active control, climate system, type of system, etc.)?
8. How are you monitoring the climate in the examination rooms (for temperature and for relative humidity)?

Storage and reading rooms climate

9. What is the climate you prefer in the repositories (relative humidity and temperature)?
10. What is the climate you prefer in the examination rooms (relative humidity and temperature)?
11. How long does the transportation of archives from the depot to the reading room take?
12. What are typical conditions at your location (indoor climate in the storage and examination rooms, seasonal and daily fluctuations)?
13. How often per day are objects requested for use in the reading room?

Climate problems

14. What are the biggest problems in maintaining the desired climate (no climate system available, power failure, powers cuts, etc.)?
15. How often does each problem occur?
16. What is the impact on your archive collection(s) due to the different climate problems?
17. Should the box also be a barrier to insects?

Archive climate data

18. Do you have particular climate data during a typical day?

Climate system

19. Do you use a climate control system in the storage rooms?
20. Do you use a climate control system in the reading rooms?
21. How often does the climate system break down?
22. How long are the breakdown periods of the climate system? Do you have a backup system?
23. Is there a different working method during a breakdown period (no access to the rooms for example)?

Outdoor climate

24. What are typical outdoor conditions at your location (outdoor climate, seasonal and daily fluctuations)?
25. What is the average external temperature and RH

Paper archive box

26. Would you be interested to use corrugated board or paperboard boxes as archive boxes?
27. For which part of the archive would you like to use the boxes?
28. What size of boxes would you prefer (in terms of capacity of the boxes in kilos)?
29. Is there a board producers located in your country or region? Is there a paper factory in the immediate vicinity that can and wants to manufacture archive boxes? Is there a paper factory in the immediate vicinity that can and wants to manufacture archive boxes?

To explore the potential of nature to improve the quality of life

Wageningen Food & Biobased Research
Bornse Weilanden 9
6708 WG Wageningen
The Netherlands
E info.wfbr@wur.nl
wur.nl/wfbr

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The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,600 employees (6,700 fte) and 13,100 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.