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PREVENTIVE CONSERVATION

Modelling and performance evaluation of storage enclosures

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Abstract
A model of moisture and heat transport was used to study the performance of storage enclosures. This paper examines several modelling approaches and presents the benefits and drawbacks of a 'simple' model which requires few input parameters. As a result, users do not need to measure many material properties, but some quality of the predictions is lost. The model is used to explore the balance of moisture exchange through ventilation holes and diffusion, the presence of buffering material inside enclosures and the effect of wall thickness. The predictions correspond well to experimental data measured in storage enclosures and a historic building. However, in order to bring modelling to the point where it can be used to engineer better enclosures, further research is needed. Experimental validation needs to be extensive and the limits of applicability of the model need to be clearly identified.

INTRODUCTION

Mathematical models of heat and moisture transport are common. However, they have seldom been used to understand the behaviour of storage enclosures in heritage, such as boxes or display cases. Much can be learned from modelling the behaviour of boxes. It is possible to determine which parameters have a bigger influence in the mediation of outdoor conditions. For example, using a model allows the effects of the thickness of the walls, the presence of ventilation holes and buffering materials or the surface area to be studied. A model can help to engineer better enclosure designs.

Many modelling approaches are available which have been developed with different aims. Michalski (1992) produced a very complete account of models for leakage prediction, which also includes a complete evaluation of the importance of different processes (i.e. diffusion through walls and through holes). His approach is sufficient to enable many design decisions. To understand an enclosure with even more detail, it is useful to predict how its internal conditions change through time. One of the most complete models that does this is HAMBASE (De Wit 2006), which has several applications in heritage (Zara 2015). This model calculates internal conditions from external conditions and requires a very complete characterisation of the enclosure. Simulations that are even more detailed can be obtained with WUFI, probably the most used system for moisture modelling, which can resolve moisture profiles within multi-layered walls, and which has been used in many heritage applications (Coelho 2018). Other researchers have developed solutions in different levels of detail, custom-made for display cases (Romano 2015) or historic buildings (Inuzuka 2016).

All these approaches work well. The key difference between them is how much detail they need to run, and how much detail they provide. We believe that this issue has not been addressed adequately in our field. In preventive conservation, often decisions need to be made with limited information. Models can support decision-making, but they usually require detailed input parameters. Can we strike a balance between the need for detailed inputs and the quality of the output? As a first step towards a model of enclosures in heritage, this paper explores the potential of a very simplified model, applicable to all kinds of enclosures, defined with as little parameters as possible.

METHODS

Modelling options

A very simple model was developed to describe the thermo-hygrometric behaviour of boxes. By 'simple' we mean that it describes a very generic enclosure with a small number of parameters. As a result, it is also mathematically simpler than other alternatives. Its inputs are a box design and environmental conditions outside the box, and its outputs are the environmental conditions within the box. This relationship can be described mathematically with various levels of detail, which were considered as part of this research. Figure 1 summarises the options the modeller is faced with. The elements of a heat and mass transport model can be called 'resistances' (which represent the ability of water and heat to be transported through materials) and 'capacities' (which represent the ability of materials to store water and heat). The most minimal model (A in Figure 1) considers that moisture and heat only need to cross a single wall and are only stored by the internal air. This can be made more realistic by introducing a wall that stores water and heat (B). However, this change creates the need for other resistances, as the relationship between the wall conditions and the external and internal conditions needs to be described. In short, the more accurately we want the model to reflect the real behaviour of an enclosure, the more constants will be unknown. In case A, the resistances are given by a heat transfer coefficient that can be easily obtained from handbooks for a variety of materials and an air exchange rate that can be easily estimated. The moisture transfer coefficient is the only real unknown parameter, but it can be obtained by fitting the model to the data. In cases B and C, however, a transfer coefficient is needed between every interface. These are not easy to estimate or measure. They require additional modelling and experiments, or they become additional fitting parameters.

One further decision the modeller needs to take is whether the heat and moisture transport processes are solved separately or independently. Naturally, heat and moisture are linked in the real world. When their amounts within the box are estimated, their combinations need to be thermodynamically

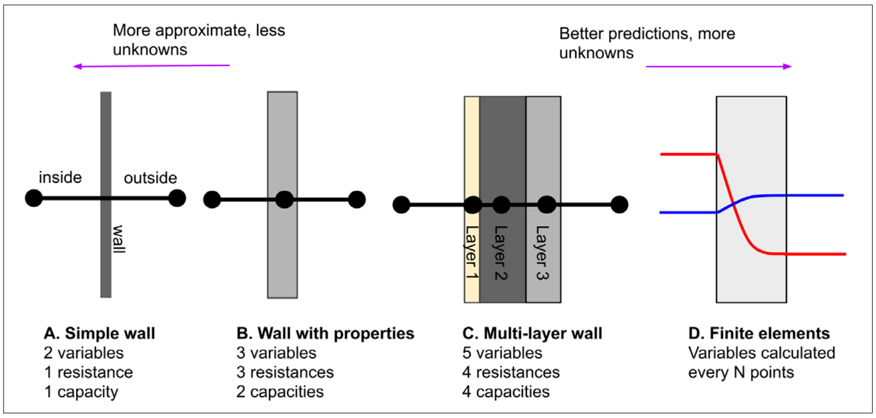

Figure 1. Representation of the main modelling approaches. The indoor and outdoor environments are in opposite sides of the wall. The round dots represent the points at which a value of T or RH is calculated. Lines represent the heat or mass transport processes. The text below each modelling approach indicates the number of variables, resistance and capacity elements for each of the parameters modelled (i.e. T or RH). If both T and RH are modelled, then the number of variables increases

possible. The water within the wall can store heat, the wall cools down when water evaporates and heats up when it condensates. A model that considers these phenomena is called 'coupled'. A model that treats heat and moisture separately is called 'uncoupled'. Coupled models are much more complex mathematically than uncoupled models because they have no analytical solution. In most cases, they need to be solved with the help of a computer. In addition, one might consider case D, in which the layers are replaced by a continuous solution of the profile of heat and moisture within the material. In this case, the complexity of the mathematical solution increases even further. These choices are ultimately defined by the context of use. Simple mathematical models can be solved in common spreadsheet software. The input parameters are easy to obtain without need for further experimentation. This research is guided by the notion that, if simple models are good enough, complicated ones are not needed. In other words, only when the limitations of simple solutions are known should more complex models be developed.

A very simple model

Following the guiding principles outlined above, the simplest possible model was developed using case A of Figure 1. It consists of a mass balance and a heat balance. This section describes the operation of the model and the main input parameters. Readers interested in the detail of the equations are welcome to contact the corresponding author.

The mass balance links the external and internal absolute humidity. The model calculates fluxes of humidity, which can be positive (the interior humidity increases) or negative (the interior humidity decreases). Humidity is assumed to move from areas of high to low concentration. There are two fluxes: one through the wall, which we call 'diffusive flux' and one through holes and cracks, which we call 'infiltration flux'. The diffusive flux depends on the properties of the wall. The infiltration flux depends on the number of holes and gaps, or, in other words, on the air exchange rate (AER).

The heat balance links the external and internal temperatures. Similarly, there are two fluxes: one through the walls, which depends on the thermal conductivity of the material, and one through holes, which depends on the AER. In sum, the modeller needs three input parameters.

This mathematical formulation is solved by numerical integration using the Euler method. The resulting model can be implemented in common spreadsheet software. Its solution is not computationally demanding and can run in any personal computer. In the future, this model will be made available both as a spreadsheet and as an online tool.

Experimental data

Temperature (T) and relative humidity (RH) conditions were monitored inside and outside boxes. In addition, T and RH were measured hourly for a one-year period in a historic property (Hellens Manor, Herefordshire). The purpose of these measurements is to test the predictions in a range of conditions, dimensions and timescales. The data used in this paper is part of a larger experiment in which 40 different boxes with various properties were used. Data from two boxes and the historic properties is used to study the model. The remaining data is currently being analysed and will be published shortly.

Humidity was measured for periods between 2 and 10 days with a 5-minute frequency using small battery-powered loggers (Onset HOBO, Massachusetts, USA). Changes in the outdoor conditions were promoted using humidification, dehumidification and heating, in a range between 15°C–25°C T and 30%–80% RH. While these loggers have an accuracy of 3% for the humidity, most of the in-out differences evaluated in the experiments exceeded this amount. In the historic house, one logger was placed in a sheltered outdoor location, 10 m from the building. Another logger was placed indoors, in an unheated room without mechanical ventilation. The room has a stone floor and walls, with a thickness of 40–50 cm, single-glazed historic windows and two doors, which connect it to neighbouring rooms. The room remains closed for most of the year, and open to visitors on weekends during summer.

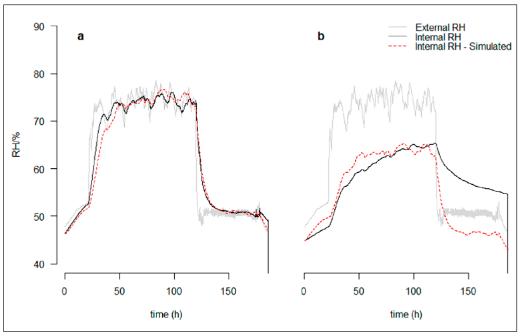

Figure 2. Experimental and calculated relative humidity within a board box, with dimensions 30.5 × 21 × 7 cm. The box has ventilation holes (a). The holes were covered and the walls of the box lined with tape (b). The Pearson correlation coefficient between simulation and experiments is 0.99 for case (a) and 0.79 for case (b)

RESULTS

Comparison with experiments

The use of a simple model allows an easy estimation of the input parameters. Figure 2 shows an example data series from a cardboard box. The geometry of the box is known: the dimensions (30.5 × 21 × 7 cm), the thickness of the board (0.3 cm) and the number and size of the holes. The physical parameters can be estimated within narrow margins: the thermal conductivity (k) of paper board is between 0.05 and 0.1 W/(m K), the heat capacity (C_a) of air 1.00 kJ/(kgK) (Engineering ToolBox 2003). The AER can be estimated using the model proposed by Michalski (1994), which gives results of the order of 0.1 d^{-1}. The only unknown parameter is the moisture transfer coefficient, which is obtained by fitting the model to the data in order to minimise the difference between the measured and predicted absolute humidity. Following this procedure, the best fit is obtained with 1.53×10^{-6} m/s. It should be noted that this value should not be compared with any well-known and measurable material property, such as permeability. As a fitting parameter, its units and value are a reflection of all the assumptions and simplifications of the model. This value is only useful for the relative comparison of model runs within this discussion but has no general value for the characterisation of enclosure materials.

Once fitted to the data, the model reflects the evolution of the indoor environment fairly well. Figure 2 displays some notable similarities and differences. Humidity inside the enclosure increases and decreases following the external conditions. The resistance provided by the walls reduces the amplitude of the external fluctuations, and the storage capacity of the air causes a delayed response. However, there are notable differences. The model over-predicts the reduction of internal humidity in every decrease. This could be due to the lack of an equation describing moisture storage within the cardboard, which would delay the response of the internal environment.

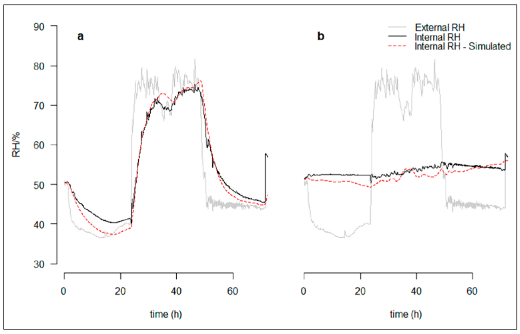

Figure 3. Experimental and calculated relative humidity within a board box, with dimensions 30.5 × 42 × 6 cm. The box is empty (a) and filled with a stack of paper (b). The Pearson correlation coefficient between simulation and experiments is 0.98 for case (a) and 0.71 for case (b)

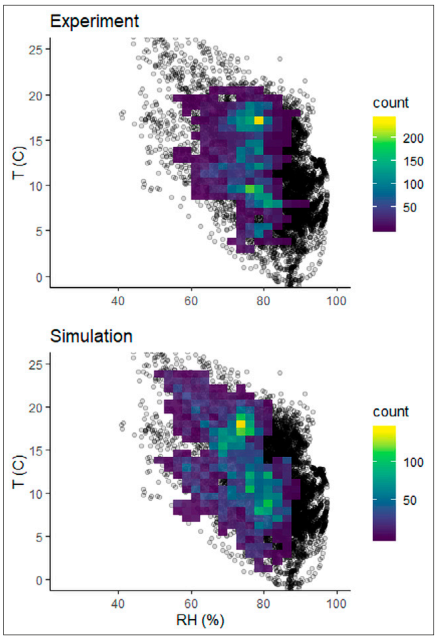

Figure 4. Measured and calculated year-long conditions in a historic house. The external experimental data is shown as black dots. The internal data, measured and calculated, is shown in a density plot. The 'count' indicates the number of hours that certain conditions are present

The usefulness of the model comes to full effect when drastic changes are made to the box design. In this case, the board was covered with a plastic film, thus reducing mass fluxes to zero (or a value so small that using zero instead does not change the output). Figure 2 shows how the model successfully predicts the resulting stable internal humidity.

The case illustrated in Figure 2 corresponds to an extreme change to the resistance to moisture transport, which translates into an equally pronounced change to the amplitude of the internal fluctuations. Figure 3 illustrates another common scenario: a change to the capacity to hold moisture of the internal environment. This usually happens due to the presence of contents within enclosures. In this case, two identical boxes were exposed to the same conditions, one empty and one filled with a stack of paper. This requires adding a fourth fitting parameter that describes the moisture exchange with the buffering material. While the model fits the data, adding more parameters increases the risk of overfitting.

The model is successful in predicting increases and decreases of humidity, particularly when they are longer than 10 hours. Shorter fluctuations are not predicted so accurately. In the case where contents are present within the box, the model successfully predicts the maximum humidity reached indoors. However, it over-predicts the decrease in humidity following an external reduction. This is, with all probability, because the model is insufficient to capture the dynamics of the equilibrium moisture content of the materials within the box. It has been shown that the equilibrium moisture content of diverse materials displays strong hysteresis, in other words, that moisture absorbs and desorbs at different rates when drying and humidifying. Since this model describes this phenomenon with a single moisture transfer parameter, it cannot capture the dependence of the rate on the direction of the flux. Naturally, another parameter could be added, with the drawbacks and benefits already discussed.

The use of plots such as Figures 2 and 3 to evaluate the model contains the implicit assumption that a very high accuracy in a dynamic prediction is desirable. After all, such plots allow differences of less than 1% RH to be visible. However, in many practical cases, knowing approximate internal conditions is enough to make a judgement about the suitability of an enclosure. The hourly dynamics of moisture change are arguably of secondary importance, while the yearly or seasonal conditions guide most decisions. Given that the model predicts daily better than hourly changes, its performance was tested using a year-long series of hourly data. The data belongs to an unheated and largely unoccupied room in a historic building, rather than a box. However, for the purposes of the model, it behaves as a very large enclosure. Figure 4 compares the experiment and the simulation. Rather than showing a time-series, it shows the scatter of external data, and a density plot of internal data, measured and simulated. The model predicts roughly how the enclosure will buffer the external environment. It successfully predicts two large clusters of frequent indoor conditions, at 15°C–20°C and 5°C–10°C T, around 70%–80% RH. It fails to predict less-frequent situations, over-predicting hot and dry days. However, the prediction is mostly correct in the most common regions.

Diffusion vs. infiltration of moisture

The model can be used to explore hypothetical scenarios. In the example of Figure 2, it has been seen that eliminating diffusion practically eliminated the exchange of moisture. This happens because, in that case, the majority of the mass transfer occurs through the walls of the enclosure (diffusion), rather than through the holes (infiltration). This will be the case for many enclosures made of hygroscopic materials. In absence of air motion, the AER caused by air movement through holes is described by Figure 5, based on Michalski's model (Michalski 1994). If we consider a hypothetical cubic box with sides of 50 cm, with a 5 cm hole on each face, the AER will be about $10d^{-1}$. If this hole is closed, the AER will vanish to 0. In this simulation, the value of the diffusive flux is the one obtained by fitting to the tests of Section 3.1. Figure 6 shows the consequences of a change in humidity in this hypothetical box. Both with the highest and lowest AER, the internal environment responds to the external change. Only by eliminating diffusion through the wall can the internal environment be completely isolated. Of course, the relative impact of infiltration and diffusion depends on material properties and box dimensions. The message from this test is clear: it is not possible to create an airtight enclosure only by eliminating cracks and holes.

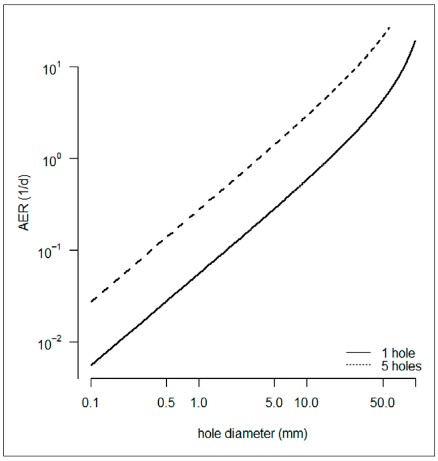

Figure 5. Estimation of the AER according to Michalski's model for holes in thin boards, assuming a cubic box with sides of 50 cm

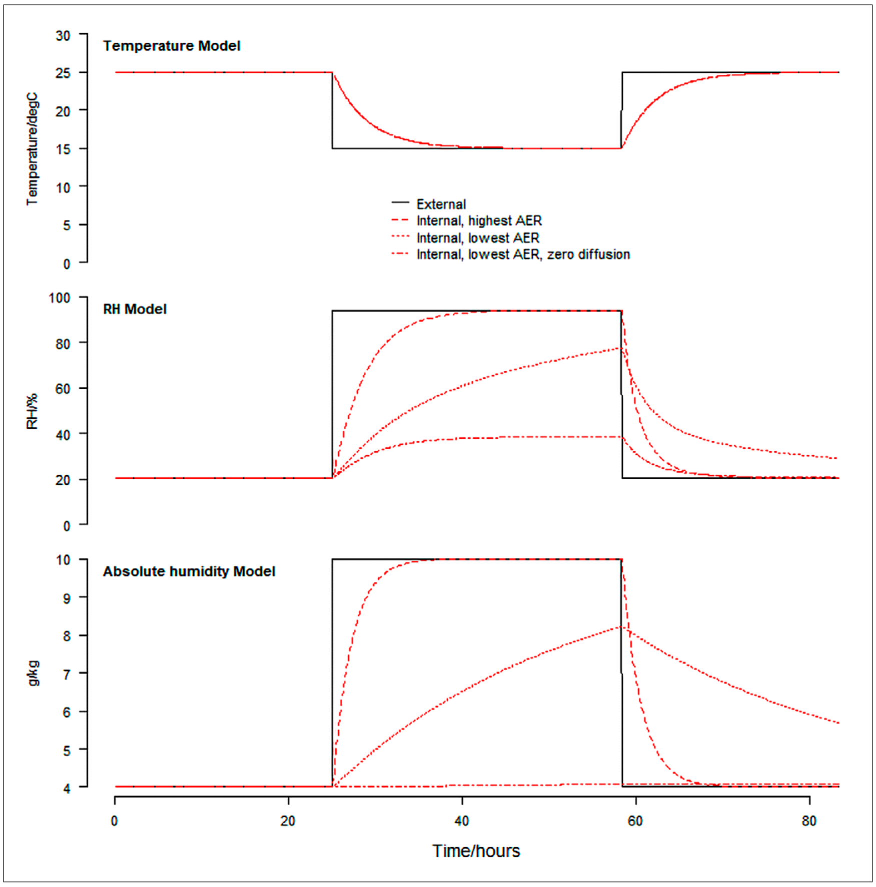

Figure 6. Simulated scenarios of humidity and temperature changes. The 'Highest AER' is $1d^{-1}$. The lowest AER is $0.01d^{-1}$. The coefficient describing the diffusive mass flux is 1.53×10^{-6} m/s or zero

Thickness of the walls

Figure 7 corresponds to another hypothetical scenario. The same box used before, with 50 cm sides and 5 cm holes in each face, is simulated with walls of thickness 5 mm, 10 mm and 20 mm. The different internal responses are due to the simultaneous reduction of the thermal and mass transfer fluxes. This plot illustrates both the potential and the limitations of the model. It shows that it has the capacity to predict the consequences of design decisions. However, it is not clear whether these results are to be trusted. If we consider a wall thickness of 20 mm, the box material will have an important thermal mass and water storage capacity. The model cannot account for those, as it does not involve the water or heat stored in the walls. It is probably underestimating the buffering capacity of this box, which is likely higher than simulated.

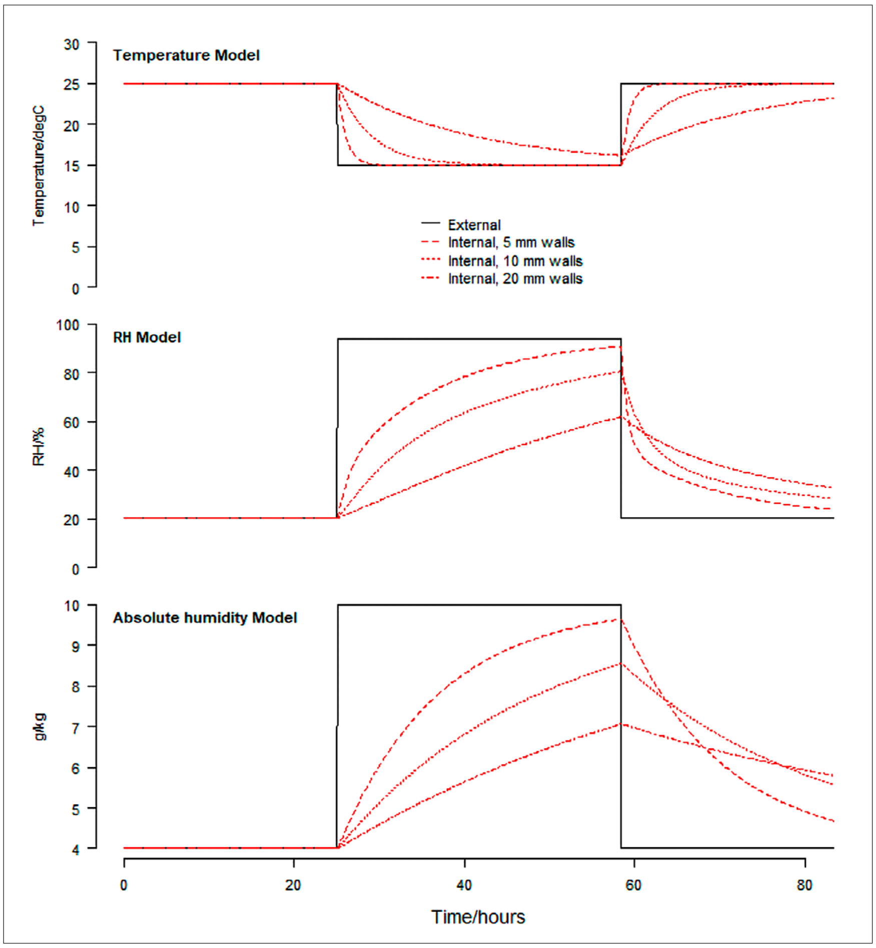

Figure 7. Simulated scenarios of humidity and temperature changes. The coefficient describing the diffusive mass flux is 1.53×10^{-6} m/s

CONCLUSION

This paper outlines several types of models ordered according to their complexity. It has been shown that a simple model with a single fitting parameter (the mass transfer coefficient, *s*) and a few parameters to define an enclosure (thermal conductivity, air properties, dimensions, thickness and air exchange rate) can provide good predictions of internal conditions. In some cases, these predictions are enough to inform decisions. However, this validation is not sufficient to trust the model in all conditions. Some observed limitations are the inability of the model to account for the buffering provided by thick walls and the poor estimation of evaporation cooling. This type of model can be useful, but only if its range of applicability is well defined. It is likely very good for display cases, but poor for thick cardboard boxes. Ongoing research is validating this approach with a wide diversity of experiments with well-defined enclosures. Guidance should be offered on which cases demand a sophisticated model, and which cases can be solved with the approach presented here. Once the suitability of the model is well stablished, model users will be able to engineer enclosures to any specification. The model presented here will be made available as an online tool, in which users will be able to upload external humidity and temperature data and visualise how different enclosure configurations would improve the internal environment.

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