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Analysis of the thermal conditions in an unheated museum store in a temperate climate. On the thermal interaction of earth and store

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ABSTRACT

A finite element model of an unheated museum store has been developed for simulating the influence of the building envelope, the wall thickness and the thermal interaction with the surrounding ground on indoor temperature of the store.

The question of whether to build the store with high thermal mass or with well-insulated walls with no thermal mass is addressed. The influence from excess humidity entering the store through cracks in the building envelope is also discussed. Finally, ways to stabilize the store temperature by improved design, such as additional insulation of the foundation, will be analysed.

The simulations are compared with measurements in a museum store in Ribe, Denmark.

1. Introduction

There is a worldwide awareness that energy consumption for comfort heating of buildings must be reduced to save energy and reduce CO_2-emissions. Within the EU, national building codes are gradually becoming stricter. For museum stores, energy consumption is usually of less significance relative to the demands of maintaining proper indoor climate for the artifacts. However, if possible, energy consumption should be as low as possible. Fortunately, the stores are unoccupied most of the time and therefore can be maintained at moderate temperatures so that heating or cooling is only necessary to a limited extent in the temperate climate of Northern Europe. While museum stores attract less public attention than exhibitions galleries, they nevertheless comprise an important part of a museums property, with requirements of a high quality of the indoor environment. In the typical museum only about 10% of the collection items will be on display, while the rest is kept in storage.

For preservation reasons the relative humidity in the store must be kept at a moderate level. Typically, museum environments are conditioned to a set point between 40 and 60% relative humidity (RH). However, it should be pointed out that the strict limits for temperature and humidity control in a store previously recommended by museum standards today has been looked upon in a more differentiated and qualified way [1–3].

Museum stores should be built as air tight as possible, and the excess humidity in the small amount of outside air inevitably entering the store should be removed by dehumidification, or the RH should be modified by heating or cooling.

We will consider a typical store of approximately 6000 m^3, without windows, and with an un-insulated floor placed directly on the ground. The importance of the thermal interaction of the store and the surrounding soil has so far not been documented properly. The goal of the present article is further to evaluate the significance of using different building materials and wall thicknesses of the building envelope with regard to the storage temperature, and indirectly, the relative humidity.

Of further interest is the role of air infiltration through cracks in the building envelope, the effect of heat capacity of the stored items on the temperature variations, and the significance of heat supplied by equipment (heaters, dehumidificators, and lighting).

To this end, a finite element method (FEM) will be used to model a store placed on the top of an infinite ground volume, in this case by Comsol [4]. The store is modeled as a typical storage building with regard to the physical dimensions of existing storage buildings in Denmark. It is not the intention to model any specific store in greater details and simplified conditions will be assumed with regard to the construction of the building envelope and to the uniformity of the surrounding ground. This means that the thermal resistance of the sandwich wall construction commonly used today in museum stores must be compared with a wall of homogeneous materials with equal thermal properties. A typical wall construction in a modern Danish museum store has a U-value in the order of 0.12 W/(m^2 K), while the 0.50 m mineral wool wall has a U-value of 0.08 W/(m^2 K).

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Nomenclature

c_p	specific heat capacity at constant pressure, J/(kg K)
λ	thermal conductivity, W/(m K)
ρ	density, kg/m^3

The simulations will be compared with measurements carried out by the National Museum of Denmark (NATMUS) on museum stores.

2. The finite element model

The two-dimensional finite element model is shown in Fig. 1. Half of an infinitely long building is placed on a ground volume sufficiently large, so that the sides and the bottom of the ground volume can be assumed to be adiabatic (perfect insulators). Due to symmetry, only half of the store needs to be modeled. The store is 12 m wide and 6.25 m high. The walls and the roof are 0.5 m thick and the floor is made of 0.3 m concrete. The ground volume is 32 m wide and 20 m deep.

The FEM model has 4000 triangular elements with a minimum element quality from 0.68 to 0.07 in the different subdomains. It takes approximately 300 s to simulate one year on a Pentium Dual-core E5300 2.6 GHz PC with 12 GB RAM, 64 bit Windows 7.

The outdoor climate is based on the Danish design reference year, DRY [5]. It provides air temperature and short-wave and long-wave thermal radiation for every hour of a non-existing but typical year, compiled from meteorological measurements. Hourly values for the air temperature vary from −21 °C in January to 32 °C in August, with a mean value of 7.8 °C. The heat transfer at the exterior surfaces (ground and building envelope) is given a convective heat transfer coefficient of 15 W/(m^2 K) and an emissivity coefficient of 0.9.

The air volume of the store is modeled as a solid with high thermal conductivity in order to ensure a uniform store temperature. The heat capacity of the air volume and the heat fluxes entering the air volume are used to obtain the energy balance for the store and thus the new store temperature. Alternatively a Computational Fluid Dynamics model could have been used, however, it is not the purpose of the present work to analyse temperature gradients in the store and it is much simpler to model the air volume as a solid. A convective heat transfer coefficient at the internal boundaries of 5 W/(m^2 K) is modeled as a solid having a thickness of 0.01 m, with thermal conductivity 0.05 W/(m K) and with no heat capacity. The simulations are repeated for several years to obtain periodic behavior.

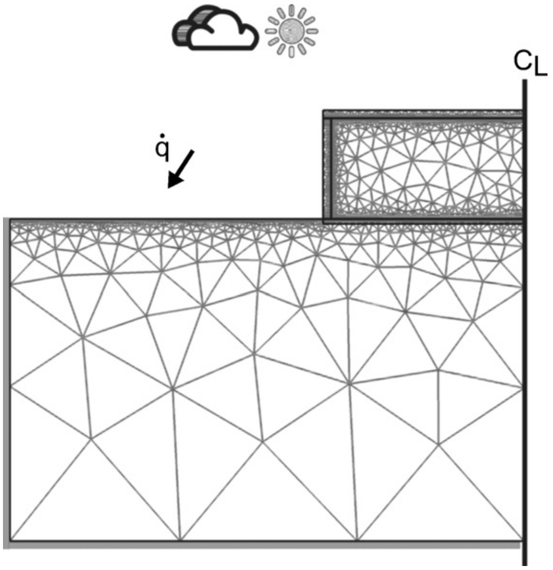

Fig. 1. The basic Finite Element Model. It consists of a store 12 m wide and 6.25 m high. The walls are 0.5 m thick and the floor is made of 0.3 m concrete. The store is placed on a ground volume 32 m wide and 20 m deep with perfect insulators on the side and the bottom.

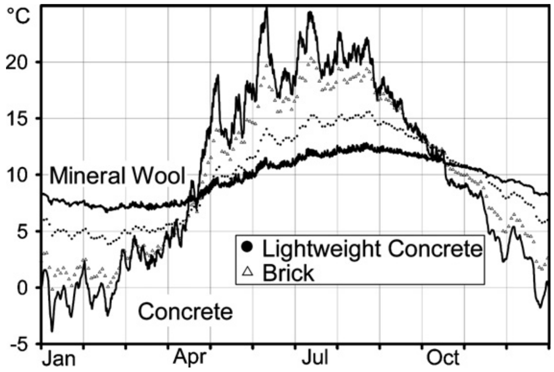

Fig. 2. Annual temperature variations for different material properties for the building envelope. Air tight and empty store.

It is known that the thermal properties of soils can vary to a great extent, for example depending on soil composition and moisture content. Therefore it was investigated how much the air temperature in the store would change by varying the soil thermal properties by ±25%. However, this influence was small.

Another factor influencing the results comes from the climate data used in the simulations. By removing the contribution from solar and long wave radiation in the thermal exposure of the ground and store we found that the air temperature in the store was reduced by 2.5 °C in the summer period. This is an extreme example and although the climate will vary from year to year, the climate in general does not appear to have a big influence on the store temperature.

2.1. Influence of the materials of wall and ceiling

In the following we will investigate the influence of different material properties of the walls and ceiling in the store on internal air temperature. Four different materials are modeled: mineral wool insulation, lightweight concrete, brick and concrete, all at 0.5 m thickness. In all cases the floor is 0.3 m concrete. The material properties are listed in Appendix A, with values for the thermal inertia $(\lambda \rho c_p)^{1/2}$ and the thermal diffusivity $\lambda/\rho c_p$. The thermal inertia is a measure for the surface temperature response of a wall exposed to a heat flux in the initial phase of the temperature rise. The thermal diffusivity is a parameter for the attenuation of cyclic temperature variations through the wall [6]. It appears from the table that mineral wool and concrete are the most different materials in this respect, so in the following only the mineral wool store and the concrete store are considered in detail.

By considering a homogeneous enclosure the difference between the material properties are more clearly seen than by using a real sandwich construction typically used today.

Fig. 2 shows the annual variation of the temperature in the store for the four different materials. A store built of 0.5 m concrete shows a temperature variation from −4 °C in January to 25 °C in June, while for a store built of mineral wool the variation is much smaller, from 7 °C in the winter to 13 °C in the summer.

The effect of varying the wall thickness is shown in Fig. 3 for mineral wool insulation. Wall thicknesses of 0.25, 0.5 and 1 m are

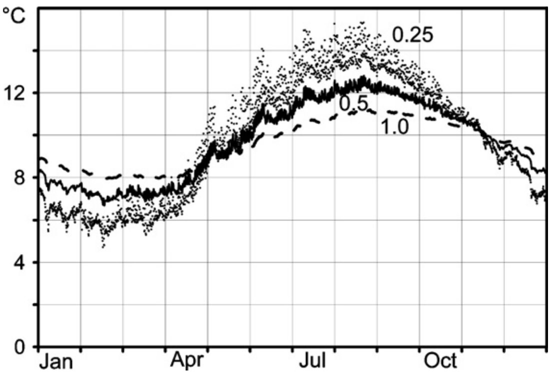

Fig. 3. Annual temperature variations for different wall thicknesses (0.25, 0.5 and 1 m) of mineral wool insulation. Air tight and empty store.

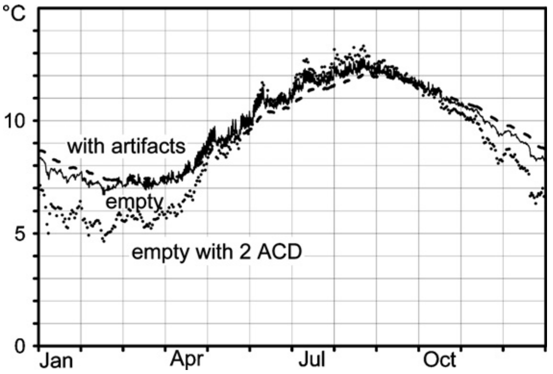

Fig. 4. Annual temperature variations for an empty store, a store with artifacts and a store with a daily air infiltration rate of 2 volumes per day. Mineral wool insulation, 0.5 m thick.

shown in the figure and as expected a bigger wall thickness will give less temperature variation. The yearly min–max temperature span is 5–15 °C, and 8–11 °C, for 0.25 and 1 m wall thickness, respectively.

So far an empty store has been considered. For comparison, Fig. 4 shows the temperature in a store with artifacts equivalent of 400 kg wood per m^2. This figure accounts for a full storage room. The loading is derived from the design maximum load of storage racks in the facilities of NATMUS, and reflects a common situation for museum stores. By increasing the heat capacity of air by a factor of 133[1], the combined heat capacity of air and artifacts was simulated, assuming a uniform temperature of air and artifacts in the store. The figure shows that the artifacts slightly diminish the temperature variations.

However, the infiltration of outdoor air into the store through cracks and leakages has a greater effect. In practice, one air change per day is attainable with the present building technology. An infiltration rate of two times per day is illustrated in Fig. 4. When cold air enters the store during winter a lower indoor air temperature will result. During summer, the indoor temperature is raised but to a lower extent.

2.2. Influence of the thermal properties of the floor

In the basic case, the floor is made of 0.3 m thick concrete. The effect of applying a higher or lower value for the thermal conductivity of the floor on the store temperature was investigated, assuming the theoretical situations of the floor made by either steel (thermal conductivity 60 W/(m K) or mineral wool. The result depends on the heat resistance of the floor compared with that of the building envelope. For adiabatic walls the influence is not big. For the mineral wool compartment the outdoor climate plays a bigger role if the floor is made of mineral wool insulation (store temperature variation −2–22 °C) than if it is made of steel (store temperature variation 6–14 °C). Thus, the heat resistance between the air in the store and the ground volume should be as small as possible.

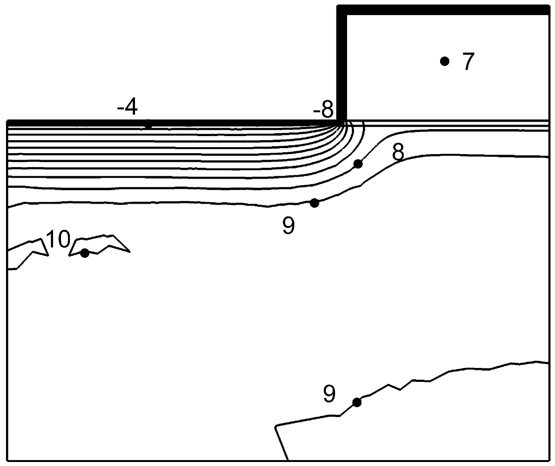

Fig. 5. Isotherms (in °C) in February.

2.3. Thermal interaction of climate, store and surrounding soil

The store and the outdoor climate exchange heat two ways: a heat flow from the outside air through the storage walls and ceiling, and a heat flow from the outside air through the surrounding soil to the store. The first heat flow follows the annual temperature cycle of the outdoor air, with a small attenuation and delay (dependent on the thermal diffusivity). The second heat flow exhibit a much greater attenuation and delay, as the heat flow is modified by the thermal capacity of the ground volume.

The idea to utilize the effect of the thermal capacity of the ground volume has been advocated for some time by NATMUS. A store with direct contact to the ground below the store, without insulation in the floor, will result in a stable indoor climate compared with a store influenced only by heat flow through the above ground envelope.

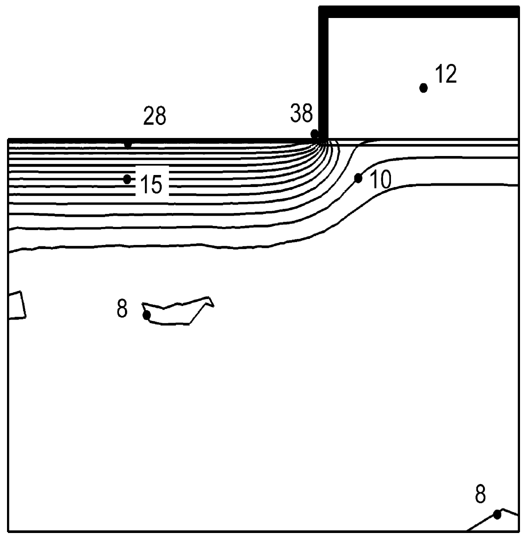

Fig. 6. Isotherms (in °C) in August.

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[1] 75 m^3 air and 4800 kg wood correspond to a heat capacity of 91 + 12,000 kJ/K. Ratio 12,091/91 = 133.

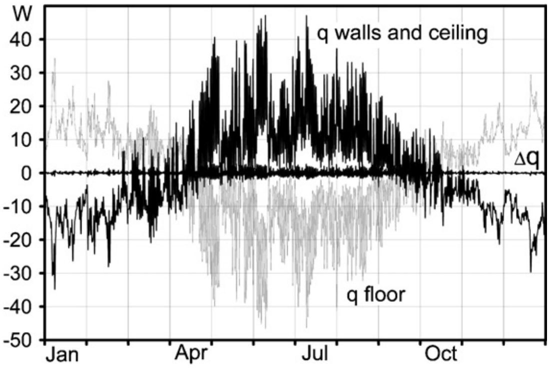

Fig. 7. Annual variation of the integral of heat flux through the floor and building envelope. Air tight and empty store, mineral wool insulation, 0.5 m thick.

The temperature distribution in the ground (i.e. under the floor) is simulated in Figs. 5 and 6 for February and August, respectively. The store strongly modifies the vertical thermal gradient seen in the undisturbed soil beside the building.

The flux distribution at the floor is rather complicated. In some cases, for instance, heat can enter the store near the wall (through the floor) while at the same time heat is leaving the store in the central part of the floor. Comsol can calculate the integral of the heat flux across a boundary but the integral value conceals the just mentioned flux distribution along the floor.

Fig. 7 shows the integrals of the flux coming through walls and ceiling, and the flux coming through the floor. The two integrals are nearly of equal size but with a small difference in magnitude and exhibit a small time delay. This difference in the two heat flows determines the change of store temperature in time. It appears from Fig. 7 that heat enters the store through the floor in winter and leaves the store in summer.

2.4. Improved storage design, cf. Fig. 8

In Fig. 9, a comparison of two cases of improved design is made regarding the store temperature with the basic case of 0.5 m mineral wool wall thickness. These are compared with the case of adiabatic walls and ceiling, i.e. the case where no heat flow is coming through the building envelope. When the heat flow only comes through the floor the seasonal variations are also smaller than in the basic case.

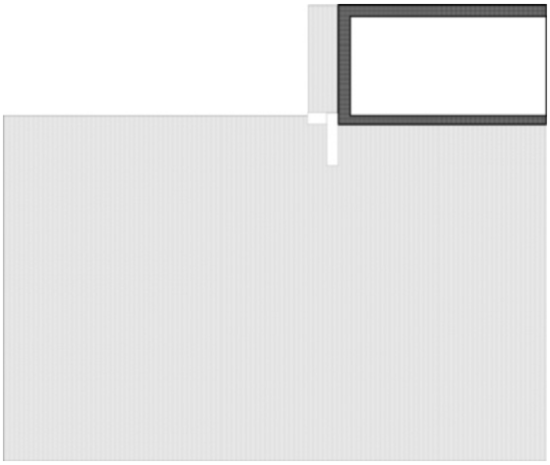

Fig. 8. Improved store design. Three cases shown: 2 × 0.4 m mineral wool apron, 2.3 × 0.5 m mineral wool foundation, 2 × 6.25 m bank of soil to the top of the store (Not to scale).

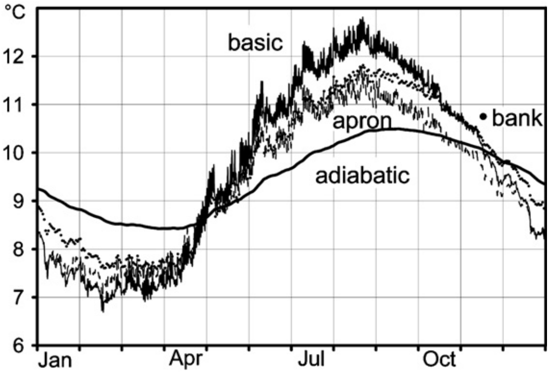

Fig. 9. Annual temperature variations for improved store design (apron, bank, adiabatic envelope, cf. Fig. 8). Air tight and empty store, 0.5 m mineral wool insulation.

A design with less influence from the outdoor climate is advantageous, as the yearly temperature variation is diminished. This is partly achieved by the improved designs: extra insulation in the form of an apron, or as an insulation of the foundation. Because the two designs are very similar the result is shown in Fig. 9 as “apron”. Finally, the influence from a soil bank on the sides of the store was also simulated (indicated with “bank”).

Both the apron and the bank reduce the annual and daily temperature variations compared with the basic case.

2.5. Superposition of internal heat gain

So far internal heat gains have not been considered. These may come from heat inflow from the end walls of the store, personal loads, electrical lighting or from mechanical equipment. The equipment can be radiators for heating or dehumidifiers for the control of the relative humidity. The associated heat load can be superposed on the previous FEM model by adding the heat load in the store air volume and setting the boundary temperatures to 0 °C.

The additional temperature rise in the store is proportional to the internal heat gain. The results are shown in Table 1 for heat sources of 0.1 and 0.3 W/m^3, respectively. These figures correspond to the heat gain from a ventilation system with and without a dehumidifier in operation, cf. Section 3.

It appears from the table that the temperature rise is approximately 10 times higher for the mineral wool store than for the concrete store.

3. Comparison with measurements

NATMUS has carried out measurements of indoor climate in museum stores and exhibitions over several years. Recently, measurements of the temperature distribution in the soil inside and outside of the stores have been added [7]. In this work a store in Ribe, Denmark, will be used as an example (Sydvestjyske Museer’s storage building, architect Bo Christensen ApS). The dimensions of this store correspond to the FEM model shown in Fig. 1.

The store was built in 2005–2006 and taken in operation in the spring of 2007. The basic store is approximately 6000 m^3. The store is without windows and well insulated with a U-value of approximately 0.12 W/(m^2 K) for the walls. The real sandwich construction

Table 1
Store temperature rise in K from internal heat gain.

Heat source [W/m^3]	Adiabatic envelope [K]	Mineral wool envelope [K]	Concrete envelope [K]
0.1	3.3	2.0	0.2
0.3	10.0	6.1	0.6

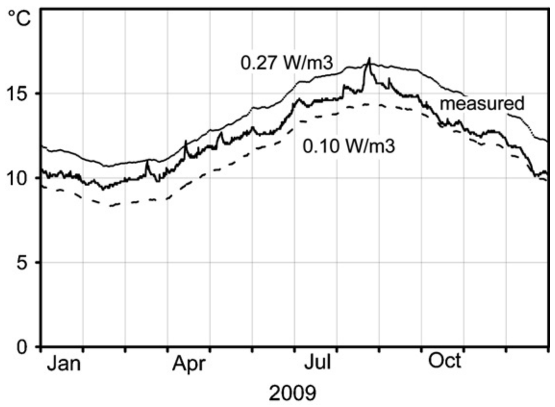

Fig. 10. Simulated and measured indoor temperature for the Ribe store. 0.10 and 0.27 W/m^3, respectively, heat supply from the ventilation system and the dehumidifier is included in the FEM model.

is treated as a homogeneous wall with a thermal conductivity of 0.06 W/(m K). The air exchange rate was measured to approximately 0.7 volumes per day by a tracer gas method. The store is not deliberately heated but takes advantage of the heat exchange with the ground through the concrete floor. Some heat is added from the fan and the dehumidifier in the ventilation system. A small amount of heat is transferred from neighbour rooms heated to comfort level through the two end walls of the store. The humidity in the store is controlled by a dehumidifier, keeping the RH at approximately 50%. Lighting will be limited to periods when artifacts are being taken in or out of the store.

Two kinds of verifications were made: the first one used measured outdoor climate, i.e. air temperature and radiation as the boundary condition. The second one used measured undisturbed soil temperatures close to the ground surface as the driving force. The influence of the building walls on the ground surface temperature distribution is only noticeable close to the wall, so the measured undisturbed surface temperature could be used for the entire ground surface as a good approximation. As the result of these two sets of boundary conditions gave almost the same result, only the first set of boundary conditions will be described in the following.

Unfortunately, a complete set of climate data is not available at the Ribe site. Therefore, climate data for 2009 were collected from meteorological stations nearby Ribe. The soil temperature measurements at Ribe started in September 2009 and consequently a year of data had to be constructed from data covering 2009 and 2010.

Firstly, the measurements in undisturbed soil were used to estimate the thermal properties λ, ρ and c_p of the soil. By nature the heat conduction problem is inverse so the soil properties cannot be determined exactly from these transient measurements. However, we found that a thermal conductivity of 2 W/(m K) gave the best agreement between measurements and simulations in the one-dimensional case.

Subsequently two-dimensional simulations were carried out. The result for the Ribe store is shown in Fig. 10. A correction was made for temperature measurements at the attic and in the neighbour rooms to account for the small heat flows entering the real store from the attic and the end walls. This did not significantly influence the calculated store temperature. In addition to this heat source terms of 0.10 and 0.27 W/m^3, respectively, were included. These values correspond to the heat generated by the ventilation system (0.10 W/m^3) and the dehumidifier (0.27 W/m^3) based on measurements during 5 months in 2010. It appears from Fig. 10 that the measured store temperature lies in between the two simulated temperatures.

4. Discussion and future work

In this work FEM simulations have been carried out for a given museum store with an un-insulated floor placed directly on the top of a ground volume. The thermal interaction of climate, store and surrounding soil has been investigated. In future work the effect of store width should be investigated to clarify how much the outdoor climate will influence store temperature when the store width gets smaller. A 3-dimensional analysis would also be interesting to see the effect of the end walls.

This work utilizes meteorological data from Danish observations (North Temperate Zone). It would be interesting to repeat the simulations for other climates, for instance for much warmer, or colder climates.

Our FEM model has been validated to a certain extent, but due to the lack of a good and complete data set it would be interesting to repeat the exercise for a suitable real museum store.

The present work has not included a moisture balance for infiltrating outside air. However, this balance can be made separately, and the necessary modification to relative humidity by dehumidification or heating/cooling can be calculated afterwards.

It is desirable to build a store which only needs dehumidification in the summer period, i.e. when the indoor temperature is below ambient. In the winter period, there is a risk of low relative humidity because the indoor temperature is above ambient. The optimal performance is when one can manage without winter humidification, and in this respect a gently varying indoor temperature gives a naturally less extreme indoor relative humidity.

5. Conclusions

Simulations by a Finite Element Model have shown how the indoor temperature in a museum store varies with material properties of the building envelope. A store built of 0.5 m concrete shows a temperature variation from −4 °C in January to 25 °C in June while the variation is much smaller for a store built of mineral wool insulation, from 7 °C in the winter to 13 °C in the summer. This result is significant because it is generally believed that museum stores should be heavy constructions to ensure a stable indoor climate. However, for the building envelope above ground good insulation is more important than thermal mass. The floor, on the other hand, should be un-insulated. The store should be built as air-tight as possible so that the relative humidity can be controlled by dehumidification in the summer period with a minimal energy use.

The influence of outdoor climate can be reduced by improving the design, i.e. adding extra insulation at the periphery of the building or covering the sides of the store with soil. However, these improved designs do not have a significant effect on the indoor temperature.

Finally, we have validated the FEM model applying it to a real museum storage using its measured indoor store temperature and meteorological data. This validation shows that more precise information is needed for the internal heat gains (dehumidifier, ventilation system, lighting, etc.), but nevertheless there is a fair agreement between measured and simulated store temperature.

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The authors would like to thank Dr. Tim Padfield, independent consultant in preventive conservation, Devon, UK, for many fruitful discussions on the topic.

Appendix A.

Material properties used in the simulations.

	λ (W/(m K))	ρ (kg/m^3)	c_p (J/(kg K))	$A = (\lambda \rho c_p)^{1/2}$ (J/(m^2 K s$^{1/2}$)	$B = \lambda/(\rho c_p)$ (m^2/s)
Soil	1.6	2200	1000	1876	7.27 E-7
Mineral wool	0.039	32	875	33	1.39 E-6
Lightweight concrete	0.14	535	1000	274	2.62 E-7
Brick	0.5	1550	800	787	4.03 E-7
Concrete	1.7	2300	1000	1977	7.39 E-7
Air volume	100,000	1.205	1007	–	–

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