Passively conditioned zero-energy storage for cultural properties and archival material

Lars Klemm

Abstract

Many types of archival material and cultural heritage objects can only be preserved in an adequate store or archive. Most museums continue to collect but the space to store growing collections is rarely expanded, and in many cases it may even be reduced in favour of additional exhibition space. Archives face a comparable situation. Every archive has the duty to conserve historical documents, which results in hundreds of kilometres of new archival documents every year to be stored and preserved. The probability that during an archivist's lifetime a new archive building will be built or the existing one will have to be extended is about 100 %.

Museums designed in the last 40 years are characterised by a series of specific functions. However, as all architectural typologies are subject to a process of change and modernisation, museums have also evolved over time to become more complex. Museums have changed from spaces of permanent exhibition, storage and conservation to public places with various functions including permanent and temporary exhibitions, study and science, storage and conservation, restaurants, commercial and education facilities and other multi-use activities. During this development, provision of sufficient storage space for collections has occasionally been overlooked.

Few museums are able to store their entire collections permanently inside their main buildings. Large parts of museum or archive collections may be located in off-site storage, where they can be exposed to significant risks of damage. Although storage is at the heart of a museum's function, in some cases surprisingly little attention is paid to providing adequate storage conditions. International standards prescribe tight climate control values, which lead to energy- and cost- consuming air-conditioning systems. However, these systems do not achieve the desired results for collections nor are they affordable in the long term. Even in times of reduced cultural budgets and rising energy prices many museums and archives pour resources into unique and expensive buildings designed to meet those climate requirements and satisfy design aesthetics. Extensive heating, ventilation and air-conditioning systems are installed to achieve stable environments and the high energy and maintenance costs are accepted.

This situation was the starting point for a study in 2011 at the Fraunhofer-Institute for Building Physics (IBP). Its main focus was on passively conditioned zero-energy storage and archive buildings. The objective was to develop an economical and sustainable solution for a zero-energy building, which achieved conservation requirements, neutral energy balance and modular design. The Fraunhofer-Institute designed a new zero-energy storage system with the following research objectives:

1. Easy and economical storage and archive solutions
2. Sustainable planning
3. Multipliable concepts by modular components
4. Cost-efficiency by applying prefabricated construction elements
5. Providing market-ready energy-efficient concepts.

Museums and archives are repositories of knowledge for a modern society; therefore, energy-efficient solutions for these buildings are necessary to maintain valued collections over generations. The results of the study demonstrate that zero-energy storage systems are possible and that technical solutions are partially ready for the market.

Study for the development and examination of a modular zero-energy storage

Modern storage and archive buildings are often very expensive: the building costs are high and the technical equipment causes unreasonably high running costs. Overall the price for a storage or archive building is about 1850 € to 2000 € per square meter. Only very few outstanding projects cross this price threshold, such as the Danish storage buildings in Vejle and Randers, the KHM store in Vienna or the new store in Freiburg/Breisgau. In a context of rising energy prices and reduced cultural budgets it is vital to find solutions for new, economic and effective storage and archive buildings.

One of the current tasks of preventive conservation is to find sustainable storage and archive solutions. That means buildings must save energy and have low maintenance costs as well as achieve conservation standards. It seems quite evident that the only way to achieve low-priced storage buildings will be to use modern industrial architecture. With a modern industrial construction concept it is possible to build a low-cost framed hall within four to six months. The challenge is to transform this building concept into an adequate standard for a store that accords with preventive conservation principles and, if possible, to optimise this concept by modular construction methods which would be suitable for most locations.

This was the aim of the study at the Fraunhofer IBP in cooperation with Südhausbau and k3-artservives. The first step was to develop the concept of different module types for storage and archive building, such as a painting module, an archaeological collection module, a furniture module, an archive module etc. The next step was to simulate a virtual model of the prototype of a modular store to examine the indoor climate conditions and the zero-energy concepts. Finally, it was intended to build the first modular store as an example of best practice. First it was necessary to define the preventive conservation parameters for a modular prototype storage building, particularly in terms of optimal room size, storage management and collection handling, functional architecture, fire protection, safety, pest management, indoor climate (including air exchange rate and wall thickness), heat transfer coefficients of walls, floor and roof and so on. It is important to refer to industrial standards (e.g., on the size of the prefabricated wall and roof elements, which define the raster, size and volume, of the storage and functional module, the shelving system, doors and gates etc.) when determining the parameters for the modular and passively conditioned concept. This is the reason why the study set its focus on prefabricated concrete double wall elements with core insulation. The aim was to develop a low price modular store type (about 1000 € per square metre including shelving system, a price achieved at the KHM store in Vienna), that complied with nearly all aspects of preventive conservation and operated as a zero-energy building. It was necessary to subordinate all other aspects to this overall goal.

A simple, safe construction approach for a conservation store requires basic, low-maintenance and energy-efficient installation engineering. Floor heating combined with ventilation is therefore the best solution. If possible a humidification and dehumidification system should be avoided. Furthermore, the building should successfully operate without cooling, even if the predefined climate limits are moderately exceeded during some days a year. The energy consumption of the storage building should be as low as possible and at the same level as the regenerative energy gain of the building. Taking into account their aspects of maintenance and use, stores or archives are the perfect building class for a passively-conditioned concept and a zero- or even plus-energy building. However, it is ineffective to achieve this standard by expensive construction materials and planning costs. The quality must be realised with a simple and low-cost construction method. For that reason all building components had to be produced by fast and efficient industrial processes. The fire prevention for the modular concept is also simple; no fire extinguishing system is required. Preventive fire precautions are strictly implemented: each module is a separate fire compartment equipped with a carbon monoxide early-detection sensor. The security and fire alarm system must be arranged at the specific location and with the input of the local emergency services.

To achieve space optimisation and to take full advantage of industrial efficiency each module can only be obtained in two room heights, 350 cm and 700 cm, and the width of walls is limited to a raster of 275 cm. This permits the application of standard shelves and mezzanine systems and limits production, transport and construction costs. It is not the aim to achieve an individual solution for each collection in the museum but rather an all-round solution that fits for a large part of every collection. The modular concept offers the possibility of future extension of the store or archive building if necessary and as far as the building site permits. For this reason, all storage and archive modules must be standardised: any extension or enlargement can be achieved simply by adding another module, no rearrangement of the collection would be necessary for future development.

This approach offers the potential for sustainability in terms of both economic and energy resources and the prefabricated modules are suited to the specific needs of museums and archives. When museum professionals or archivists start to think about new storage and archive buildings, one of the first issues to be addressed is the climate conditions required. For optimal preservation of the stored artworks, storage buildings and archives require stable interior climate conditions, with minimal and slow variations in temperature and relative humidity. Stable climate values are important but there are also other significant risks to be considered seriously: fire, theft, high-operating expenses and the overall costs of the building during its full life cycle. However, for the study the interior climate conditions were balanced with

Table 1. Environmental conditions for the archive and painting modules

Module Type	Temperature [°C]	Relative Humidity [%]
Archive Module (DIN ISO 11799)	14 – 18 plus or minus 1	35 – 50 plus or minus 3
Painting Store	16 – 22 plus or minus 2	40 – 55 plus or minus 5

economic efficiency and low energy consumption. The aim was to create a suitable overall climate for 95 % of the collection, while special solutions had to be found for the remaining 5 %. The German Standard DIN ISO 11799 describes the requirements for the environmental conditions of archive collections. These climate limits are similar to the current version of the British standard PAS BSI 198:2011 Specification for environmental conditions for cultural collections. Other comparable regulations do not exist in Germany. Within the study two modules with different indoor climate conditions were tested: an archive module mainly for paper and a storage module for paintings. To define the climate range for the painting store the loan contracts of several German museums were adapted. Table 1 shows the condition range for the archive module and for the painting storage module.

To examine a variety of construction materials and for the assessment of construction strategies for both module versions (the archive indoor climate and the painting storage indoor climate) the prototype architecture was built up in a hygrothermal building simulation programme (WUFI-Plus®). The prototype store is a basic building within two modules, a functional module with delivery, workshops and engineering room and a storage module (Figure 1). The simulation results supported the decisions

Figure 1. Prototype of a modular storage building

about which type of wall insulation, which air exchange rate and other conditions met the requirements of a modular passively conditioned zero-energy storage and archive building. Calculations of the building's energy modelling based on the German Standard DIN V 18599 (Energy Efficiency of Buildings) where used as the basis for the evaluation of optimisation measures. The primary aims of these optimisation measures were:

- reducing the humidification, dehumidification, conservation heating and cooling necessary to achieve a passively-conditioned climate instead of active conditioning with heating, ventilation and air-conditioning (HVAC) systems;
- optimisation of prefabricated construction elements and the effects of additional insulation of walls, roof and floors;
- examining the impact of user behaviour on air exchange rates;
- achieving long-term indoor climate stability to protect the objects;
- the use of thermal and hygric buffer materials for both types of storage modules;
- maximum airtightness for the building allowing a minimum energy supply.

Hygrothermal building simulation

The WUFI-Plus® software was used for the hygrothermal building simulation to examine the annual climate conditions in the store and to examine the influence of construction and insulation materials. The calculations were performed for the storage room rather than for the whole building. Table 1 shows the environmental conditions for temperature and relative humidity for the archive and for the painting module. The hygrothermal calculations for both types assume an operating time of five years and the representative outdoor climate conditions of Würzburg. The long-term behaviour is assessed by the evaluation of the fifth year to guarantee exact results. The influence of the construction moisture in a nearly air-tight store is demonstrated by evaluating the first year's simulation results. The simulation includes the outside conditions, the building envelope (walls, roof and ground

Table 2. Specifications for the three variations

Variation	Basic variation	Optimised variation	Foam glass variation
Floor	10 cm XPS 30 cm Concrete Bitumen lane 6 cm Parquet U-Value: 0.276 W/m^{2}K	20 cm Foam glass 30 cm Concrete Bitumen lane 6 cm hardwood construction U-Value: 0.177 W/m^{2}K	As basic variation
Outer Wall	6 cm Concrete 14 cm EPS 18 cm Concrete U-Value: 0.214 W/m^{2}K	6 cm Concrete 14 cm Phenol resin foam 10 cm Concrete U-Value: 0.151 W/m^{2}K	28 cm foam glass panels U-Value: 0.132 W/m^{2}K
Roof	Roofing membrane 16 cm mineral foam sheets 25 cm porous concrete U-Value: 0.153 W/m^{2}K	Roofing membrane 16 cm Phenol resin foam U-Value: 0.098 W/ m^{2}K	As basic variation
Inner Wall	10 cm Phenol resin foam 13 cm Concrete U-Value: 0.274 W/m^{2}K	As basic variation	As basic variation

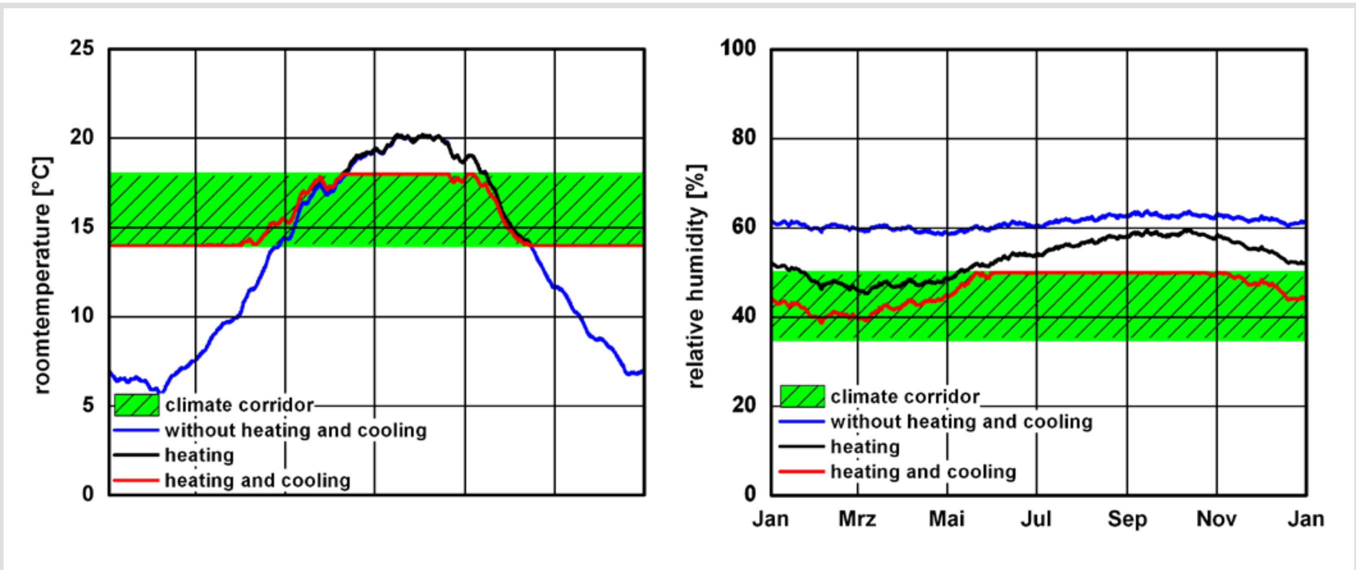
floor), the conditions for heating and cooling, indoor climate, air exchange rates, lighting and CO_2). The specific material parameters are provided from the WUFI®-Plus database or were determined experimentally (canvas, wooden painting frames, paper archive material and metal shelves). The conditions for the ground are defined as 9 °C plus or minus 4 °C, and 100 % RH; for the delivery zone as 18 °C plus or minus 9 °C, and 60 % RH plus or minus 10 %; and for the workshop as 18 °C and 50 % RH plus or minus 5 %. The simulation was based on three variations, two of different prefabricated double wall structures with core insulation: one with polystyrene foam insulation, which was the basic option, and the other with phenol resins foam insulation, the optimised option. A third variety of wall consisted only of foam glass so a type of construction without the negative effects of construction moisture could be evaluated.

The basic variation reveals thermal and hygric behaviour as presented in the graphics of figure 2. In the simulation the following climatisation strategies were varied:

1. No climate control
2. Heating only
3. Heating with cooling to achieve the climate marked in green.

With no climate control in the archive storage the temperature in winter would drop to 5 °C and in summer exceed 20 °C, so the target of a maximum of 18 °C could not be met. To achieve the strict conditions of the climate limits for the archive storage (as fixed in DIN ISO 11799) heating and cooling would be necessary. Furthermore, the relative humidity in the storage is not acceptable without climate control. With a level of about 60 %, the relative humidity would be permanently too high. If the archive was heated in the winter, the limit of 14 °C could be achieved and the relative humidity could be reduced at least in the first four months of the year. In the summer, the same temperature curve arises and the relative humidity would be slightly over the limit. Only control of both heating and humidity would guarantee conditions within the required climate corridor. If the store were only heated, the daily fluctuations of temperature would be 0.3 K and 0.9 % RH. The acceptable maximum of daily fluctuations is 1 K and 3 % RH,

Figure 2. Air conditioning strategies for the simulation: no climate control, heating only, and heating with cooling



which could be achieved with the heating strategy combined with the basic construction design option. With a wider climate range the situation for the painting storage is more favourable. With no climate control, there would be a similar environment to that of the archive module in terms of ambient temperature. Indeed, the established maximum temperature would not be exceeded so cooling would not be necessary. However, over the annual and daily time-frames the relative humidity shows higher fluctuations. This is due to the weaker humidity-buffering capacities of a painting collection when compared to a paper archive of the same size. For a painting storage unit daily fluctuations of 3 K and 5 % RH (average value based on different loan contracts) are allowed. With heating, maximum daily fluctuations of 0.4 K and 1.1 % RH can be achieved with the basic construction design option.

Conclusion of the building simulation

The results of the simulation demonstrated that the basic and the optimised options would be more suited for painting stores (or other collections with the same climatic limits). The indoor climate range of 6 K and 15 % RH has a bigger potential for a passive conditioned status. Cooling is not necessary with a maximum temperature of 22 °C; heating would ensure the RH remains within the specified range (though there would be some occasions in spring when the RH would be too low, and some days autumn when the humidity would be too high).

Should these conditions be considered satisfactory it is possible to achieve a very good conservation store by using the optimised construction option, which has a minimal energy requirement (except for during the first operational years when the moisture in the construction materials would need to be dried out). However, the more rigid conditions for the archival material would require HVAC in the archive module, with concurrent higher energy consumption for heating and cooling. The prescribed climate conditions for both collections can be achieved with the optimised module option. In the case of the archive module, heating and cooling would be necessary, but the daily fluctuations are limited to 0.3 K and 0.9 % RH (with the heating only strategy) as an effect of the massive hygric buffer of the archive papers. Without this buffer, the daily fluctuation for the painting module (with a lower hygric mass of wood and canvas) is 0.4 K and 1.1 % RH with the same strategy of climate control (heating only).

All variations of environmental control and building option were compared. All variations for the archive module achieved low daily fluctuations of 0.3 K and 0.9 % RH. The maximum daily fluctuations in the painting storage were 0.4 K and 1.1 % RH for the basic and optimised building options, and 0.8 K and 1.2 % RH for the foam glass variation.

Furthermore, the influences of the construction moisture, the air exchange rate, the archive material (amount of paper) and the floor plate were examined for the archive module because of their likely hygrothermic impact. The construction moisture and its influence in the basic building option are shown in figure 3. It appears that the existing high construction moisture in the prefabricated concrete double wall (with or without core insulation) causes high moisture content in the store. Due to the low air exchange rate of 0.05 per hour, this influence was reduced very slowly and would

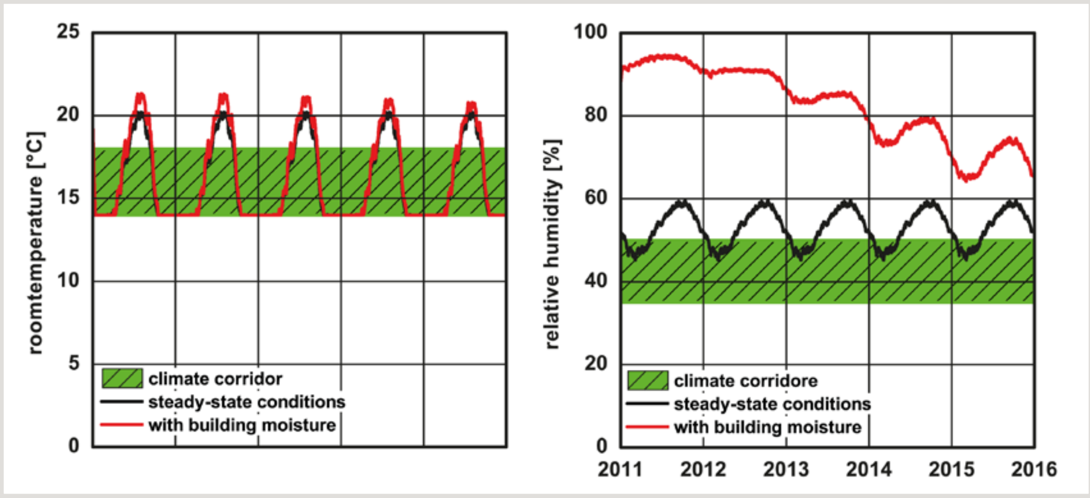


Figure 3. Influence of concrete construction moisture on the low air exchange rate module

continue to affect the store even after five years. Because concrete dehumidifies slowly, a very long drying period would be necessary before the store would be ready for the installation of collections.

Figure 4 shows that an increase of the air exchange rate causes lower summer temperatures and lower relative humidities in winter. With an air exchange rate of 0.2 per hour the maximum daily fluctuation is still within the limit values, but clearly higher than with an air exchange rate of 0.05 per hour. When increased to 0.5 per hour, the daily fluctuations are considerable, at 5.7 K and 5.5 % RH, thus clearly out of the acceptable range. The size of the archive collection in the store has a marked impact on the indoor climate. The summer temperatures are similar with a full or a half-filled archive module, but when empty there are noticeably higher temperatures. In terms of relative humidity, there is also only a small difference between a full and half-filled store though the short-term fluctuations are higher when the archive is half filled. Without any archive material at all the annual fluctuations in relative humidity are much more severe, ranging between approximately 38 % and 64 % RH. The size of the archive collection also has a big influence on daily relative humidity fluctuations: the maximum daily fluctuation is 4.1 % RH in an empty archive, which exceeds the acceptable values. The influence of the insulation of the ground floor is also significant. The absence of floor insulation (as observed in the Danish store in Vejle) causes lower temperatures in summer but initiates high humidity, of up to 70 % RH, and so a longer heating period combined with dehumidification is necessary.

With all variables considered, it became clear that the optimised building option could achieve very good conditions to store a collection without high costs. This result applies to both module types and both types of collection. A prefabricated double wall with optimised core insulation, concrete core cooling or under-floor heating (a smart and energy-efficient way of cooling and heating), floor insulation, a thick construction, low air exchange rate and user behaviour that supports passive conditioning can achieve a perfectly acceptable environment for a large component of every collection.

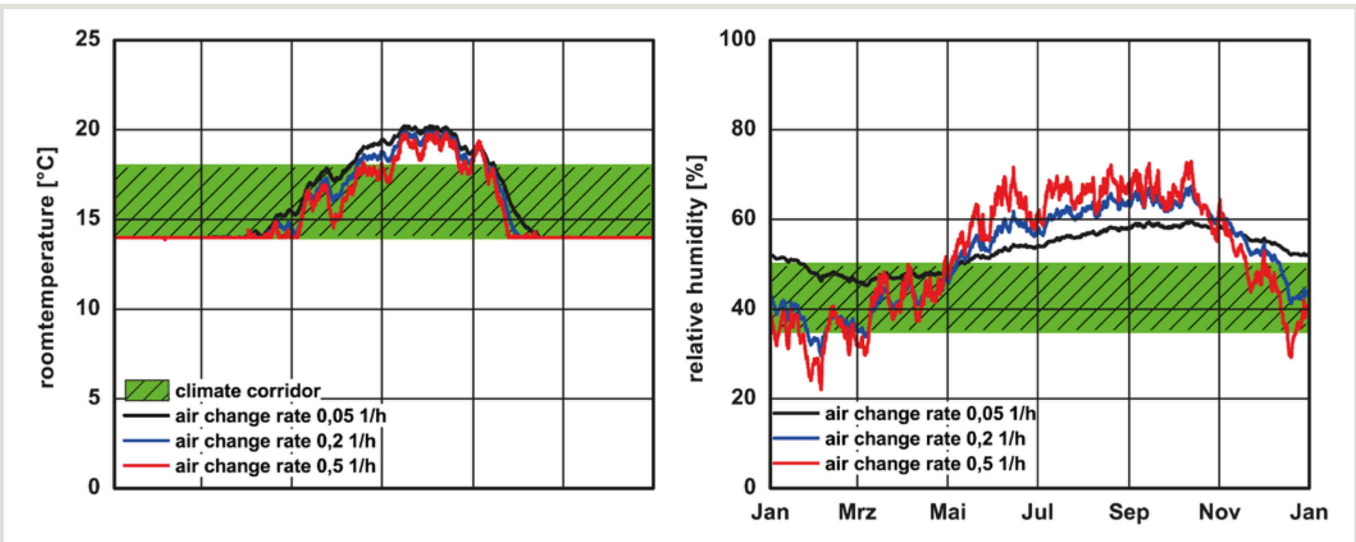
Under these circumstances it is possible to build a new modern storage building quickly and easily. In order to enhance sustainability it is necessary to optimise the indoor climate conditions, lower the energy consumption for ventilation and dehumidification, reduce the maintenance cost and extend the effective life of the building. Therefore, some more expensive, but in the long term more effective, materials for core insulation and ground insulation are indispensable. This means increased investment in energy-optimised windows and gates (for the delivery area, workshop etc.), quality management during the construction period, a two-year-monitoring of the building construction, energy-optimised HVAC systems as well as the use of renewable energy sources (geothermal heat pump, solar thermal energy and photovoltaic cells). This upgrade concept is key to achieving sustainability as it can deliver low maintenance, zero-energy storage or archive buildings, which will last for a long time.

Figure 5 shows the annual energy consumption (electricity in yellow and gas in grey) for a painting storage module (right) and an archive module (left) for all simulated variations. The red line shows the profit of solar energy for the basic module of 300 m^2, which is an overall annual gain of 30000 kWh. The use of an archive wall construction reduces the energy consumption further because dehumidification is not necessary.

Wall construction/ archive wall

Super-insulated buildings can create dangerous levels of entrapped moisture and cause a high risk of mould growth or other humidity-induced damage. To solve the problem of construction material moisture being retained in a thick building with very low air exchange rates, a building material with little moisture must be identified for any of the construction elements that affect the indoor climate conditions such as walls, roofs and floors. The material must be feasible to produce on an industrial scale without generating additional costs. The prefabricated, pre-stressed concrete roof elements can be pre-treated before construction with a coating that avoids construction moisture. The concrete elements of the roof are limited to 15 % of the whole concrete mass of the building, so other roof elements can be made of materials that do not contain construction moisture. The floor, which for reasons of construction and stability is made of concrete poured in situ, can be isolated with a layer of epoxy resin. Only the prefabricated double wall elements must be reconsidered. For this reason, a study at the Fraunhofer IBP was initiated to find a dry concrete which exhibits

Figure 4. Influence of air exchange for the indoor climate variations



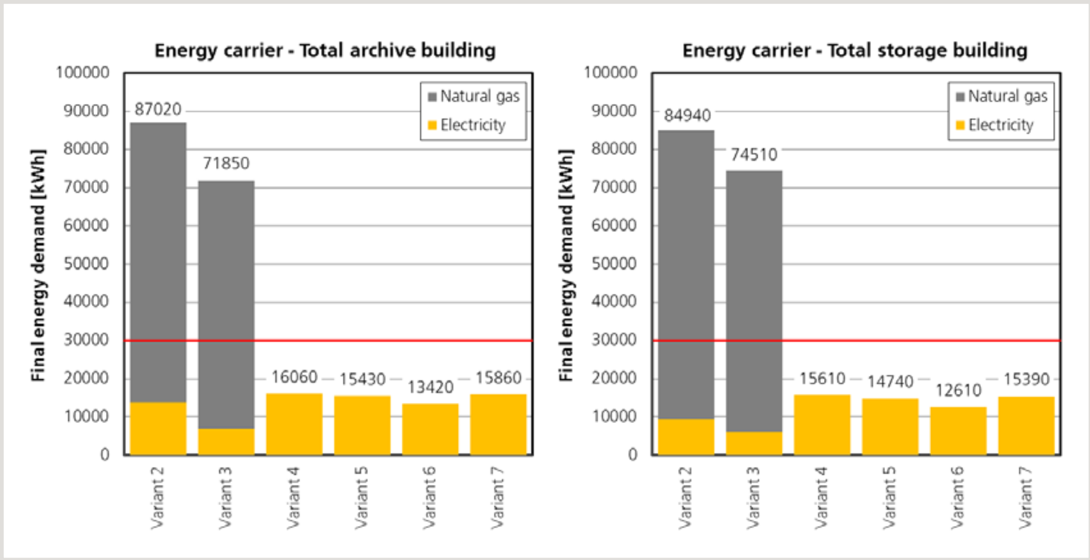


Figure 5. The annual energy consumption for a painting storage (right) module and an archive module (left) for all simulated variations

the German Standard DIN attributes but emits only a minimum of construction moisture because it contains only the water necessary for the hydration. A patent for this Archive concrete has been applied for. It can be used with the optimised construction option (double wall element with core insulation of phenol resin foam). The main advantage of the core insulation double wall element, with a U-Value of 0.14, and a dry concrete layer on the interior, is that it can lower and rationalise the energy consumption of the store or archive significantly.

Summary

The trend of current storage and archive projects is moving slowly in the direction of economic and efficient solutions. Unfortunately many stores and archives are still established with unnecessary expense and exceed their original budgets. This study and some good examples from the recent past demonstrate that it is possible to build effective buildings to store art collections and cultural heritage objects at a low cost. Traditional construction methods such as the archive concepts based on the Cologne or Schleswig model are obsolete and economically outdated. By incorporating industrial elements it is possible to build more favourable storage buildings quickly and efficiently. Of course, it will be necessary to evaluate specific conditions relating to building height, orientation and urban development but the basic construction method will remain the same. Furthermore, the Archive concrete saves energy on dehumidification, prevents mould growth, reduces the drying time and minimises construction moisture. The passively conditioned modular zero-energy storage and archive building is a product offered by the Fraunhofer IBP Spin off ModulDepot GmbH.

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Author

Lars Klemm works at the Fraunhofer Institute for Building Physics in the Department of Climate. He coordinates research into retrofitting museums, storage and archive buildings. Since 2011 he has been leading the development of the Fraunhofer Spin off ModulDepot GmbH, including the patenting of the archive wall construction method. Within the ModulDepot GmbH he is also responsible for the customer advice service, marketing, sales, research and development.

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