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PREVENTIVE CONSERVATION

Performance of Danish low-energy museum storage buildings

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ABSTRACT

In Denmark, several purpose-built low-energy museum storage houses have been erected since the 1980s. The construction principles behind these buildings have improved over time and fall into five major categories. The performance of three low-energy museum storage buildings, representing the three most recent categories, is evaluated according to three different parameters: storage quality, construction costs and energy consumption. All three buildings have floors without thermal insulation. The building in Vejle completed in 2003 has heavy concrete walls. The building in Ribe, completed in 2005, has heavy brick walls, while the new building in Vejle, completed in 2013, has thinner walls and a very airtight construction. The new building in Vejle has the highest preservation quality, the lowest energy use – reducing energy consumption by 99% compared with conventional climate control – and the lowest construction cost per cubic metre of objects stored.

INTRODUCTION

Inadequate storage facilities are a common problem for many museums. The aim of conservators is to protect cultural heritage from degradation and our work is in vain if objects are stored in conditions where the building immediately causes new damage. At Conservation Centre Vejle in Denmark (a regional conservation unit owned by several museums in the area), we have since 2000 taken the lead in establishing new, shared storage buildings attached to the conservation centre, as this initiative has the potential to prevent damage to thousands of objects. The storage building, an institution in its own right, is known as the Shared Storage Facilities in Vejle. Together, the two institutions are known as the Cultural Heritage Centre Vejle. In 2003, the first low-energy concrete museum storage building was erected, providing space for 5,650 m^3 of museum objects from 16 museums and archives (Knudsen and Rasmussen 2005). The goals were low construction costs, very low energy consumption and high preservation quality. These factors are interdependent and normally one would calculate that a very high preservation quality would require high energy consumption and high building costs. The aim of the Vejle 2003 building project was to optimise the building design and use the geothermal impact of the building in a way that kept the cost and energy consumption low and the quality of storage conditions high. The building performed very well and numerous museums from Denmark and other countries have copied – or want to copy – the building design for their own purposes.

In 2009, a research project was established in collaboration with the Technical University of Denmark (DTU) in which Associate Professor Jørgen Erik Christensen of the DTU Department of Civil Engineering evaluated the 2003 building and recommended an improved design for an extension to that original building. The aim of this new project, entitled ‘Vejle 2013’, was to construct an even better low-energy storage building than the ones that had been built until then (Christensen 2010, Christensen, Janssen and Tognolo 2010, Janssen and Christensen 2013). In 2013, the new building was finished. As climate and energy consumption data has now been collected for over a year, it is possible for the first time to evaluate the performance of the new building. This paper further evaluates the resulting construction and compares its performance and costs with the previous designs. As was found with our shared storage facility raised in 2003, its success is determined in large part by the cooperation between the now 20 museums and archives, and the Conservation Centre Vejle (Knudsen and Rasmussen 2005).

PRIOR CONSTRUCTION PRINCIPLES OF MUSEUM STORAGE BUILDINGS IN DENMARK

Often, museums use old, existing buildings as storage space for their collections. It might be the attic or the basement of a historic building used for museum exhibitions, or an existing building some distance from the museum, perhaps the basement of a school or a residential home. What these storage rooms often have in common is low rent, difficult access, unsuitable climate and the fact that they are difficult to keep clean (Ræder, Knudsen and Brøndlund Jensen 2006). To change this, it is important to convince the decision makers that storage that is very cheap in the short term is often very expensive in the long term, as collections are damaged by handling, mould growth and degradation, and cleaning and conservation are time-consuming and expensive – and that the objects would be better and more cheaply protected if adequate storage were used from the beginning. It is thus important to be able to construct cheap buildings with high storage quality. In Denmark, a range of museum storage buildings has been built since the 1980s (Table 1). The first cheap, purpose-built museum storage building was erected in Rudkøbing, Langeland by Langelands Museum in 1988. It is a wooden barn of 620 m^2 with heating and an insulated floor (Lange 1989) (Construction principle 1). Access is good, but the humidity fluctuates between 35% and 65% even though a dehumidifier is installed.

Table 1. Low-energy museum storage buildings in Denmark constructed according to different building principles

Purpose-constructed low-energy museum storage buildings in Denmark

Building	Owner(s)	Construction principle	Year of construction
The Storage Building	Langelands Museum	1	1988
Storage buildings	The Old Town, Women's Museum and Museum of Natural History	2	1990
Storage building	Moesgaard Museum	2	1992
Shared Storage Facility, Vejle (Vejle 2003)	Museums and archives in The Triangle Region	3	2003
The Storage, Museum South West Jutland, Ribe (Ribe 2005)	Museum of Southwest Jutland	4	2005
Shared Storage, Museum East Jutland, Randers	Museum East Jutland	3	2007
The Shared Storage, Ugerløse	Museums in West Zeeland	3	2010
Windum Flytteforretning, Hillerød	Designmuseum Danmark (rented)	3	2010
Collection House, Vestbjerg	The Historical Museum of Northern Jutland	3	2011
Shared Storage Facility, Vejle (Vejle 2013)	Museums and archives in The Triangle Region	5	2013

In 1990, Kvindemuseet, Den Gamle By, Naturhistorisk Museum and in 1992 Moesgaard Museum, all situated in or near Aarhus, built new storage houses for their collections – the first three at a shared site. The building principle behind these storage houses was created by architect Bue Beck and conservator Lars Vester Jacobsen from Den Gamle By and was a further development of standard industrial buildings. The building principle was uninsulated concrete floors, metal trusses and thermally isolated sheet metal walls and roofs with inner walls made of plasterboard. Dehumidifiers are installed and there is no heating (Construction principle 2). These storage buildings are an improvement on the existing storage facilities, but the sheet metal does not provide an airtight building and the temperature fluctuates over the year from 2°C to 25°C (Olsen 2012), which lowers the preservation quality and makes the storage unsuitable for longer working periods during the winter. The relative humidity of the Moesgaard storage facility fluctuates between 35% and 65% RH and the energy consumption is 9 kWh/m^3/year (Ryhl-Svendsen, Jensen, Bøhm and Klenz 2012, 8). Furthermore, the sheet walls do not provide good protection against burglary.

At the beginning of the 21st century, a new building principle was brought into use based on the research of engineer Lars Christoffersen (Christoffersen 1995). The primary focus of this building principle was:

- heavy construction;
- the hygroscopic properties of the building materials and the stored items;
- as little human activity in the storage rooms as possible;
- a floor with no thermal insulation and impervious to moisture; and
- the expectation that after a few years of dehumidification the building itself would be able to control the climate without additional dehumidification.

Unfortunately, the last point has been found not to work (Christensen 2010, 2), but the construction principle clearly raised the quality of the storage buildings compared to the earlier building methods.

Around 2002, two different museum storage buildings based upon Lars Christoffersen’s work were planned. In cooperation with the Villum Kann Rasmussen Foundation, the Ribe Museum of Southwest Jutland (Now Museum Southwest Denmark) raised a storage building for five different museums and their collections (Ribe 2005) where it was possible to use the best building principles and materials (Petersen and Ræder Knudsen 2014a) (Construction principle 4). In Vejle, 16 museums and archives went into cooperation and planned a shared storage facility with Conservation Centre Vejle as project manager (Vejle 2003). To complete this project, it was necessary to find the cheapest building principles and materials suitable for the purpose (Knudsen and Rasmussen 2005, Rasmussen 2007, Petersen and Ræder Knudsen 2014b) (Construction principle 3).

In Ribe (Ribe 2005), the main building principles were:

- heavy construction: walls made of brick, thermal insulation, concrete and inside walls made of fired MoClay;

- a floor with no thermal insulation and impervious to moisture; and
- a roof slope of 20°, 300 mm of thermal isolation and sheet metal.

In Vejle (Vejle 2003), the main building principles were:

- heavy construction: walls made of 250-mm-thick concrete and sheet metal and thermal insulation on the outside;
- a floor with no thermal insulation and impervious to moisture; and
- a roof slope of 4° made of sheet metal, 300 mm of thermal insulation and asphalt roofing.

It was expected that the buildings (Vejle 2003 and Ribe 2005) would exhibit different performance as regards their quality as storage for cultural heritage and the energy consumption required to provide a stable climate, but research shows that the storage rooms at 50% RH have the same preservation index (TWPI = 115) and energy consumption (1.5 kw/m^3/year) (Ryhl-Svendsen, Jensen, Bøhm and Klenz 2012, 8).

THE NEW BUILDING, VEJLE 2013

The museums already involved in the Cultural Heritage Centre Vejle needed more storage space and more museums wished to join the Centre. Therefore, the Centre decided to construct an additional storage building in Vejle. In 2009, the DTU Department of Civil Engineering joined the project to design a new and better version of the museum storage building (Vejle 2003) and carried out an advanced investigation using the previous five years of climate data and the newest simulation technology.

The building envelope

The building design of Vejle 2003 and Ribe 2005 focused on heavy construction and hygroscopic materials in the storage rooms to help equalise the climate. The new building principle suggested that a lighter construction of the building and high demands on its airtightness would yield an improvement in energy consumption, making the building cheaper and improving its preservation quality.

The new, improved museum storage was finished in 2013 as an extension to the existing storage and conservation lab building in Vejle (Figure 1). The concept incorporates sufficient thermal insulation, an extremely airtight building envelope and an uninsulated floor, while there is less focus on high thermal and hygric inertia (Christensen 2010, Christensen, Janssen and Tognolo 2010).

Figure 1. The new extension to the Cultural Heritage Centre Vejle – Shared Storage Facilities (Vejle 2013)

In the new extension of the storage building in Vejle (Vejle 2013) (Construction principle 5), the main building principles are:

- construction: walls made of 180-mm-thick concrete, sheet metal and thermal insulation on the outside;
- air change of less than 0.01 ACH (air changes per hour);
- a floor with no thermal insulation and impervious to moisture; and
- a roof slope of 4° made of sheet metal, 300 mm thermal insulation and asphalt roofing.

Climate control and interior design of the new building

The area of the building is 2,535 m^2, and 90% of the area contains storage rooms divided into two different humidity zones: 40% RH and 50% RH. The remaining 10% of the area is reserved for packing, anoxia treatment against pests and quarantine, etc. The relative humidity of the storage rooms is supported by two rather small dehumidifiers (capacity at 20°C and 60% RH; basic: 7.4 kg/h and dry: 4.4 kg/h). The storage building provides rooms for about 5,650 m^3 of museum objects and works of art on 5.4-metre-high compact racks (Figure 2). The Vejle 2003 building has normal racks and aisles and an in-built first floor giving a height of ca. 2.4 m on each floor.

Figure 2. Compact racks inside the Cultural Heritage Centre Vejle (Vejle 2013)

METHOD OF PERFORMANCE EVALUATION

To evaluate the performance of low-energy museum storage buildings in this article, three factors were chosen as the most important: the quality of the building in terms of storage for cultural property, the construction cost and the energy consumption used to keep the climate at approximately 40%/50% RH and a slightly fluctuating temperature within acceptable limits, between 10°C and 15°C (Ryhl-Svendsen et al. 2010, 13). One might say that cheap construction costs are not a parameter concerning the quality of the building, but experience shows that providing new and better storage facilities for museums has a much higher success rate if the new building is cheap compared to other solutions.

The time weighted preservation index (TWPI) developed by James Reilly at the Image Permanence Institute (IPI), Rochester Institute of Technology (Reilly, Nishimura, and Zin 1995) was chosen as a simple way to compare the preservation quality of a building.

Every collection manager who wants to evaluate the 'preservation quality' of a collection environment will need to analyse the observed environmental readings with respect to common preservation problems, such as mould growth or metal corrosion. One important problem is the very general one of how heat and moisture combine to affect the rate of spontaneous chemical reactions that occur naturally for all organic materials in storage. The collection manager needs some method to estimate the kinetics (reaction rate) associated with changing conditions over time (Reilly, November 2016). Several authors have put forward kinetics-based approaches to this general problem, but IPI's TWPI metric was the one found most useful.

To make it possible to compare prices, the cost of stores built at different times is adjusted using the Statistics Denmark Cost Index for concrete constructions.

It was chosen to compare building costs, including the cost of shelves, as this, in our experience, gives a museum the easiest way to compare prices (for detailed construction accounts, see http://magasinmanualen.dk/?p=295). All three buildings have shelves of about 5.4 metres in height, thus this is not a problem in the comparison. The main difficulty with comparing prices of these three buildings is that the relative area of additional rooms around the stores is different. But as the cost is essential to decision makers, it was found useful to compare prices despite that.

Energy consumption is measured in kWh/m^3/year, where m^3 refers to the amount of space within the storage rooms in total.

It was decided to use results from three different buildings for which there are reliable measurements of climate and energy consumption as well as knowledge of building costs. Furthermore, they represent three different low-energy construction principles: principles 3, 4 and 5.

RESULTS

Relative humidity, temperature and energy consumption for the storage rooms with basic and dry climate (ca. 50%/40% RH) in the new building (Vejle 2013) were measured over a period of one year. The results were compared with low-energy storage buildings based on earlier construction principles with basic/dry climate (Vejle 2003 and Ribe 2005) published by Ryhl-Svendsen, Jensen, Bøhm, and Klenz (2012, 8). As these measurements represent data collected in different years, they may represent a source of error.

The detailed construction costs are published on the webpage www.magasinmanualen.dk, where conservators have collected information about exemplary museum storage buildings (Petersen and Knudsen 2014a and a).

Quality

The quality of the new building (Vejle 2013) is enhanced slightly with a TWPI of 116 against 115 in both older buildings regarding the storage rooms with approximately 50% RH, whereas the storage room with approximately 40% RH has increased the TWPI from 88/130 to 156 (Table 2) (Figure 3). James Reilly has defined a storage room with TWPI of 45 or less as having a RISK of decay, a TWPI between 45 and 75 as OK, and a TWPI of more than 75 as GOOD (Reilly 2016). A TWPI of around 115 thus indicates very good climate conditions which support the long-term preservation

Table 2. Preservation quality of three museum storage buildings representing building principles 3, 4 and 5

Storage room basic/dry climate	Relative humidity [%]	Temperature [°C]	TWPI [index]
Vejle 2003 basic*	45 – 55	7 – 17	115
Ribe 2005 basic*	45 – 55	9 – 15	115
Vejle 2013 basic**	48 – 51	9 – 15	116
Vejle 2003 dry*	35 – 45	10 – 18	130
Ribe 2005 dry*	32 – 38	11 – 22	88
Vejle 2013 dry**	37 – 42	8 – 16	156

*Ryhl-Svendsen (2012, 8, 13).
**Measurements in 2016.

of the stored collections. The TWPI of the dry storage in Ribe – a rather small room measuring 99 m^2 – is 88. The new building (Vejle 2013) has a TWPI of 156, whereas the dry store of the old building at the same site (Vejle 2003) has a TWPI of 130. It is thus safe to say that the new building concept of Vejle 2013 performs extremely well with regard to its quality as a museum storage facility.

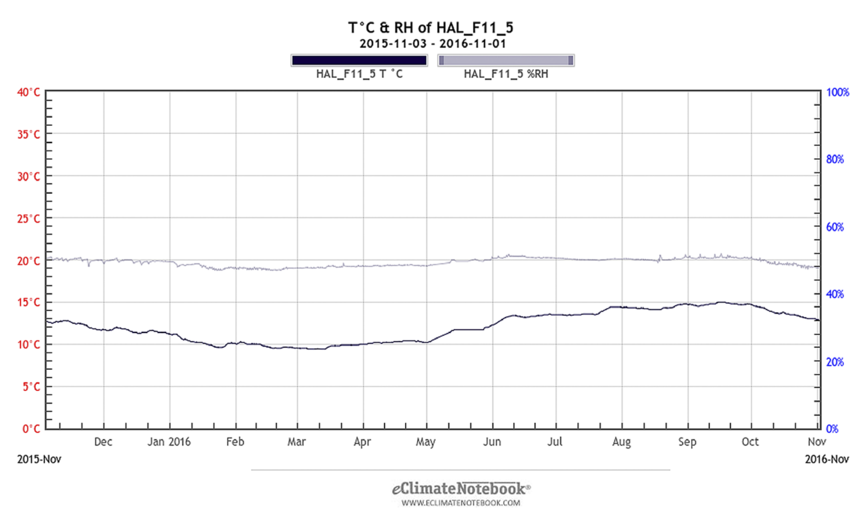

Figure 3. One year of climate data from the new extension to the Cultural Heritage Centre Vejle (Vejle 2013)

Cost

The present-day building costs per m^2, including shelves, of the brick building in Ribe (Ribe 2005) are higher, as are those of the first concrete building in Vejle (Vejle 2003). In addition, the new building in Vejle is slightly more expensive than the old concrete building at the same site (Vejle 2003), but it is cheaper than the brick building in Ribe (Table 3). The cost of buildings is mostly related to cost per square metre, but as a further improvement of the performance of the new building, the use of moving compact shelves was introduced to optimise the number of objects and works of art that the building could contain (high-density storage) (Figure 2). Compact shelves are more expensive, and thus a more accurate

Table 3. Cost of construction per m^2 of built area, cost of construction per m^3 of stored objects and works of art at the three museum storage buildings, and energy consumption per m^3 at the three storage buildings representing building principles 3, 4 and 5

Storage building	Area of building [m²]*	Construction cost ex site and tax, incl. shelves [€/m²]	Volume of stored objects and works of art [m³]	Construction cost ex site and tax, incl. shelves per m³ of objects and works of art [€/m³]	Energy use in storage room basic climate [kWh/m³/year]	Energy use in storage room dry climate [kWh/m³/year]
Vejle 2003	3.417 (Basic storage: 2505, dry storage: 383)	780	4.500	593	1.5	4.0
Ribe 2005	1.835 (Basic storage: 994, dry storage: 99)	1.550	?	?	1.5	?
Vejle 2013	2.535 (Basic storage: 1310, dry storage: 484)	900	5.650	406	0.4	1.4

*The area of the building includes storage rooms, loading area, pest disinfection, offices, etc. and aisles and walls.

cost count would not relate to the area of the building but to the volume of objects and works of art per m^3 it could contain (Table 3). Unfortunately, it has not been possible to measure the number of m^3 that can be stored in Ribe 2005, but these numbers are available for both Vejle 2003 and Vejle 2013 (Table 3). The construction cost of the new building in Vejle (Vejle 2013) is the lowest, with a price of only €406 per m^3 of stored objects, which is a saving of 32% compared with the old building at the same site (Vejle 2013). Vejle 2013 has the lowest construction cost in relation to the amount of space for storage.

Energy consumption

The first column in the energy consumption table expresses the total energy used by the 50% RH storage room during a one-year period (Table 3). The major part will be electricity for the dehumidifier, but also small amounts of energy are used to run the compact racks and for lighting. No energy at all is used for heating. Energy consumption is very low for basic storage in both Vejle 2003 and Ribe 2005 at 1.5 kWh/m^3/year compared to a building with conventional climate control, such as, for example, the Royal Library Copenhagen Stack 1, which has an energy consumption of 28 kWh/m^3/year (Ryhl-Svendsen et al. 2012, 8). The energy consumption of the basic storage rooms of the new low-energy building is even better, using only 0.4 kWh/m^3/year, which is a saving of 73% compared to Vejle 2003 and Ribe 2005, and of 99% compared to the storage building using conventional climate control. A further benefit is that the storage room of 40% RH in Vejle 2013 has an energy consumption of 1.4 kWh/m^3/year. Vejle 2013 has the lowest-known energy consumption and thus the lowest CO^2 impact.

CONCLUSION

The new museum storage building in Vejle, opened as planned in 2013, is an airtight concrete building with no thermal insulation on the floors. Quality is very high and it therefore offers very good preservation conditions for the storage of cultural heritage. Energy consumption of the basic storage is very low, at only 0.4 kWh/m^3/year, a saving of 99% compared to conventional climate-controlled buildings and of 73% compared to low-energy buildings constructed according to prior building principles. The construction cost of the new low-energy building is low (about €400 per m^3 of stored objects and works of art).

The aims of the research project have thus been achieved:

- to raise the quality of the building constructed as cultural heritage storage;
- to lower CO^2 emissions; and
- to lower construction and running costs.

This is very important news for conservators and museums in climate zones comparable with Denmark, as the building principles presented here could help save large sums of money and spare the world from a large amount of CO^2 emissions without a decline in preservation quality.

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