Improving the Energy Performance of Museum Buildings - Development and Evaluation of Sustainable Refurbishment Strategies

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ABSTRACT

The energy performance of museum building is strongly influenced by preventative conservation requirements on the indoor climate. Structural refurbishment measures therefore have to be evaluated carefully by thermal and moisture simulation before an overall refurbishment strategy can be developed. The financial requirements and the decision making process in public building, however, makes it difficult to recommend a comprehensive refurbishment strategies. Therefore, strategies have to be developed that can be applied on a step by step basis. Each step must be part of the overall energy performance improvement strategy on its own.

1. Introduction

The energy performance of museum buildings is generally characterized by strict indoor climate conditions originating from preventative conservation requirements. Reducing the energy demand of a museum, while simultaneously providing a stable indoor climate, is therefore a challenging task that becomes increasingly complex when all influential variables are considered (e.g. fluctuations in the numbers of visitors). In addition, engineers' and architects' freedom of action is, in many cases, limited by cultural heritage protections. On the other hand, museums, like all public buildings, contain a high potential for raising public awareness regarding important issues such as carbon emissions reductions and sustainable refurbishment measures.

To meet these challenges a national research programme regarding sustainable refurbishment of museum buildings was established. A research group consisting of building physicists, architects, systems engineers and conservators from five German universities guide local museum partners through the process of refurbishment. Regular meetings are held by the research team to share experiences and results. The overall results of the research will be combined into a sustainable refurbishment manual for museum buildings.

In this paper the authors present the potential, as well as the restrictions, of refurbishment strategies for museum buildings through the detailed examinations of a refurbishment project they had the chance to engage in, the Collection Schack in Munich.

2. The Collection Schack

Erected in 1909, the Collection Schack (Figure 1houses one of the most important collections of 19th-century German painting, founded by Adolf Friedrich von Schack (1815–1894). Suffering minimal damage during the Second World War, the building largely remains in its original state.

Today, only two of the three existing floors (the ground floor and the first floor) are used as exhibition space (Figure 2).

Figure 1. Historical postcard showing the Collection Schack in 1909

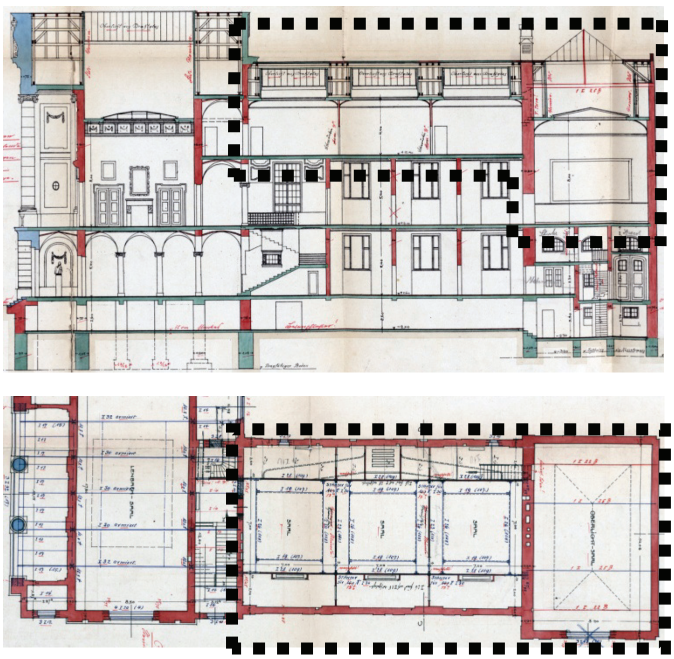

Figure 2. Section of the Collection Schack showing the second floor attic galleries, which are to be refurbished (non-scale division)

However, the collections owner, the Bavarian State Picture Collections, wishes to utilize the vacant second floor attic galleries.

Therefore, a redesign of the fire escape routes became necessary, resulting in an overall refurbishment of the second floor and roof. This enabled the building authorities to take on a more holistic approach by participating in the national research programme.

3. Development of a Refurbishment Strategy

3.1 Present Situation

3.1.1 Building Components

The exterior walls are solid brickwork construction (Table 1). The interior walls between second floor gallery and attic space consist of either honeycomb brick or concrete blocks. The interior walls between the galleries consist of solid brick of varying thickness (Table 2).

Table 1. Construction and resulting U-value of exterior wall

Layer	Material	Thickness [mm]	λ [W/(mK)]
1	interior render	15	0,70
2	solid brick	450/600/1000	0,81
3	exterior render	20	1,00
	$U_{exterior\ wall}$ =	**1,3/1,1/0,69**	**[W/(m²K)]**

Table 2. Construction and resulting U-value interior walls

Layer	Material	Thickness [mm]	λ [W/(mK)]
1	interior render	15	0,70
2a	honeycomb brick	115	0,50
2b	concrete blocks	150	2,10
2c	solid brick	300/450/900	0,81
3	interior render	15	0,70
	$U_{interior\ wall\ a}$ =	**1,9**	
	$U_{interior\ wall\ b}$ =	**2,7**	**[W/(m²K)]**
	$U_{interior\ wall\ c}$ =	**1,5/1,2/0,71**	

The floor slabs presumably consist of a so called "Kleinsche Decke": a solid brick construction dating back to the early 20th century (Table 3).

Table 3. Construction and resulting U-values of floor slabs

Layer	Material	Thickness [mm]	λ [W/(mK)]
1*	parquet flooring, structural solid timber	30	0,13
2	cement screed	50	1,40
3	solid brick	200	0,81
4	interior render	15	0,70
	U_{floor} =	**1,1**	**[W/(m²K)]**
	$U_{top\ floor\ slab}$ =	**1,4**	

* not on top floor slab

The unisolated steep roof consists of wood rafters with timber planking underneath the roof tiles (Table 4).

Table 4. Construction and resulting U-value of unisolated steep roof

Layer	Material	Thickness [mm]	λ [W/(mK)]
1	roof tiles	---	---
2	timber planking	30	0,130
3	timber rafter 8/14, e=60	---	---
	$U_{steep\ roof}$ =	**2,5**	**[W/(m²K)]**

The overhead lights are covered with single glazing, U_g = 5,0 W/(m²K).

3.1.2 Systems Engineering

The buildings heating demand is supplied by district heating. Radiators along the exterior walls, in most cases placed underneath the windows, distribute the necessary space heating.

In the second floor galleries the space heating is similarly distributed also by radiators along the exterior walls. Ventilation grids in the exterior walls allow the warm air to enter the gallery space as well as the air space above the dust cover (Figure 3).

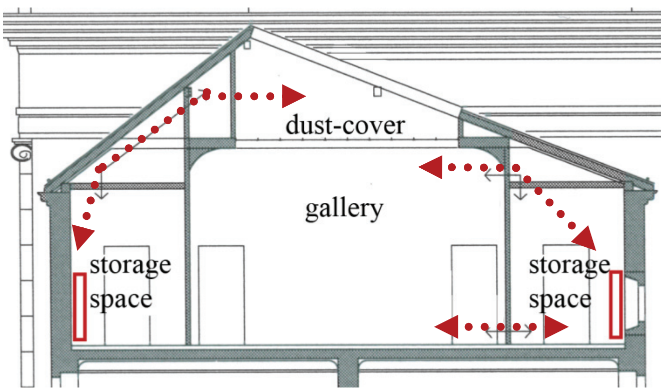

Figure 3. Section showing the heating supply of the interior second floor galleries by air inlets from attic spaces (non-scale division)

3.1.3 Indoor Climate

Since March 2011 indoor air temperature, surface temperature, heat flow rates, and relative humidity have been recorded to serve as basis of comparison for the simulation models created, using [WUFI+] and [TRNSYS].

3.2 Refurbishment Strategies

Refurbishment strategies that were evaluated by thermal simulation using the models mentioned above, and are arranged in two different levels: basic and alternative measures (Table 5).

3.2.1 Basic measures

The fundamental refurbishment includes the isolation of the roof areas according to the requirements of the German Energy Saving Ordinance [EnEV 2009] ($U_{steep\ roof} \leq$ 0,24 W/(m²K)), the replacement of the existing roof top glazing by prism glazing (U_g=1,5 W/(m²K), g=15%), and the application of LED-technology for the lighting system.

In terms of the heating system, the client wanted to examine a panel heating system installed in the interior walls between the attic and gallery space, and a building element tempering system installed near to the surface according to [Henning Grosseschmidt]. As the modelling results of the two systems did not significantly differ a combined system was implemented.

3.2.2 Alternative measures

In addition to the basic refurbishment measures, which are to be implemented by the Bavarian state planning office, the following alternative measures were considered:

- advanced isolation level of $U_{steep\ roof} \leq 0{,}24$ W/(m²K),
- advanced isolation level of overhead lights through triple glazing with $U_g = 1{,}0$ W/(m²K),
- interior isolation of exterior attic walls $U_{exterior\ wall} = 0{,}36$ W/(m²K),
- fluorescent lighting as an economic alternative to LED-technology,
- activation and/or closure of existing ventilation ducts between the attic and the gallery space (respectively, air space above the dust cover) as shown in Figure 3. Section showing the heating supply of the interior second floor galleries by air inlets from attic spaces (non-scale division)Figure 3.

Table 5 shows the combinations of individual measurements that were evaluated using thermal simulation models which will show the resulting indoor climate, and thus determine which refurbishment strategies should be applied.

3.3 Simulation results

3.3.1 Heating demand

Table 6 shows the resulting heating demand of the refurbishment measures according to Table 5.

If only the basic measures are applied the heating demand can be reduced by 22%. The installation of fluorescent lighting instead of LEDs for the lighting system does not show any effect on the heating demand. The alternative measures, however, show significant improvements in energy performance, especially when all 3 measures are combined. The research shows that the resulting heating demand is 38% lower than the baseline energy demand.

Table 6. Resulting heating demand, based on floor space of second floor attic galleries, see Figure 2.

Resulting Heating Demand	**Base-line**	**BM**	**BM _FL**	**BM _SR$_{max}$**	**BM _II**	**BM _3G**	**BM _SR$_{max}$ _II _3G**
[kWh/(m²a)]	342	267	266	260	224	256	212
[%]	100	78	78	76	66	75	62

abbreviations see Table 5

Table 5. Measurement combinations evaluated by thermal simulation

			Alternative Measures Systems Engineering			
			Lighting		Ventilation	
			LED-technology (included in BM)	fluorescent lighting (FL)	activation of existing ventilation ducts (status quo)	closure of existing ventilation ducts
	Description:	abbrev.	LED	FL	V1	V2
Basic Measures	• isolation of roof areas according to EnEV 2009 minimal requirements ($U_{steep\ roof}$≤0,24 W/(m²K)) • replacement of the existing overhead lights by prism glazing (U_g=1,5 W/(m²K), g=15%) • panel heating system / building element tempering system	BM	included in BM	X	included in BM	(X)
Alternative Measures Building Construction	1: advanced isolation level of steep roof (SR) ($U_{steep\ roof}$≤0,24 W/(m²K))	SR$_{max}$	X			
	2: interior isolation (II) of exterior attic walls ($U_{exterior\ wall}$=0,36 W/(m²K))	II	X			
	3: advanced isolation level of top roof glazing by implementing triple glazing (3G) with U_g = 1,0 W/(m²K)	3G	X			
	combination 1+2+3		X			(X)

(X) combination not included in this paper

3.3.2 *Indoor Air Temperature (T_{int}) and Relative Humidity (RH) in Gallery Space*

The indoor air temperature (red) as well as relative humidity (blue) over the course of one year is shown in Figure 4 (thin lines). The results from the basic measurements (Table 5) are also presented (thick lines).

Due to the new heating system the interior temperature reaches a constant level of 20°C during the winter months, as required by the museum's conservators. During the summer months the peak temperatures no longer exceed the maximum allowable temperature of 24°C. In addition the interior temperature is generally more stable. Relative humidity increases slightly during the summer months due to the lower indoor air temperature, but rises slightly during the winter months.

Looking at Figure 5 one can see that by implementing the basic measurements a significant improvement in terms of the indoor air temperature can be achieved as the percentage of hours during which the required temperature exceeds the range of 16-24 °C is reduced. The required indoor air temperature is met 99.4 % of the year instead of 61.8 % as it presently is the case, meaning the indoor air temperature becomes more stable. However, as the thermal quality of the building envelope improves, the number of annual hours during which the indoor air temperature exceeds the required temperature range increases as transmission heat losses decrease.

In terms of relative humidity, the analysed refurbishment measures do not show much effect (Figure 6).

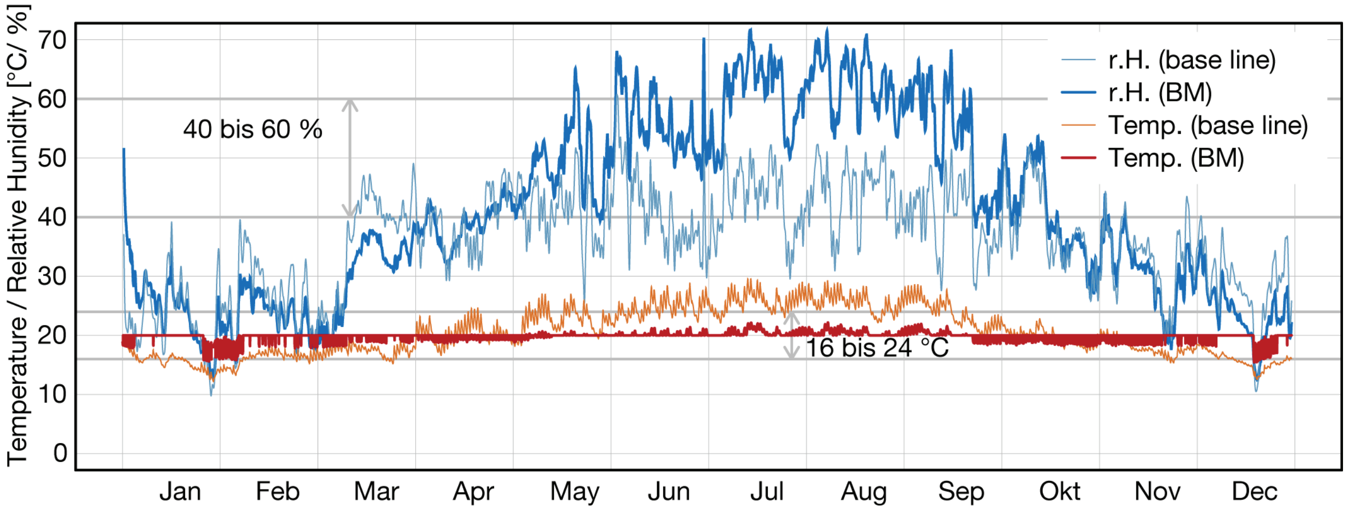

Figure 4. Indoor air temperature (red lines) and RH (blue lines) in gallery space, base line (thin lines) compared to implementation of basic measures (thick lines)

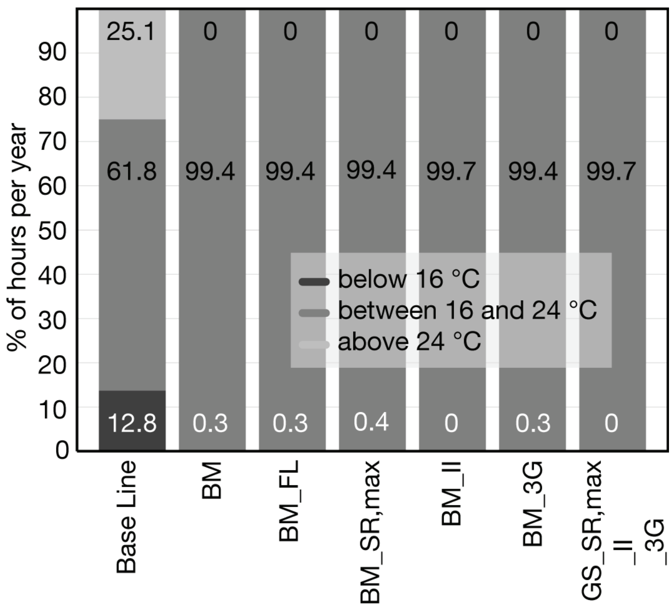

Figure 5. Percentage of hours during which the indoor air temperature is below or above the temperature range of 16-24°C, as required by preventive conservation, categorized by measurement combination according to Table 5.

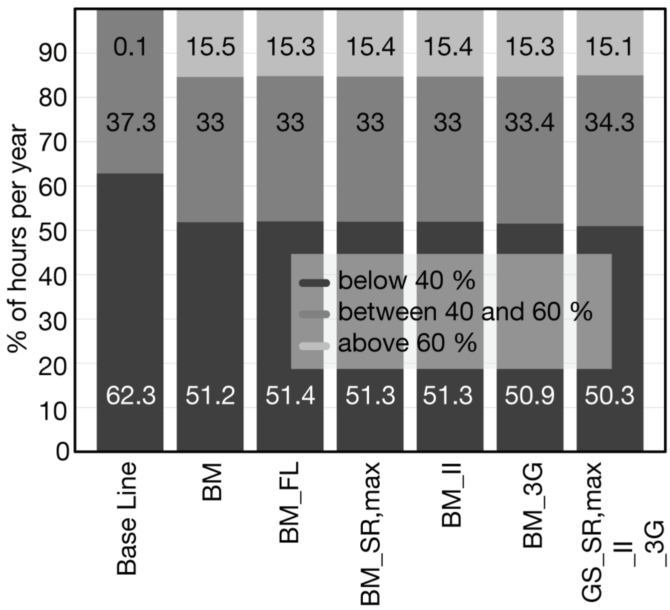

Figure 6. Percentage of hours during which the relative humidity is below or above the range of 40-60%, as required by preventive conservation, categorized by measurement combination according to Table 5.

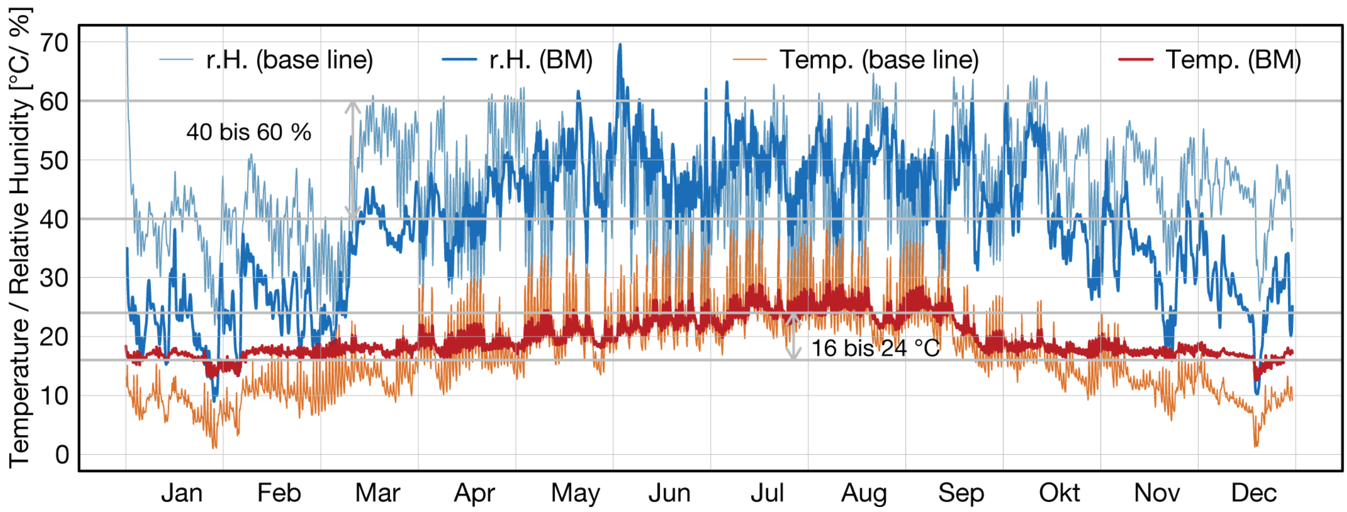

Figure 7. Indoor air temperature (red lines) and RH (blue lines) in the air space above the dust cover, base line (thin lines) compared to implementation of basic measures (thick lines)

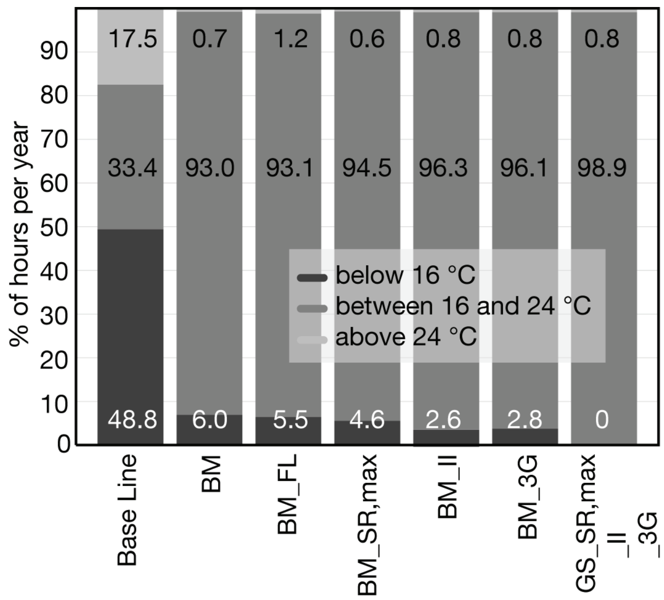

Figure 8. Percentage of hours during which the indoor air temperature is below or above the temperature range of 16-24 °C, as required by preventative conservation, distinguished by measurement combinations according to Table 5.

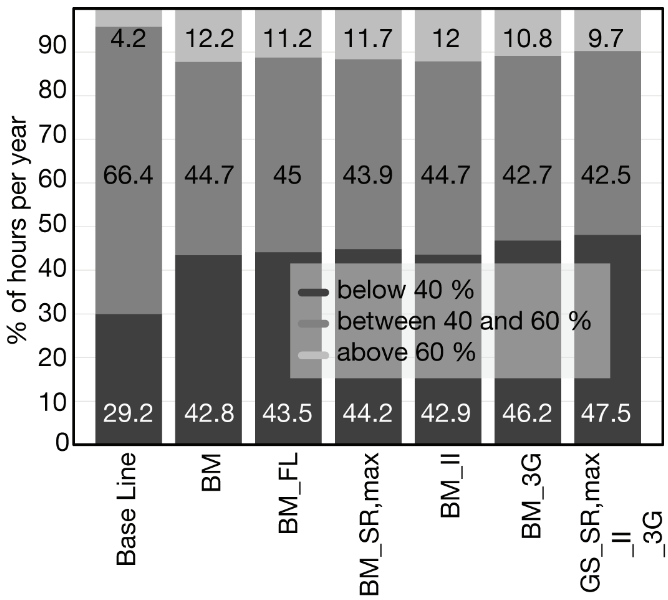

Figure 9. Percentage of hours during which the relative humidity is below or above the temperature range of 40-60 %, as required by preventative conservation, distinguished by measurement combinations according to Table 5.

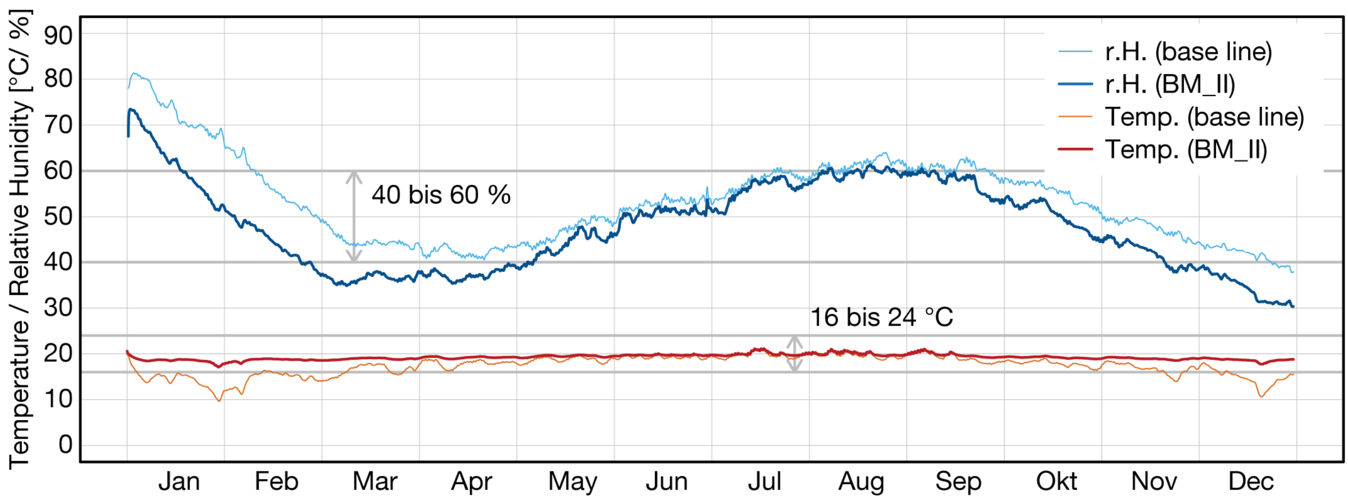

Figure 10. Annual interior surface temperature and relative humidity in the east attic space

3.3.3 Indoor Air Temperature (T_{int}) and Relative Humidity (RH) in Air Space above the Dust Cover

Figure 7 shows the indoor air temperature (red lines) as well as relative humidity (blue lines) over the course of one year before (thin lines) and after (thick lines) the implementation of the basic refurbishment measures. As for the gallery space itself, the indoor air temperature stability increases, whereas there are no significant effects on relative humidity.

The percentage of hours during which the required temperature is below or above the range of 16-24 °C decreases significantly (Figure 8).

3.3.4 Interior Surface temperature of exterior attic walls

The implementation of the basic refurbishment measures results into similar effects as in the main gallery space. However, as the museum director considers expanding the exhibition space by turning the eastern attic into an exhibition room, the influence of an interior isolation of the exterior walls on the interior surface temperature of the exterior walls requires additional analysis. Figure 10 shows that an interior isolation of only 8 cm results into a more or less stable surface temperature of 20 °C, providing the required climate for paintings hung on the exterior wall.

4. Conclusions

The simulation results show that the basic refurbishment as planned by the building authorities already leads to a significant heating demand reduction and increased stability of the indoor air temperature. These effects can be enhanced through applying the additional measures outlined.

The financial requirements and the decision making process in public building, however, makes it difficult to recommend a comprehensive refurbishment strategies. Therefore, strategies have to be developed that can be applied on a step by step basis. Each step must be part of the overall energy performance improvement strategy on its own.

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