



**CONSERVATION
SUPPORT**

Simulation research

Metamorfoze

KB National Library

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1 Introduction

The National Library in The Hague, The Netherlands, (KB) plans to build a new repository building. This new building will be a unique concept not shown in The Netherlands before., in which books are stored in crates in a fully automated and robotized passive storage. The example for this storage can be found in the Kooperative Speicherbibliothek located in Büron, Switzerland. The collection of the KB will be placed in a similar building on the outskirts of The Hague.

The KB was granted a research subsidy from the Metamorfoze foundation to perform in-depth research on the indoor climate conditions in the new storage building. Using an advanced simulation model various aspects of the building will be investigated further in order to assess the optimal storage conditions for books and also to make as little as possible use of energy sources.

The Cultural heritage Agency of The Netherlands is an official partner in the project and the Kooperative Speicherbibliothek has kindly offered to share its experiences. The University of Eindhoven is a sparring partner.

2 Research questions

The simulation model will be used to answer the following questions:

- What is the most optimal build-up of the building constructions?
 - Thickness of insulation in walls
 - Thickness of insulation in the roof
 - Color (absorption factor) of the roof covering
 - Effect of possible settling of soil below the ground floor
- What is the effect of internal air flow within the building?
 - Effect of ingest of crates
 - Effect of horizontal mixing
 - Effect of vertical mixing
 - Effect of additional stratification reduction measures
- What is the influence of the local environment?
 - Effect of a higher ground temperature
 - Effect of a lower ground temperature
 - Effect of climate change over a longer period
- What will be the effect of collections to the indoor environment?
 - Effect of an empty building
 - Effect of a full building
 - Effect of a steady ingest of collections over time
 - Effect of the outdoor weather conditions during ingest period
- What is the effect of a low oxygen system?
 - Inflow of very dry air
 - Inflow of air with humidity compensated for



3 Setting up a basic simulation model

For this simulation study HAMbase¹ is used. It is developed at the University of Technology, Eindhoven. This model consists of a number of files in a Matlab or Octave environment; a building consists of multiple zones. Each zone is filled in into the model using its physical properties.

3.1 Spaces in the building

When looking at the floor plan (see figure 1), a division into 2 parts can be made. The collections part is located on the back of the building and is 69 meters wide, 45.4 meter deep and has a height of about 17 meters. At the front a working area is present. It has similar dimensions except for the depth; this is 9 meters.

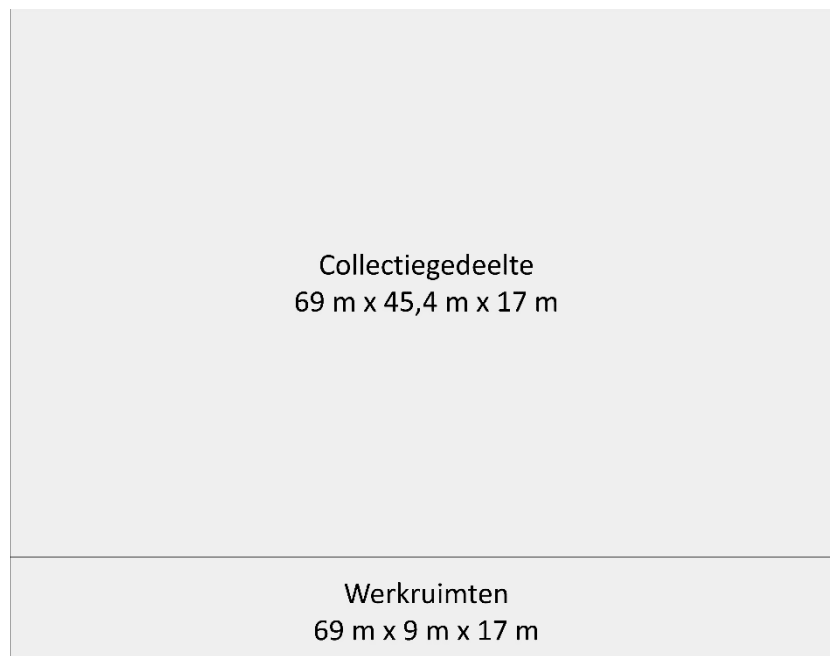
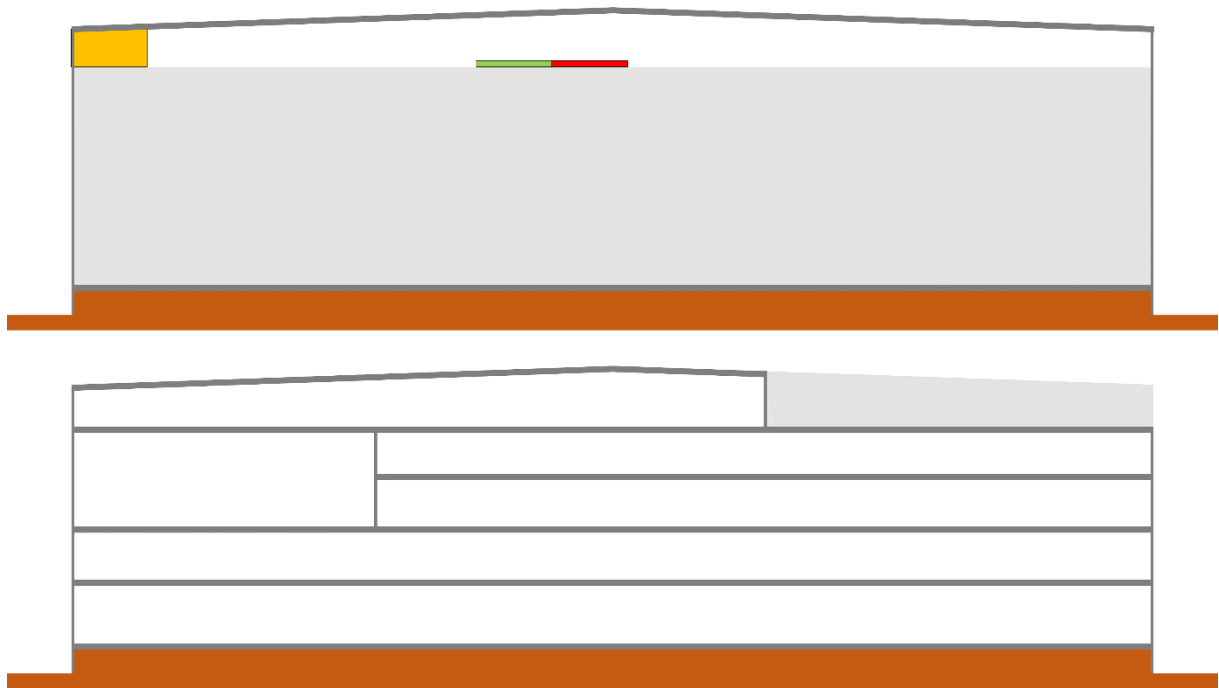


Figure 2 shows a vertical cross section including both collection part (top) and working area (bottom). The collection part is a large open space in which a huge racking system is placed (referred to as shelves). 2 crossings are present at the top (in red a crossing for maintenance of the robot system where all conveyer belts are located, in green an additional crossing where oversized collections are being kept which do not fit in standard crates). Also an amount of space is allocated for climate systems or air handling units; this crossing is colored orange in figure 2. The working area is vertically divided into parts by floors; in these parts logistics, picking stations and the low-oxygen system are placed (left side with additional height).

¹ Wit, de, M. H. (2006). Hambase : heat, air and moisture model for building and systems evaluation. (Bouwstenen; Vol. 100). Technische Universiteit Eindhoven



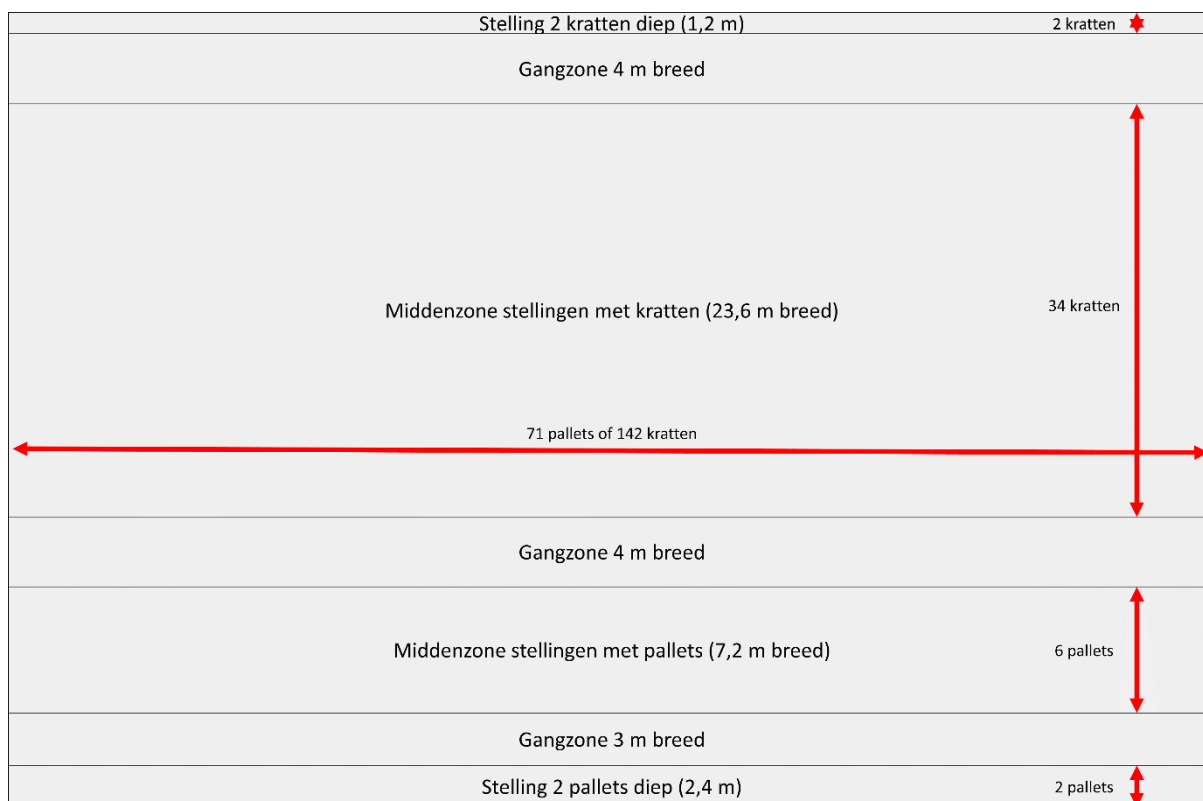
3.2 Zones setup

The model consists of several zones. All working areas are combined into one zone, as well as the zone for climate systems. Because of the massive height of the collection space and the expected differences in placement of collections, this area is divided into 29 different zones. These are displayed in figures 3 and 4.

The main goal of this type of zoning is to be able to show differences in indoor climate between top and bottom, between middle and sides and between working area side and outdoor envelope side.

Horizontally it starts with a zone adjacent to the working area (2 pallets deep), a corridor, a middle section with pallets (6 pallets deep), another corridor, a middle zone with crates (34 crates deep), another corridor and a zone adjacent to the outer envelope (2 crates deep). To limit the amount of zones, corridors that have the same boundary conditions are combined; the 2 corridors in the pallet section and the 9 corridors in the crates section are regrouped into 3 fictitious corridors.

Vertically the largest zone is located above all shelves. No collection is present in this area except for some oversized items. The corridors are divided into 4 parts. Also the shelf areas are divided into 4 parts, but a fifth part is added at the bottom where no collection is present. 16 zones in total will contain collections; these are either pallets, lower crates or higher crates. For each zone the maximum number of storage units is calculated; see figure 4. For an easy comparison of variants, this maximum amount is multiplied by the actual filling percentage, which will be in between 0 and 100 %. Each zone can have a unique filling percentage.



Lege bovenste laag, 2,5 m hoog						
568 pallets,	Gang	1.704 pallets 1,6 m hoog	Gang	19.312 hoge kratten, 1,6 m hoog	Gang	1136 hoge krat
1.704 pallets	Gang	5.112 pallets, 4,8 m hoog	Gang	57.936 hoge kratten, 4,8 m hoog	Gang	3408 hoge krat
1.704 pallets	Gang	5.112 pallets, 4,8 m hoog	Gang	77.248 lage kratten, 4,8 m hoog	Gang	4544 lage krat
852 pallets	Gang	2.556 pallets, 2,4 m hoog	Gang	38.624 lage kratten, 2,4 m hoog	Gang	2272 lage krat
Leeg 0,6		Leeg 0,6 m		Leeg 0,6 m		Leeg

3.3 Constructions

The construction drawing of the new building show a typical build-up of floors and walls. These are displayed in figure 5. For this model, the envelope is defined, as is the roof construction and floor construction. Also the inner wall between working area and collection area is displayed. To also



include the collections within the building – collections have a large thermal mass and strong hygroscopic behavior which both influence the indoor climate – also 2 constructions for crates and pallets are being defined. The lower crates consist of a thin plastic bottom with on average 15 cm of books on top; higher crates contain about 25 cm of books.

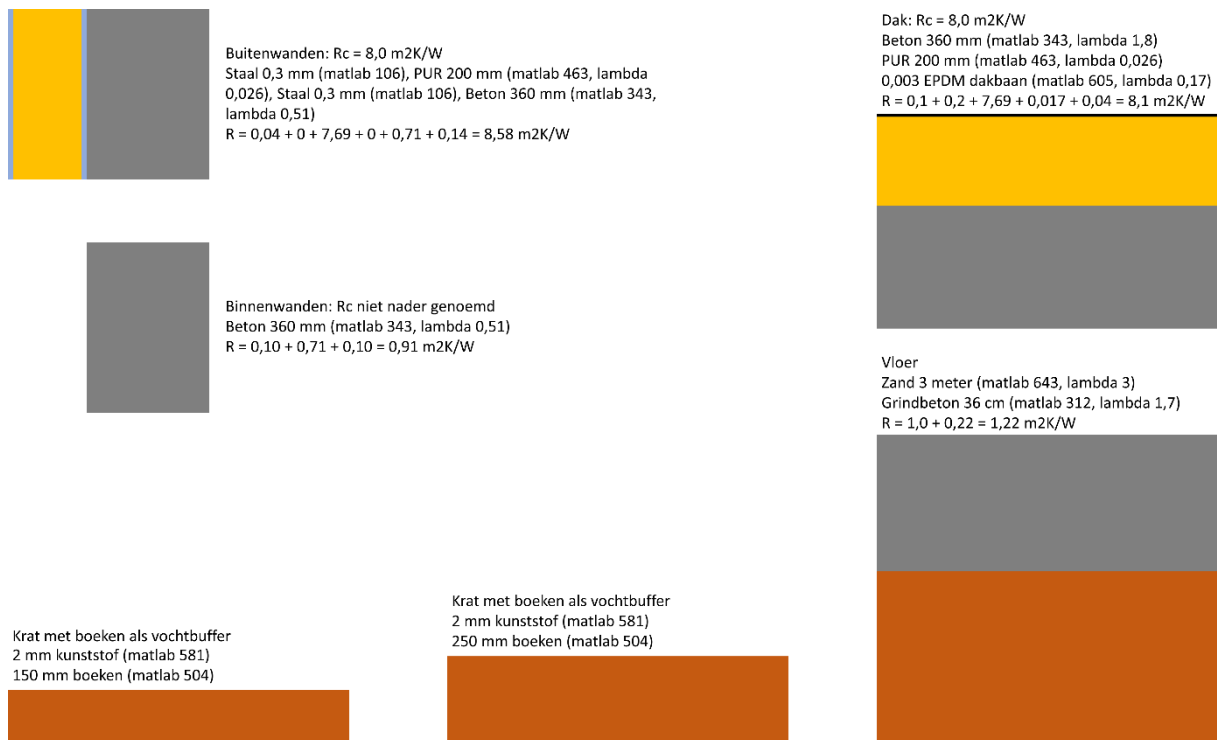


Figure 5: Constructions used in the model; matlab code refers to a list of materials for HAMbase

3.4 Building use

In the working areas people are present during office hours. These spaces are also heated; it might be that additional (de)humidification is needed later on. All other zones do not allow for people to be present other than for extensive inspections. The corridors and top zone of the collection area are equipped with robots and related logistical elements (conveyer belts) which produce heat. This heat is distributed and spread across the entire repository area.

3.5 Air exchange

As described in 3.2, the collections part is divided into multiple zones. These zones are in open connection with one another; air will be exchanged. Driving forces are either differences in specific weight (warm air will rise as will moist air. Dry air will sink as will cool air) or by movement caused by robots. Also the low-oxygen system will extract air and insert air with nitrogen added to it.

Figure 6 shows the air exchange in between zones. 5 different air flows are to be distinguished:

- Horizontal flow in between corridor and shelves (blue)

- Horizontal flow in between corridor and below shelves (red)
- Vertical flow in between corridors and from the top part into and out of the corridors (green)
- Forced flow, which enters in the top zone (by a system) and leaves at the bottom in 4 different corners of the repository (yellow)
- Forced flow, which enters in the top zone from the working stations and vice versa (because of the ingest of crates and pallets) (purple)

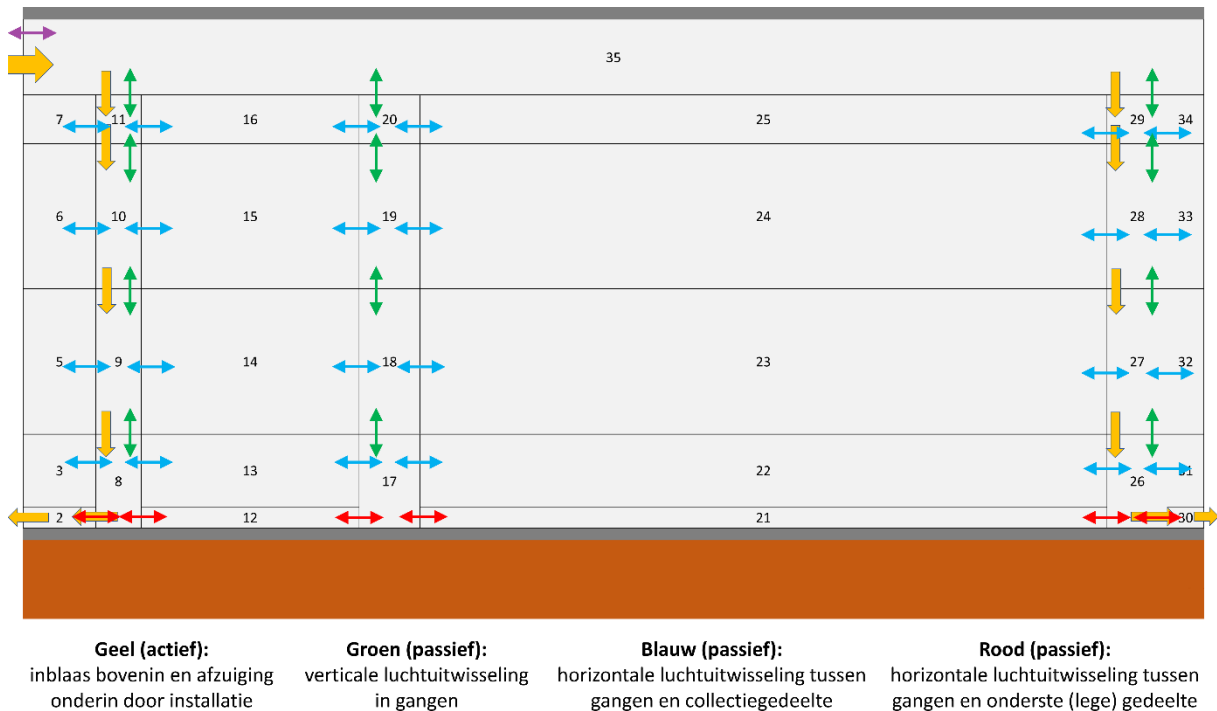


Figure 6: Air flows in between zones in the model

3.6 Simulation period

The initial simulation period used starts on January 1st 2001 until December 31st 2010. It contains hourly values for the whole decade, measured at an air field at 2 kilometers from the location of the new storage building. For assessment of indoor climate quality, only the last 5 years are used. Most of the simulated variants do not show a stable behavior during the first 5 year period.

4 First results

This paragraph shows the first results of the so-called basic model. These results are discussed in-depth; later on – for all variants – a short summary shall be given only. This summary includes pinpointing the differences.

4.1 Spatial differences

Figure 7 shows temperature in a number of zones in the new repository. Working area is displayed in red; this area is heated to 18 °C. In summer temperatures can go up to 21 °C. Relative humidity is in between 25 %RH in winter and 90 %RH in summer.

The climate system area is displayed in blue, green shows the top zone in the collections repository. Temperatures range in between a minimum of 9.5 and 11.0 °C in winter and 17.5 and 19.0 °C in summer, depending on the outdoor climate. RH shows a slow yearly fluctuation of 8 to 10 %RH. It can be seen that RH is slowly increasing over a decade; eventually the average rises up to 63 %RH. This is caused by the Dutch climate; the equilibrium will occur when yearly average indoor specific humidity and outdoor specific humidity are in balance. Important to point out is that in this basic simulation no low oxygen environment is present; this will lower the average RH.

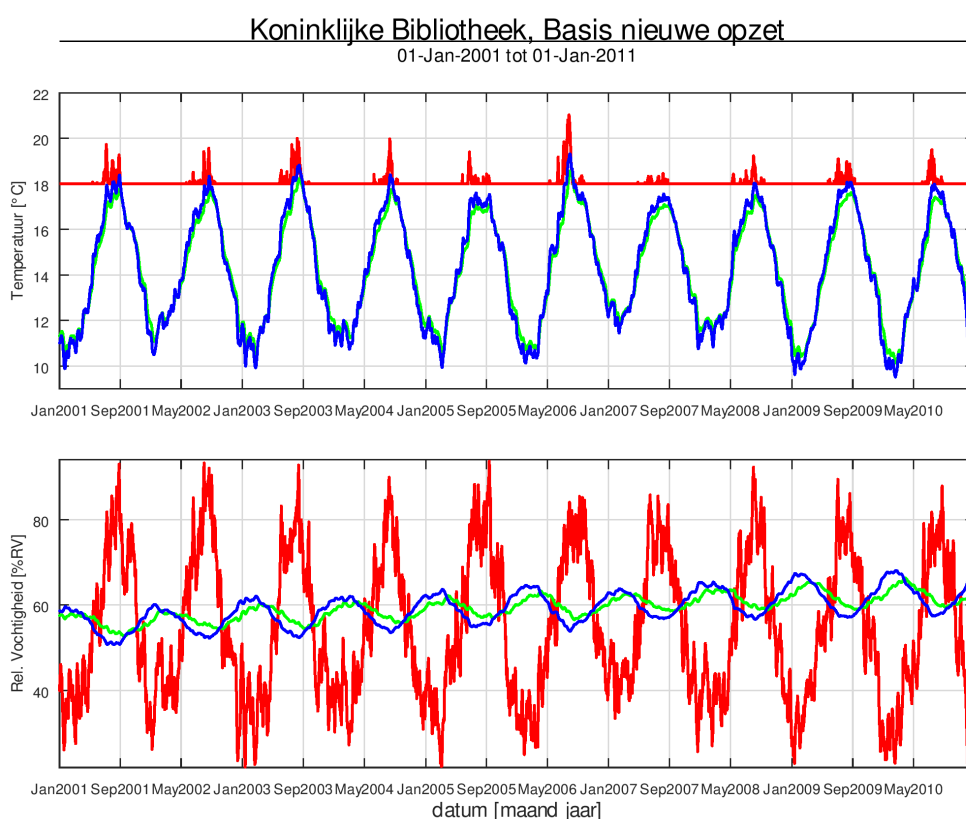


Figure 7: T (top) and RH (bottom) in the repository

Also the energy load on the climate systems can be assessed. This is displayed in figure 8. But 2 zones are actively controlled: working area (heating only) and the climate system zone (if needed). All other zones do not have any means to adjust temperature or relative humidity.

The working area is slightly heated to be comfortable for people to work in. The red line shows the power needed for heating; a maximum of 25 kW is needed. Also in summer heating is needed: the cooling effect of the adjacent repository (which has a quite low temperature) is clearly noticeable. In green the climate system zone is displayed. In this zone, air is extracted from the repository and nitrogen is mixed in. Also the RH can be controlled by humidifying. In the simulation displayed here, the system is still off. The green lines show no heating or cooling power and also no moisture added or removed. In upcoming simulations there will be also a load for this climate system.

Figure 8 also shows that for a 10 year period 785.5 MWh of heating energy is needed. On average, this equals 78.55 MWh annually. When supplied by a heat pump with a COP of 3.5, with an energy supply delivered by solar panels of 240 Wp each, 93 solar panels are needed to deliver the amount of energy. This consumes roughly 1/3 of the roof above the working area.

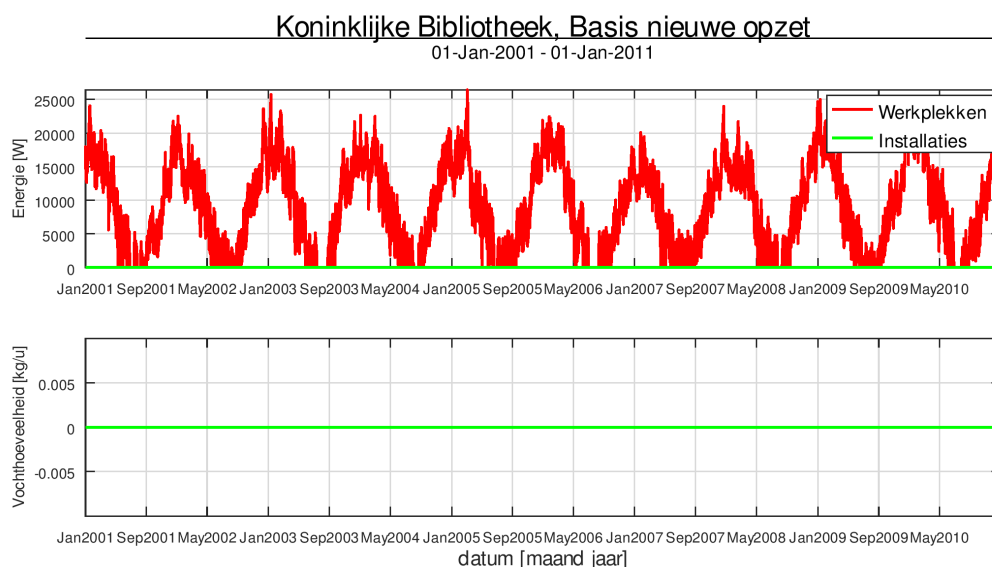


Figure 8: Momentary energy use for heating and cooling (top) and amount of water needed for (de)humidification (middle), integrated over the whole period per zone (bottom)

4.2 Differences in height (stratification)

For the large number of zones in the collection area various graphs can be presented. Because of this large number, stratification is shown here. Each graph shows only the zones that are placed on top of each other.

Figure 9 shows 5 zones closest to the working area. Temperatures are in between 13.5 and 19.3 °C, as displayed in the top graph. The bottom is practically always cooler than the zones above; the only exception occurs during winter when the top zones show a slightly lower temperature. Stratification changes sign: it is positive in summer (cool floor, warm roof) and negative in winter (warmer floor but cooler roof).

The bottom graph shows temperature differences. The zone with the lowest average temperature is subtracted from the other zone temperatures. Layer 4 shows the largest annual cycle, both positive and negative. It also shows that layers 1, 2 and 3 are always warmer than the bottom layer. This is exceptional: it only occurs very close to the wall in between (heated) working area and repository. On other positions it does not occur.

At the bottom of figure 9 two numbers are printed: -0.91 °C and 2.16 °C. These are the maximum differences between all zones during the decade displayed. This is an indication of stratification magnitude. In this special case (close to the working area) the top layer behavior is responsible.

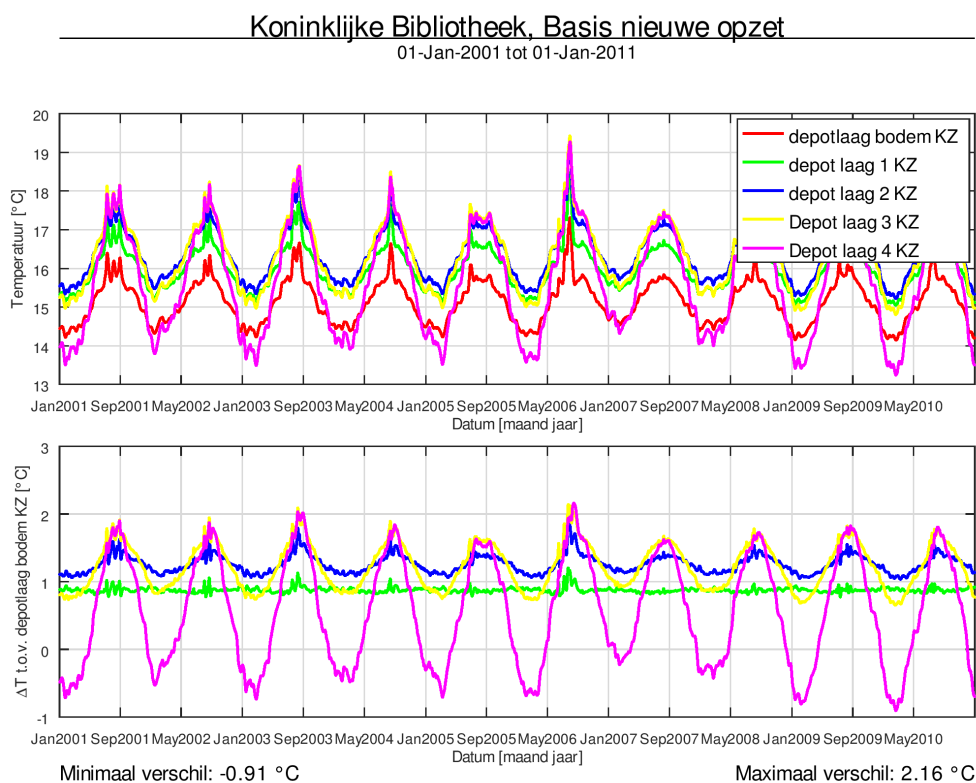


Figure 9: Temperature stratification shelves near working area

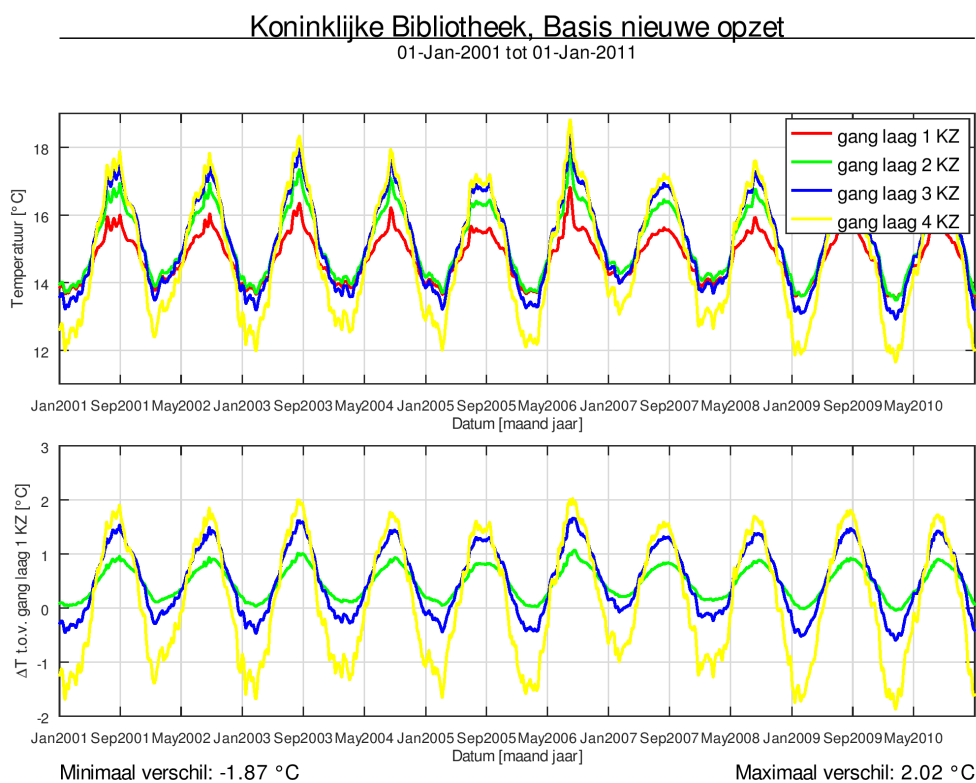


Figure 10: Temperature stratification corridor near working area

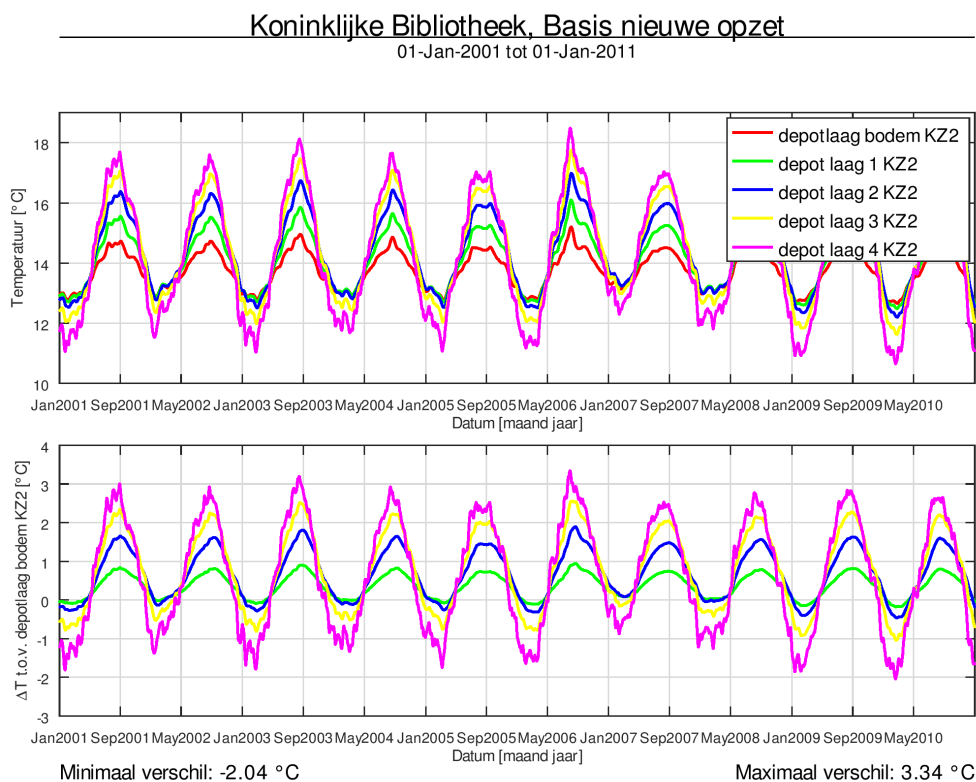


Figure 11: Temperature stratification pallet shelves middle

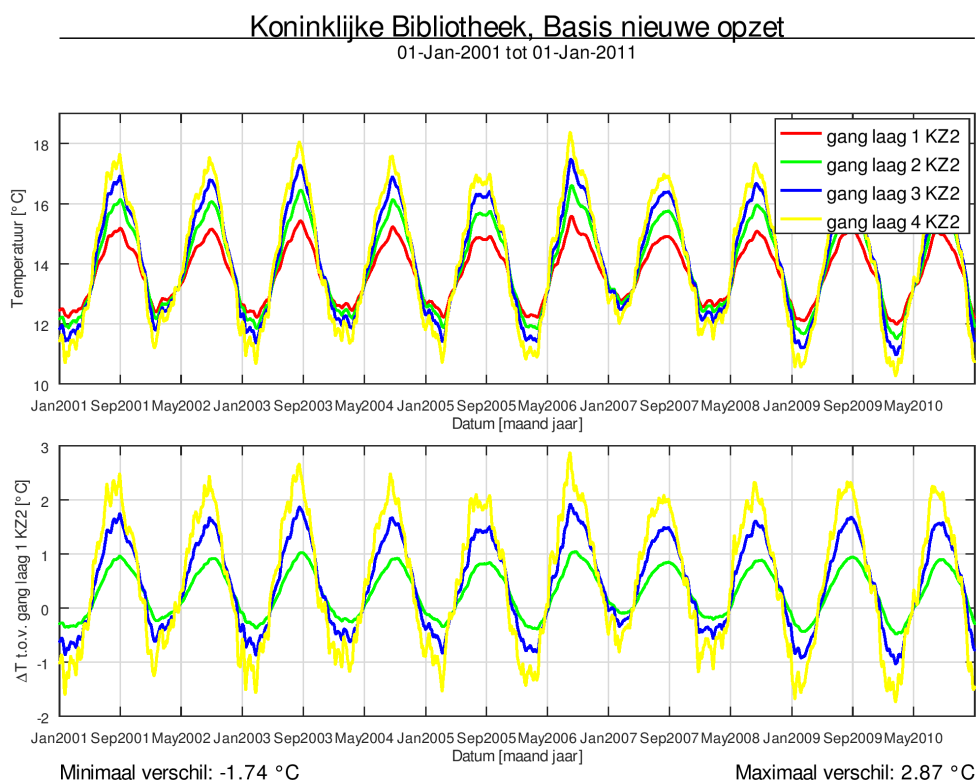


Figure 12: Temperature stratification corridor middle

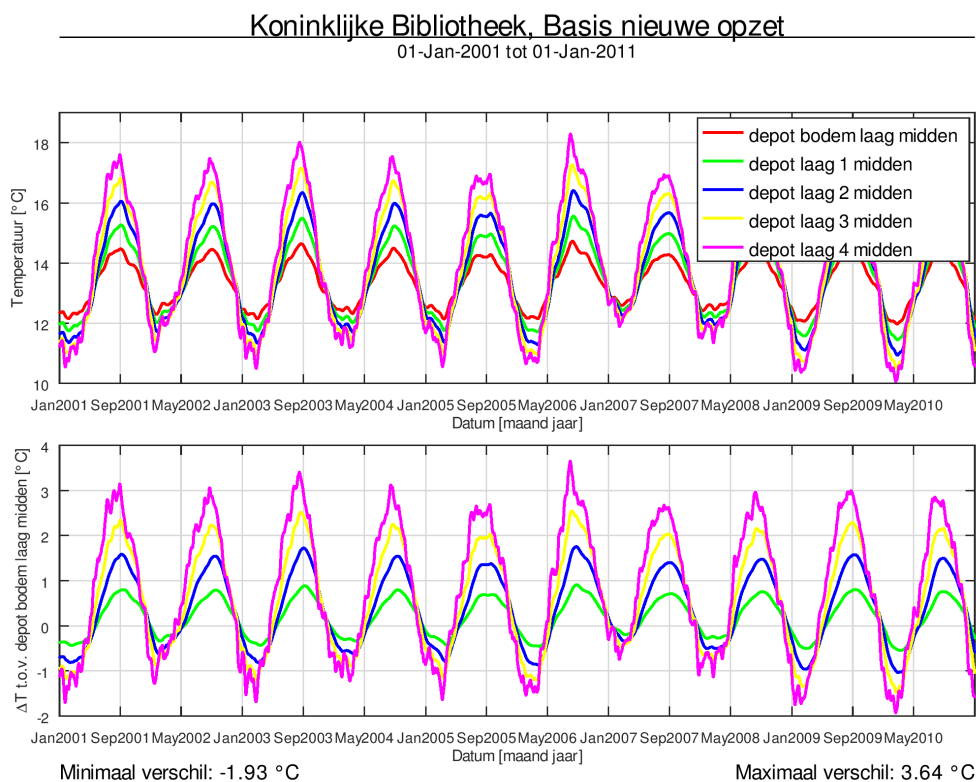


Figure 13: Temperature stratification crates shelves middle

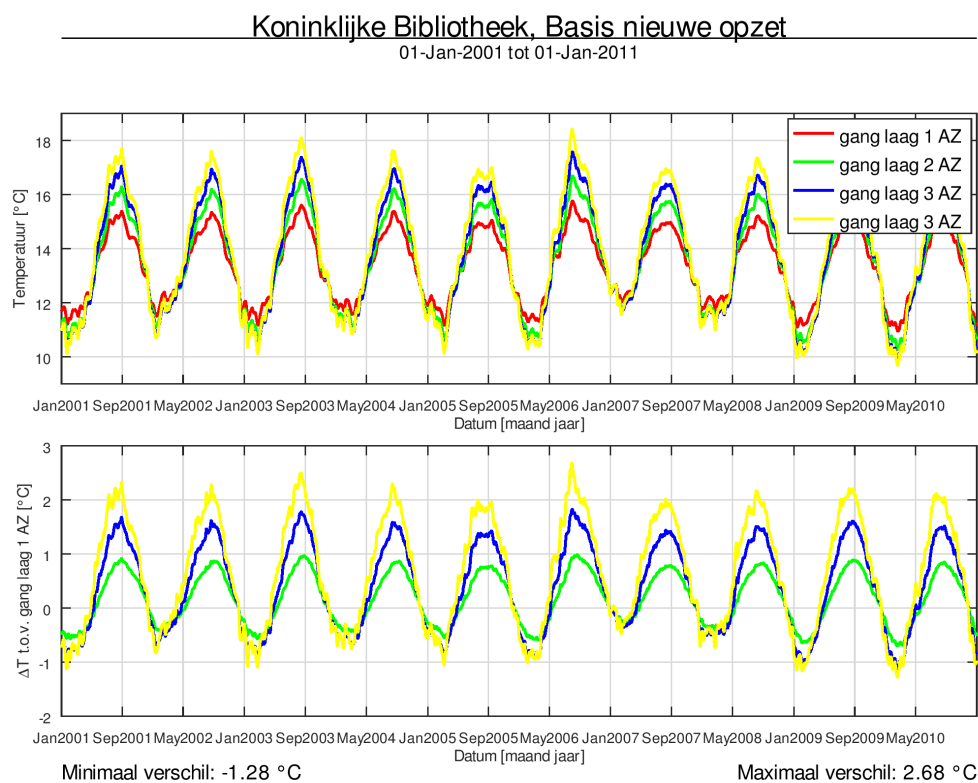


Figure 14: Temperature stratification corridor near the back wall

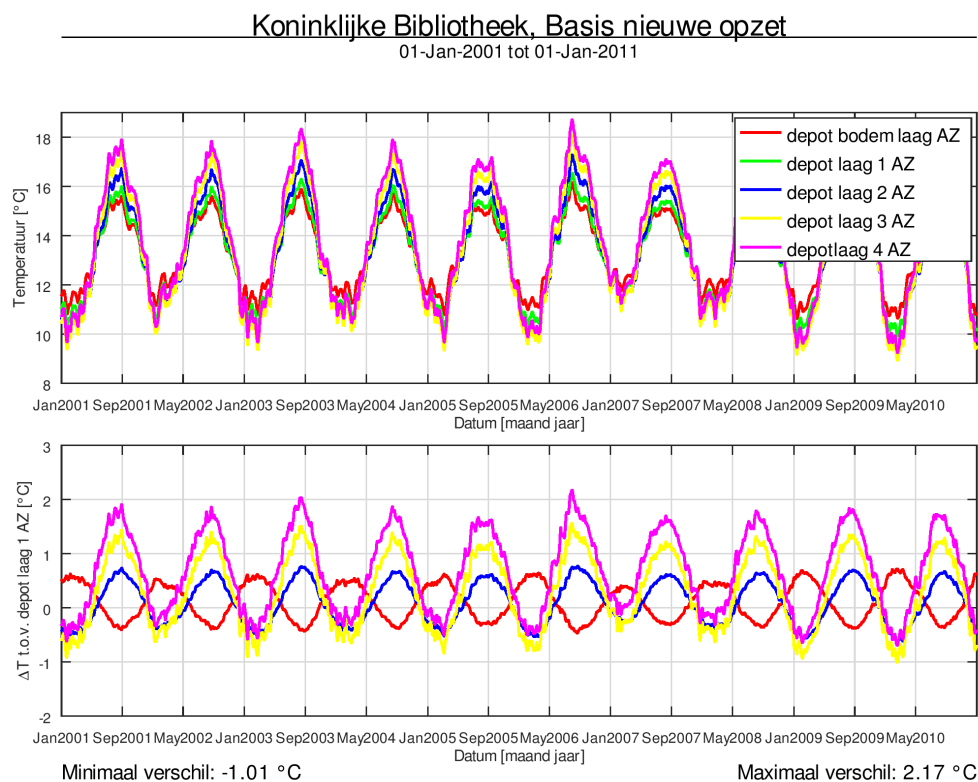


Figure 15: Temperature stratification crates shelves at the back wall

Table 1: Results of the basic model variant, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.91	-1.87	-2.04	-1.74	-1.93	-1.28	-1.01
Maximum [°C]	2.16	2.02	3.34	2.87	3.64	2.68	2.17

WA = working area side; M = middle; BW = back wall side; corr = corridor

When all 7 verticals in repository zones the minimum and maximum values are combined, a table like table 1 can be made. The stratification in the 3 corridors is nearly identical. There are some differences over the different shelves, because of their position in the building (near envelope or heated working area) and because of its sheer size.

The above table will be used to compare stratification in all other variants. It can be interesting to know whether a change in construction or control leads to an increased or decreased stratification.

4.3 Extreme and average values

In order to limit the amount of data to compare, the most average zone shall be examined further. This is zone 23 in the model. Also some more extreme zones will be included: zone 3 is located at the bottom adjacent to the working area, zone 7 at the top near the working area. Also zones 31 and 34 are examined; both lie near the outer envelope at the back of the repository; 31 is located at the bottom and 34 at the top.

Of all 5 zones a mathematical analysis is carried out. This analysis is displayed in figure 16. On the left temperature is displayed and on the right relative humidity is presented.

The top figure shows the simulated results for the last 5 year period (of 10 years of simulation data). The black dotted line presents the total average. In text also minimum, maximum and average are displayed. The middle graphs show the total average subtracted from all values. This represents deviations from this total average. It can be seen that the values follow the seasons. A running average using a 3-month period (a season) is also plotted; in text a number indicates how much this running average differs from the total average, both positive and negative.

The bottom graph shows what remains when also the seasonal running average is subtracted from the simulated values. It shows the remaining fluctuations which are shorter than a season. By calculating the mathematical standard deviation, these fluctuations can be assessed in terms of magnitude. 66 % of all values are in a bandwidth of one standard deviation, 95 % of all values is within a bandwidth of twice the standard deviation and finally 99 % is in a bandwidth of three times the standard deviation.

As measure for short term fluctuations, twice the standard deviation is used here. This equals 0.42 °C and 0.03 %RH; both very small numbers. It is indicated as 'short' in table 2.

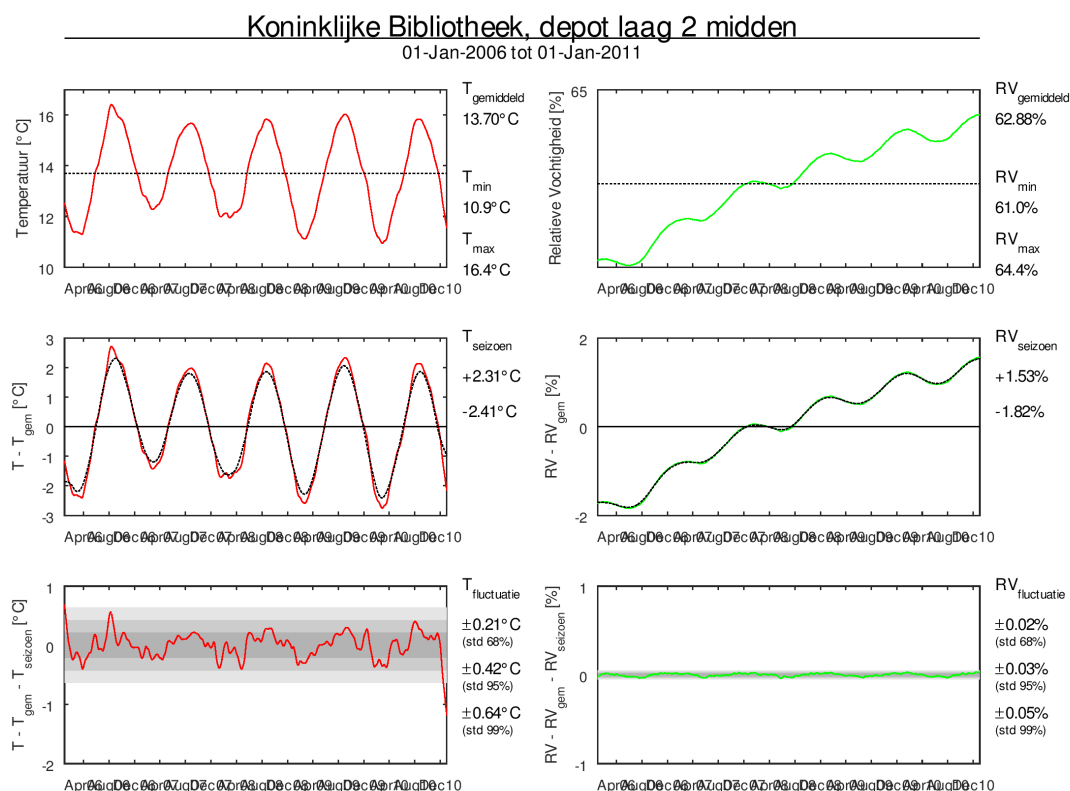


Figure 16: Mathematical parameters of the indoor climate, basic model zone 23

Table 2 contains all values from figure 16, also from the other positions in the storage. Most striking difference is the average temperature; there is a 2.8 °C difference. The highest average occurs near the working area at a low level, while the lowest value is detected low at the back side. For relative humidity, this difference is exactly opposite: high at the back and lower near the heated working area.

In terms of fluctuations seasonal changes are smallest near the working area and larger near the back. For relative humidity, seasonal fluctuations are largest at the outer edges and smaller in the middle. Shorter fluctuations are marginally larger at the back. For RH, these fluctuations are smallest in the middle, where much collection is present and the influence of boundaries (warm front area or cooler outer wall) are minimized.

Table 2: Results for the basic model, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	18.4	16.0	0.82	1.06	0.33	49.2	59.6	54.8	5.14	4.27	0.65
Front area high	13.2	19.3	15.7	2.09	2.21	0.48	53.1	57.6	55.7	2.43	1.77	0.19
Middle	10.9	16.4	13.7	2.41	2.31	0.42	61.0	64.4	62.9	1.82	1.53	0.03
Back side low	10.0	16.5	13.2	2.76	2.56	0.62	63.4	67.0	65.3	1.76	1.63	0.11
Back side high	9.3	18.7	13.9	3.87	3.67	0.83	57.6	67.0	62.3	4.48	4.32	0.54

5 Variant study first round

Using the basic model and making minor changes to it, various variants were calculated. The purpose is to find out what changes – in either construction, use or technical systems – have a positive effect and also determine the extent of this effect.

For each variant table 1 and 2 are presented, containing the new results obtained from the changed model. These numbers also are colored, based on the comparison with the original basic model:

- Green when a lower number is encountered (negative number: green at higher values)
- Red when an higher number is encountered (negative number: red at lower values)
- White when both variant and basic model show identical numbers

For each variant it can be concluded whether the results are beneficial or not. Also the magnitude is estimated.

5.1 Variant 1: soil settling

This variant explores the difference when the soil below the ground floor might settle over the years, thus creating an air gap in between sand and concrete. This affects thermal resistance and therefore buffering capacity of the ground below the repository.

Table 3: Results of variant 1, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.95	-1.88	-2.00	-1.69	-1.85	-1.19	-0.93
Maximum [°C]	2.09	1.94	3.18	2.78	3.57	2.60	2.11

Table 4: Results of variant 1, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	18.8	16.1	0.86	1.15	0.38	49.1	59.4	54.7	5.10	4.23	0.65
Front area high	13.3	19.4	15.7	2.10	2.27	0.50	53.1	57.6	55.7	2.43	1.78	0.20
Middle	10.9	16.5	13.7	2.47	2.38	0.43	61.0	64.3	62.8	1.78	1.50	0.03
Back side low	9.9	16.7	13.2	2.85	2.65	0.63	63.5	66.9	65.2	1.67	1.60	0.11
Back side high	9.3	18.8	13.9	3.88	3.71	0.83	57.6	66.9	62.3	4.42	4.26	0.53

The tables show that stratification is reduced a little. Maximum temperatures rise a bit (less thermal buffering of the soil), causing RH to drop slightly. Seasonal and shorter fluctuations for temperature increase slightly, while for RH a decrease can be seen.

It can be concluded that settling of the soil does not make a significant difference. For RH it is somewhat beneficial, while for temperature a disadvantage is noticed.

5.2 Variant 2: lower roof absorption

In this variant the absorption of the roof construction is changed; by choosing a light color topping the absorption coefficient drops from 0.9 to about 0.4; a smaller fraction of sunlight will be converted into heat.

Table 5: Results of variant 2, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.95	-1.58	-2.12	-1.82	-2.02	-1.34	-1.02
Maximum [°C]	1.88	1.94	2.64	2.24	2.88	2.04	1.57

Table 6: Results of variant 2, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.0	17.8	15.9	0.73	0.83	0.23	49.2	59.2	54.7	5.02	4.06	0.61
Front area high	13.2	18.3	15.4	1.88	1.87	0.41	53.4	58.2	56.2	2.59	1.92	0.18
Middle	10.9	15.8	13.4	2.22	2.08	0.39	61.3	65.0	63.3	1.95	1.66	0.03
Back side low	9.9	16.1	13.0	2.63	2.40	0.60	63.2	67.5	65.4	2.11	1.99	0.13
Back side high	9.2	17.7	13.5	3.57	3.32	0.78	58.9	67.9	63.4	4.28	4.17	0.49

This variant shows a larger reverse stratification in winter and a larger normal stratification in summer. Nearly all temperatures drop or do not change much, both averages, extremes and fluctuations. For RH most values rise, except in the far corners of the repository. More reflection is beneficial in most cases; degradation will be slower. Slight side effect is that the RH, which in the basic model is already quite high, needs to be prevented from becoming too high.

5.3 Variant 3: More insulation

The effect of more insulation in walls and roof is examined by increasing insulation thickness from 0.2 to 0.3 m. The total Rc value will climb from 8 to nearly 12 m²K/W.

The additional insulation causes stratification to decrease on all positions. Minimum and maximum temperature are more closely together, while the average increases slightly. All fluctuations become smaller. The net effect on temperature is therefore very pleasing.

Nearly all RH values go down, which is beneficial as well. It can be concluded that additional insulation has a positive and quite large effect.

Table 7: Results of variant 3, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.44	-1.25	-1.21	-1.06	-1.10	-0.68	-0.59
Maximum [°C]	1.92	1.73	2.80	2.39	3.05	2.24	1.84



Table 8: Results of variant 3, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.4	17.8	16.1	0.59	0.75	0.21	50.1	58.8	54.9	4.37	3.54	0.52
Front area high	14.0	18.4	15.8	1.55	1.62	0.33	53.1	57.2	55.5	2.27	1.63	0.16
Middle	11.8	15.9	13.9	1.80	1.73	0.31	60.7	64.0	62.5	1.79	1.44	0.03
Back side low	10.9	15.9	13.4	2.07	1.93	0.47	62.8	66.5	64.8	1.91	1.65	0.10
Back side high	10.7	17.7	14.2	2.91	2.78	0.60	57.8	65.3	61.6	3.62	3.44	0.40

5.4 Variant 4: Less insulation

This variant is the opposite of the previous one. The insulation thickness is reduced from 0.2 to 0.1, thus lowering the Rc value to about 5 m²K/W.

This variant shows an increased stratification. Also minimum and maximum temperatures drift further apart, while on average temperatures go down. RH increases, while both seasonal and short fluctuations become larger.

Less insulation has a destabilizing effect, which is not beneficial. Moreover, the effect is considerable in size.

Table 9: Results of variant 4, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-1.74	-2.69	-3.49	-2.97	-3.42	-2.23	-1.48
Maximum [°C]	2.72	2.96	4.31	3.73	4.73	3.37	2.55

Table 10: Results of variant 4, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	14.4	19.5	15.9	1.30	1.67	0.60	47.5	60.7	54.7	6.43	5.33	0.88
Front area high	11.8	20.7	15.5	3.12	3.28	0.80	53.1	58.1	56.0	2.66	1.96	0.26
Middle	9.3	17.4	13.4	3.54	3.36	0.64	61.6	65.2	63.5	1.87	1.69	0.04
Back side low	7.9	17.9	12.8	4.11	3.73	1.03	64.1	68.3	66.1	1.75	2.02	0.21
Back side high	6.7	20.5	13.4	5.62	5.23	1.28	57.2	69.8	63.4	5.96	5.78	0.78

5.5 Variant 5: Additional heating workspace

Working space is heated to 18 °C in the basic model. Now, it is increased to 20 °C. It is assumed that the whole working area, including logistic spaces, are all heated uniformly.

Table 11: Results of variant 5, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.81	-1.78	-1.81	-1.55	-1.66	-1.06	-0.87
Maximum [°C]	2.33	2.14	3.50	2.96	3.77	2.76	2.25

Table 12: Results of variant 5, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.7	18.5	16.9	0.84	0.91	0.35	47.0	56.8	52.4	4.86	4.03	0.63
Front area high	13.9	19.4	16.5	2.10	2.06	0.49	51.0	55.1	53.4	2.23	1.59	0.18
Middle	11.2	16.6	14.0	2.40	2.26	0.42	60.8	63.9	62.5	1.68	1.38	0.03
Back side low	10.1	16.6	13.4	2.75	2.52	0.62	63.6	66.9	65.3	1.63	1.52	0.10
Back side high	9.6	18.9	14.2	3.86	3.60	0.82	56.9	66.1	61.5	4.37	4.21	0.54

From table 11 and 12 it turns out that stratification increases. Only during winter, reversed stratification becomes a bit less, because the repository area cools down less. On average the repository has a 0.3 to 0.5 °C higher temperature caused by the additional heating in the workspace. Also minimum and maximum temperatures both increase. Seasonal changes decrease. Only short fluctuations are not affected much.

In terms of RH most values decrease. More stability is noted, while the average RH is also lower and more beneficial. The total effect on climate seems positive.

The only downside is its energy usage. An increase from 78.55 to 100.1 MWh/year is noticed. This is an increase in cost of about 27 %. It also results in less sustainability.

5.6 Variant 6: Empty repository

The basic model shows a full repository. The effect of hygroscopic material (books) can be assessed by also calculating an empty one without any hygroscopic material. The model does have empty crates in it.

Table 13: Results of variant 6, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-1.12	-2.11	-2.21	-1.84	-2.17	-1.38	-1.08
Maximum [°C]	2.62	2.51	4.08	3.26	4.26	3.04	2.48

Table 14: Results of variant 6, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.3	19.1	16.9	0.98	1.03	0.53	47.7	61.0	54.8	6.34	5.49	1.00
Front area high	13.3	20.3	16.5	2.44	2.30	0.69	53.0	57.8	55.9	2.56	1.74	0.28
Middle	10.4	17.8	13.9	2.91	2.59	0.80	62.2	69.5	66.0	3.50	3.03	0.61



Back side low	9.3	17.5	13.4	3.30	2.75	0.98	66.4	70.0	68.4	1.70	1.43	0.32
Back side high	8.8	20.0	14.2	4.44	3.95	1.10	58.7	70.0	64.5	5.25	4.91	0.70

Results show that stratification is much higher. All fluctuations are higher too, both in temperature and RH. Some of the minimum values become lower, while all other values go up. The collection is very beneficial for keeping the climate within range.

5.7 Variant 7: Low-oxygen system on

To assess the effect of a low-oxygen system, an airflow is introduced from repository to installation space and vice versa. This installation space is dried in order to simulate the drying effect of releasing nitrogen in air. Nitrogen does not contain any water vapor. It is simulated that by recirculation the inlet air has 2/3 of its initial RH.

Temperatures do not change; only RH is affected. All values drop; On average the RH goes to a more desired level of around 50 %RH. Locally lower values are encountered. The total effect is high, so in practice the means of control needs to be very well balanced in order to obtain a proper RH.

Table 15: Results of variant 7, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.91	-1.87	-2.04	-1.74	-1.93	-1.28	-1.01
Maximum [°C]	2.16	2.02	3.34	2.87	3.64	2.68	2.17

Table 16: Results of variant 7, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	18.4	16.0	0.82	1.06	0.33	36.7	45.0	41.0	4.03	3.63	0.52
Front area high	13.2	19.3	15.7	2.09	2.21	0.48	39.9	43.5	41.9	1.88	1.48	0.17
Middle	10.9	16.4	13.7	2.41	2.31	0.42	48.3	51.1	49.6	1.29	1.38	0.03
Back side low	10.0	16.5	13.2	2.76	2.56	0.62	47.5	50.6	49.0	1.43	1.47	0.10
Back side high	9.3	18.7	13.9	3.87	3.67	0.83	43.9	50.9	47.1	3.03	3.45	0.39

5.8 Variant 8: Airflow by ingest

On a daily basis, crates are extracted and new crates inserted. Next to the effect of adding and removing hygroscopic material (which might be at a different equilibrium) this also has an effect because of the airflow from workspace to repository and vice versa. This air exchange is based on exchanging 1 small crate every 5 seconds; this is a large number.



The effect is that seasonal fluctuations in temperature become smaller and some of the minimum temperatures go up. In winter stratification rises, while in summer is drops slightly. The most effect is noticed on RH; the RH increases considerable and fluctuations are larger. Only at the outer boundary of the repository fluctuations are somewhat reduced (they were highest on this position to start with).

This airflow is unavoidable in reality. The effect is not beneficial, but in combination with the previous variant (low-oxygen) it can be compensated for.

Table 17: Results of variant 8, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.89	-1.84	-2.00	-1.70	-1.89	-1.24	-0.99
Maximum [°C]	2.16	2.02	3.35	2.88	3.65	2.68	2.18

Table 18: Results of variant 8, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	18.4	16.0	0.81	1.06	0.33	54.6	66.5	60.9	5.70	5.07	0.82
Front area high	13.3	19.3	15.7	2.07	2.20	0.48	58.7	64.5	61.9	2.92	2.42	0.33
Middle	11.0	16.4	13.7	2.39	2.30	0.42	67.6	70.9	69.7	2.06	1.12	0.06
Back side low	10.0	16.5	13.2	2.76	2.55	0.62	69.7	74.5	72.5	2.69	1.82	0.27
Back side high	9.3	18.7	13.9	3.85	3.65	0.82	64.9	72.6	69.2	3.89	3.08	0.45

5.9 Variant 9: Raised soil temperature

Dutch soil has a temperature of about 11 °C when going down a few meters into the ground. By placing the repository building on this soil without adding insulation material, the soil will help to buffer temperatures in the building. In this basic simulation soil temperature is estimated at 13 °C. This variant tries to find out what happens when raising it from 13 to 14 °C. This might be caused by climate change or by changing the equilibrium because of the building which is present and which might heat the soil below somewhat over time. This is backed by noticing that the average temperature in the building is 13.7 °C.

A higher soil temperature leads to a smaller stratification in summer, but a higher one in winter. All temperatures go up, both minimum, maximum and average. Fluctuations increase slightly. RH values become more optimal. Fluctuations remains similar, but all other values are lower and therefor more beneficial. The average matches better.

Table 19: Results of variant 9, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-1.17	-1.80	-2.42	-2.04	-2.34	-1.57	-1.08

Maximum [°C]	1.95	2.09	2.98	2.59	3.28	2.42	1.52
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Table 20: Results of variant 9, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.4	19.0	16.4	0.84	1.16	0.39	48.9	58.9	54.4	4.95	4.08	0.65
Front area high	13.5	19.7	16.0	2.11	2.29	0.52	53.2	57.3	55.6	2.23	1.60	0.19
Middle	11.5	17.0	14.3	2.41	2.33	0.43	59.9	62.9	61.5	1.61	1.32	0.03
Back side low	10.6	17.2	13.8	2.77	2.57	0.62	62.0	65.1	63.6	1.57	1.14	0.11
Back side high	9.6	19.1	14.3	3.88	3.70	0.83	57.1	66.3	61.7	4.35	4.19	0.54

5.10 Variant 10: Lowered soil temperature

In relation to the previous variant, this one focuses on lowering soil temperature from 13 to 12 °C. The effects are reversed compared to the previous variant: in summer stratification increases and in winter it decreases. Practically all temperatures drop and RH values rise.

In case global cooling would occur, this soil temperature might become reality. It is however a very long-term effect and the presence of the building will cause the soil temperature to also rise.

Table 21: Results of variant 10, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.64	-1.65	-1.66	-1.43	-1.52	-0.98	-0.82
Maximum [°C]	1.32	2.24	3.70	3.15	4.01	2.93	2.37

Table 22: Results of variant 10, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	14.7	17.9	15.7	0.80	0.98	0.28	49.4	60.1	55.2	5.33	4.40	0.65
Front area high	13.0	18.8	15.5	2.07	2.13	0.46	53.0	57.8	55.8	2.61	1.94	0.19
Middle	10.4	15.8	13.1	2.40	2.28	0.42	62.2	66.0	64.2	2.03	1.75	0.03
Back side low	9.4	15.9	12.6	2.76	2.55	0.62	64.9	68.8	66.9	1.96	1.85	0.10
Back side high	8.9	18.3	13.5	3.86	3.64	0.82	58.0	67.7	62.9	4.60	4.45	0.53

5.11 Variant 11: Extra mixing for stratification

The basic model estimates the total air exchange by either climate systems and/or low-oxygen systems. This variant is created to find out whether air mixing would be better if the amount of air is increased. Both combined systems extract air in the bottom corners of the building and introduce air at the top.

Table 23 shows that stratification is minimized on all positions in the repository, during the whole year. Table 24 shows a similar behavior: whether an increase or decrease is encountered, depends

on the position in the building. Top and bottom show opposite findings and more similar results. The extreme values are improved. The overall effect of this variant is beneficial and quite large.

Table 23: Results of variant 11, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.27	-0.69	-1.67	-1.47	-1.72	-0.83	-0.34
Maximum [°C]	0.78	1.34	3.10	2.69	3.48	1.54	1.09

Table 24: Results of variant 11, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	14.5	18.6	15.9	1.18	1.38	0.37	50.5	59.1	55.2	4.33	3.49	0.52
Front area high	13.4	19.1	15.7	1.94	2.07	0.47	52.7	57.8	55.7	2.77	2.02	0.25
Middle	11.1	16.4	13.7	2.31	2.22	0.41	61.0	64.4	62.8	1.81	1.50	0.03
Back side low	9.9	17.2	13.5	3.00	2.80	0.67	61.8	66.6	64.3	2.41	2.18	0.20
Back side high	9.6	18.5	13.9	3.64	3.44	0.79	57.9	66.9	62.4	4.31	4.14	0.50

5.12 Variant 12: Extra internal air mixing

Instead of air mixing by using the existing system for low-oxygen or climate control, also additional mixing can be achieved by using the robot. This variant researches the effect when horizontal and vertical airflow are increased by a factor of 4 (which will be a high number; in practice it will be lower).

Results are visible in table 25 and 26. First it needs to be noted that differences are small; much smaller than in the previous variant 11. Stratification is reduced in the middle, but not at the outer edges of the repository. Also short fluctuations in RH are larger.

It can be concluded that the result is not very beneficial, while additional energy use and wear of the robots are expected.

Table 25: Results of variant 12, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-0.90	-1.92	-2.03	-1.74	-1.91	-1.29	-1.03
Maximum [°C]	2.17	2.05	3.29	2.88	3.62	2.70	2.21

Table 26: Results of variant 12, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.0	18.4	16.0	0.83	1.07	0.33	47.8	61.0	54.8	6.39	5.49	0.98
Front area high	13.2	19.2	15.7	2.10	2.22	0.49	52.9	57.9	55.7	2.62	2.05	0.29
Middle	11.0	16.4	13.7	2.40	2.30	0.42	61.0	64.6	63.1	2.07	1.45	0.08



Back side low	10.0	16.5	13.2	2.72	2.52	0.60	62.2	68.7	65.3	2.81	3.11	0.43
Back side high	9.3	18.7	13.9	3.85	3.65	0.82	55.5	69.4	62.5	5.90	6.16	0.94

5.13 Variant 13: Reduced air tightness

For maintenance of robots doors are present in the building. Each corridor has its own door. In case these doors are not completely air tight, unwanted ventilation might take place. This variant uses a ventilation rate of 0.01 h^{-1} ; the whole repository space is therefor ventilated once per four days. This is 5 times higher than is the basic model. Moreover, ventilation does not take place directly (by air leakages in the repository area) but indirectly by the low-oxygen system or by transport of crates and pallets.

Important to note: cracks in doors can also cause draught, fungal growth, pests etc., so for multiple reasons it is important to prevent air leakages.

Stratification is increased. Fluctuations are larger, both in T and RH. Minimum values become lower and maximum values higher. The average T drops slightly, while average RH increases slightly. The effect of air tightness is considerable.

Table 27: Results of variant 13, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	-1.13	-2.11	-2.39	-1.95	-2.26	-1.50	-1.20
Maximum [°C]	2.21	2.06	3.38	2.88	3.68	2.69	2.18

Table 28: Results of variant 13, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	14.8	18.6	15.9	0.97	1.20	0.36	43.6	77.8	60.5	15.2	15.2	2.61
Front area high	12.8	19.4	15.5	2.34	2.43	0.54	49.5	73.7	61.6	11.2	10.6	1.88
Middle	10.2	16.6	13.5	2.81	2.66	0.50	55.2	84.1	69.9	12.5	12.1	2.53
Back side low	9.5	16.7	13.1	3.05	2.80	0.69	60.8	83.8	72.2	10.8	10.2	1.72
Back side high	8.6	18.9	13.7	4.24	3.99	0.91	61.1	76.8	69.1	7.21	6.58	1.21

5.14 Variant 14: Extra heat production robot

In Büron differences between estimated energy use and actual energy use are encountered. These differences are considerable: in Büron it seems 6 kW or energy use is always present, even when all systems are off. This amount of energy is dissipated into the top area of the repository and in the corridors.

The additional energy leads to a stratification which does not invert during winter. Even in winter, the top is always warmer than the bottom. The average temperature increases – dependent on

location – 0.8 to 2.0 °C. Fluctuations become somewhat smaller, especially the seasonal ones. In RH, most values drop; short fluctuations are almost identical.

Table 29: Results of variant 14, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BW corr	BW crate
Minimum [°C]	0.15	-0.36	-0.10	-0.13	-0.02	-0.14	-0.75
Maximum [°C]	3.36	3.59	5.34	4.54	5.68	4.32	4.13

Table 30: Results of variant 14, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.8	19.7	16.8	0.88	1.29	0.48	50.6	59.3	55.3	4.26	3.49	0.63
Front area high	15.0	21.5	17.5	2.15	2.41	0.57	51.1	53.8	52.7	1.44	0.99	0.19
Middle	12.9	18.5	15.7	2.42	2.36	0.43	58.0	59.6	59.0	0.97	0.65	0.03
Back side low	11.5	18.1	14.7	2.77	2.59	0.62	61.6	63.7	62.7	0.99	0.79	0.11
Back side high	12.1	21.7	16.7	3.89	3.75	0.84	51.1	59.2	55.1	3.78	3.64	0.53

It can be concluded that the total energy consumed by the robot system is a huge influence on the indoor climate. Also the speed of chemical decay of collections will rise. It is advised to look more closely to the robot's energy use and find ways to estimate it properly and/or reduce it.

5.15 Conclusions of first simulation round

The overview of all variants is displayed in table 31. This table describes each variant, sums up the effect (positive or negative) and also provides the impact (small to large) on the indoor climate. This table is used to assess all options and to optimize the building. Further on, some of these variants are combined into a new model.

Table 31: Results of the first round of simulations

Variant	Description	Effect	Impact
1	Soil settling	Minimal	Minimal
2	Lower roof absorption	Positive, if RH compensated for	Small
3	More insulation walls and roof	Positive	Fair
4	Less insulation walls and roof	Negative	Fair
5	Additional heating workspace	Positive, but 27 % extra energy use	Fair
6	Empty repository	Negative	Large
7	Low-oxygen system on	Positive, if well adjusted and mixed	Huge
8	Airflow by ingest	Negative but not avoidable	Fair
9	Raised soil temperature	Positive for RH	Small
10	Lowered soil temperature	Negative for RH	Small
11	Extra mixing for stratification	Positive	Fair



12	Extra internal air mixing	Negative	Small
13	Reduced air tightness	Negative	Large
14	Extra heat production robot	Negative for T, but RH seems better	Huge

Table 31 shows that additional insulation, less adsorption in the roof, a well controlled low-oxygen environment and additional air mixing all have beneficial effects. Next to that, an empty repository would be undesirable, also the air flow in between working area and repository is undesirable. Yet, the building will start out empty and some air flows simply are unavoidable.

Also these variants show that during a considerable amount of time some changes might occur which might need future attention. A changing ground temperature and settling of the soil are such effects. Finally, when over time the number of crates ingest changes, this will also change long term equilibrium. In future the systems used might be adjusted to cope accordingly.

The largest difference is caused by variant 14: the power consumption of the robot. This has a huge effect. It appears that the initial estimated power consumption (a mere 0.00016 W/m³ in normal use, thus leading to 8,5 W for this repository) is very far from the measured power consumption (6 kW or 6,000 W). This needs further research.

Incorrect assumptions can have a dramatic effect; simulations can be affected in such a way that predicted optimizations have even an opposite effect.

6 Büron measurement results

In Büron measurements are carried out. These consist of T and RH measurements (8 in top of the repository and 8 in the bottom) and measurements of the oxygen level. The accuracy of the sensors is not known; yet the RH values do not have any decimals.

Figure 17 shows temperature to follow the seasons more than in the previous simulations. This can be caused by the Swiss climate. Temperatures range between 8 °C in winter and 24 °C in summer. The stratification is apparent; this is about 0.1 °C in winter and 3.2 °C in summer.

RH shows a slow upward trend over the years, just as the simulations show. In winter RH is quite uniform, while in summer RH seems to differ at most 6 %RH between all measured positions. This seems to be caused by temperature differences alone.

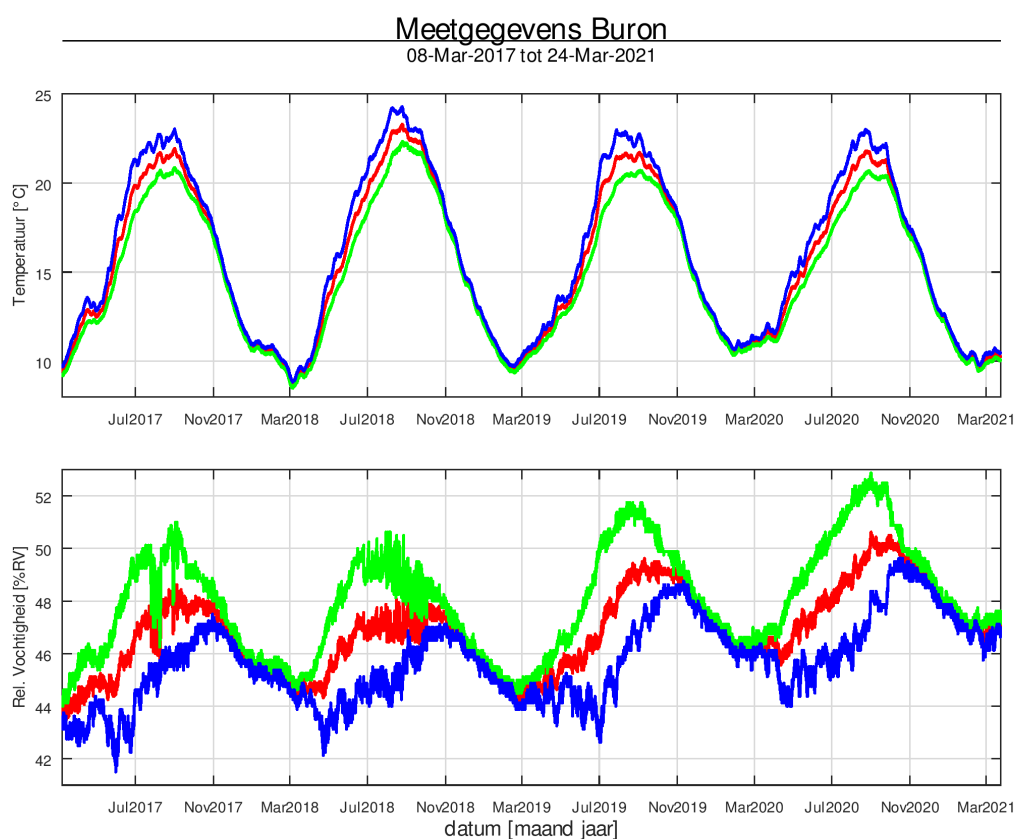


Figure 17: Average T and RH top (blue), bottom (green) and combined (red) in Büron

Figure 17 shows average values based on height: high in the repository 8 sensors are placed (blue), as are at the bottom (green). Figure 17 therefore shows averages of 8 sensors or 16 (top and bottom sensors combined, red).

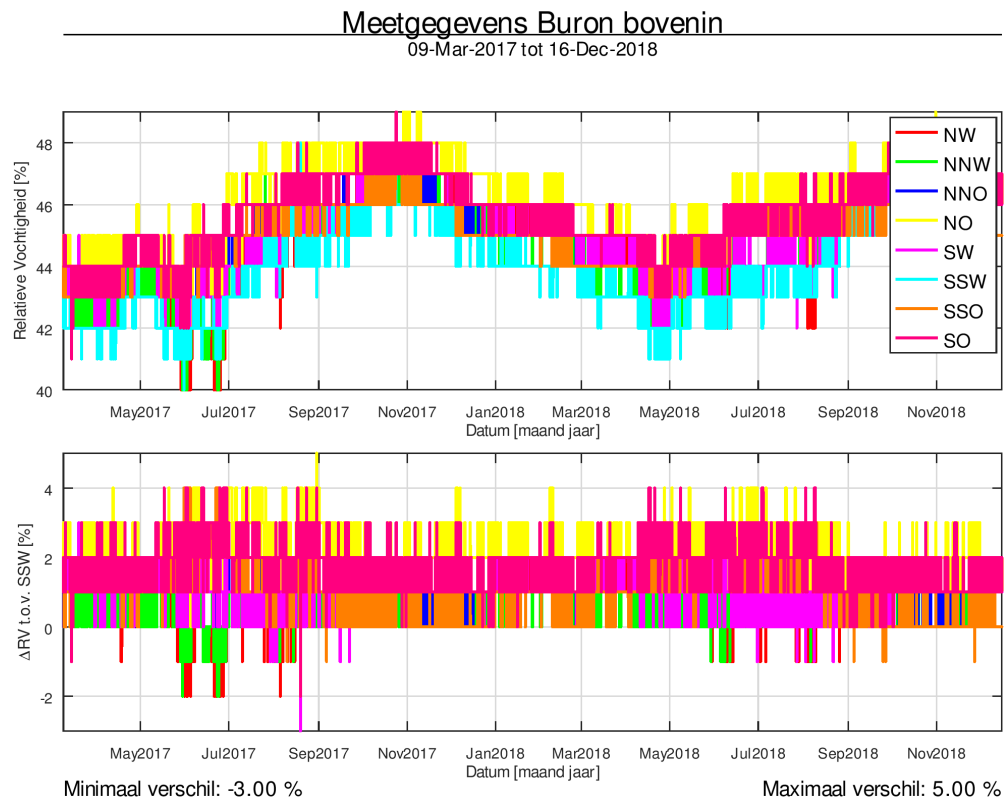


Figure 18: RH from 8 different sensors, top of the repository

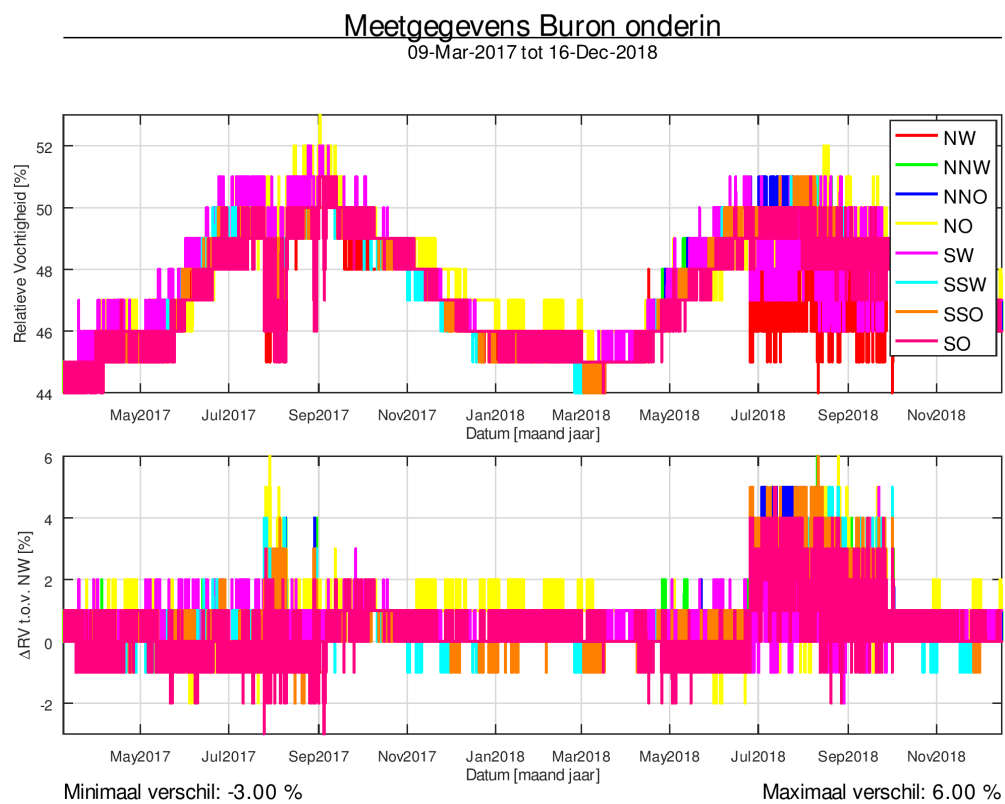


Figure 19: RH from 8 different sensors, bottom of the repository.

When comparing figures 18 and 19 it can be noticed that the RH scale differs 4 %RH. Usually a 4 %RH difference is noticed in between top and bottom. The difference in between sensors at a similar height is usually in between 3 and 6 %RH.

It is remarkable to see that during the summer of 2018, much larger differences are noticed at the bottom of the repository. It turns out that local dehumidifiers were used, because RH was considered too high. In 2019 and 2020 RH values were higher, but dehumidification cannot be discerned from the data.

Table 32 shows mathematical parameters of the indoor climate in Büron. Minimum and maximum temperatures are more extreme than simulation for the Dutch repository show, for all simulated variants. The average temperature is closest to the variant in which additional heat is produced (variant 14).

In terms of RH the average is much lower; this is caused by both the low-oxygen system (variant 7), but also because the Swiss climate differs from the Dutch climate (note: Büron is located about 500 m above sea level, while the Dutch repository is only a few meters above sea level).

Table 32: Results of Büron

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Top average	8.9	24.2	16.1	5.98	6.83	1.25	42.1	49.5	45.8	2.58	3.06	0.82
Total average	8.7	23.2	15.6	5.63	6.50	1.11	43.7	50.4	46.9	2.66	2.97	0.59
Bottom average	8.6	22.3	15.0	5.29	6.23	1.00	44.2	52.6	48.1	2.94	3.80	0.84

6.1 Air tightness and oxygen reduction

Büron supplied some numbers about oxygen reduction. On a daily basis, 520 m³ of pure nitrogen is added to the repository. When translated to the Dutch situation, the full repository is ventilated once every 100 days with pure nitrogen. When half of the volume is being taken in by shelves, robots and collection, the remaining air is refreshed once every 50 days. Pure nitrogen however is not what is exchanged.

When the above number is interpreted in another way, one could state: 520 m³ of nitrogen is needed to make up for all daily ventilation losses. A certain amount of air at 13 % oxygen is replaced by a similar amount of air at 20 % oxygen (outdoor air, or air that originates from the working area). In order to keep nitrogen levels at 87 % instead of 80 %, 520 m³ of nitrogen needs to be supplied. Every m³ of ventilation causes a 7 % loss of nitrogen which is 0.07 m³. Daily 520 m³ of nitrogen suppletion therefor matches a daily ventilation of 7,400 m³ using outdoor air. This would lead to a total ventilation rate of once every 7.2 days. When shelves, robot and collection are included, ventilation is once per 3.6 days. This seems far from air tight!

The effect on humidity can also be calculated: 520 m³ of nitrogen replaces 520 m³ of repository air which in most cases contains about 6 to 7 g/kg of absolute humidity. This represents a daily drying of 3.7 kg for the entire depot area.

6.2 Questions for Büron

The measurements lead to a number of questions which would be interesting:

- What could cause the large difference in energy use, between prediction and measurement, of the robot?
>> Robot does not switch off but stays in idle mode, power supplies remain on. Initial estimate was too low.
- Why were dehumidifiers used in summer 2018? From the data it looks like this was not repeated in later (more humid) years?
- How was dehumidification carried out?
 - What type of device was used?
 - How many devices were placed?
 - What was their position in the building?
 - Is the amount of moisture extracted known?
- Are there any drawbacks in routine use of the building and its robots?
- How did you manage to get airtight doors for robot maintenance?
- How many daily or weekly ingest are encountered and what is the future prediction?
- What changes, if any, did you make since the start of using the repository building?
- Could you explain more about the low-oxygen system:
 - Does it use overpressure?
 - Does it extract air and, if yes, from which part of the building?
 - Does it compensate for lack of any moisture in pure nitrogen?
 - Is the air fully mixed, with constant O₂ and N₂ levels at all positions?
 - What is the (daily or yearly) energy demand of the low-oxygen system?
- Did you use simulation beforehand, in the design process?
 - If so, how was this carried out?
 - Does the simulation match reality?
- Is the working area in some way controlled (T and/or RH)?
- What is the (estimated) average ground temperature in Büron?
- What would you do differently considering you are thinking of planning an extension to the current building?



7 Round 2: Combinations of variants

This chapter discusses the combination of previous variants. Also it focuses on paper behavior.

7.1 Realistic new basic model

The previous basic model is used, but it is enhanced with all the following combined:

- Less absorption of roof (variant 2)
- Low-oxygen system is on (variant 7)
- Ingest is set to normal routine when full (variant 8)
- Extra air mixing using the low-oxygen system, 0.1 times the air volume per hour (variant 11)
- High internal load because of robot energy use (variant 14)
- Slight modifications to internal air flow to compensate for middle area (in reality more corridors)

Tables 33 and 34 show the simulated results, just as previously. It can be seen that reversed stratification in winter is nearly non-existent. In summer, regular stratification is a bit lower near the edges of the building and higher in the middle.

Table 33: Results of new realistic basic model, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.28	0.07	-0.35	-0.42	-0.34	-0.24	-0.36
Maximum [°C]	2.38	2.16	4.66	3.86	5.04	2.52	2.05

Table 34: Results of new realistic basic model, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	19.8	16.8	1.33	1.72	0.50	42.2	52.4	47.4	4.94	4.65	0.47
Front area high	14.7	21.0	17.2	2.15	2.37	0.58	41.8	50.2	46.1	4.01	3.83	0.36
Middle	12.4	18.7	15.5	2.66	2.50	0.55	47.9	54.9	51.6	3.49	3.16	0.25
Back side low	10.8	19.2	15.0	3.38	3.07	0.83	48.3	56.1	52.5	3.93	3.43	0.33
Back side high	11.4	21.2	16.3	4.00	3.69	0.90	44.9	51.8	48.7	3.53	3.01	0.29

What is satisfying to see, is that this combination shows more similar results to the Büron measurements than any of the previous simulations. The average temperature differs only 0.2 °C, average RH is nearly 5 %RH lower in Büron. Seasonal RH differences and short RH fluctuations are within the same range.

Figure 20 shows an example of temperatures during a decade. As in figure 17 (measurements from Büron) it can be seen that during autumn and winter differences are reduced. The average is similar, but minimum and maximum are less extreme than in Büron.



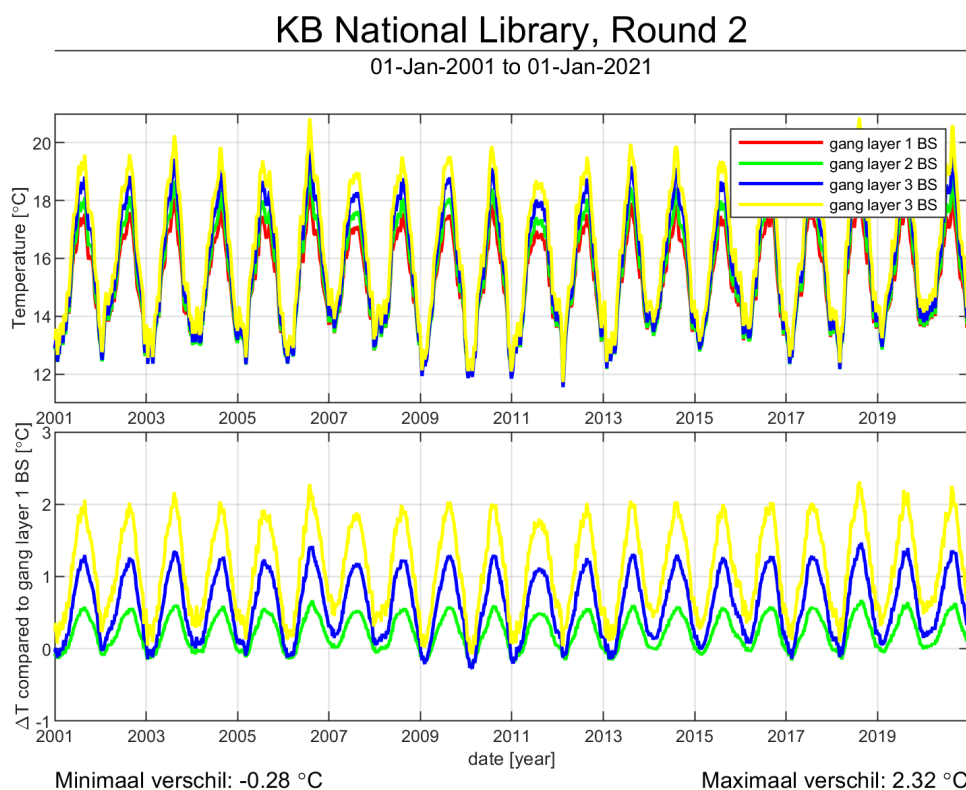


Figure 20: Temperature in one of the corridors in the repository and calculated differences (bottom)

7.2 Behavior of paper collections

This basic model is now used to assess equilibrium moisture content (EMC). Figure 21 provides a basic impression of the EMC which depends both on temperature and relative humidity. For this, the Hailwood-Horrobin equations are used to determine the equilibrium moisture content for all combinations of temperature and relative humidity. As can be seen in figure 21, the EMC slowly decreases when temperature rises. When humidity rises, also EMC rises but this is not linear. The EMC is most stable in between 40 and 60 %RH.

To make sure absorption and desorption are accounted for, the one calculated pane in figure 21 is transformed into 2 panes by multiplying with 0.97 for the absorption curve and with 1.03 for the desorption curve.

The calculation of EMC is done as follows:

- The initial EMC is calculated based on the first value of T and RH;
- For each following time step the new equilibrium is determined;
 - If the current EMC is within the absorption and desorption curve, the EMC does not change;
 - If the current EMC is below the absorption curve, the EMC slowly rises using a response time of 10 days;

- If the current EMC is above the desorption curve, the EMC slowly drops using a response time of 10 days;

This causes the EMC to be constant as changes in T and RH are small and slowly decreasing or increasing when changes become larger.

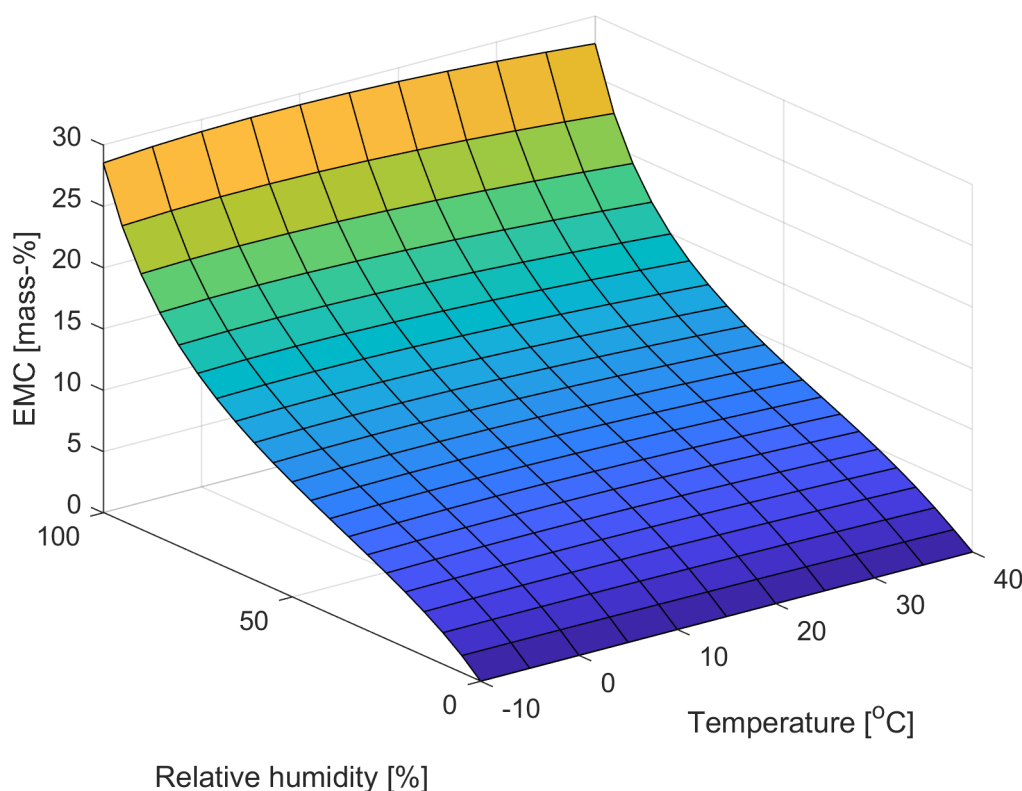


Figure 21: EMC as a function of both temperature and relative humidity. For temperature a linear relation is assumed, while RH and EMC have a relation according to the hygroscopic curve.

When EMC is calculated for the 5 positions in our depot, the following figure 22 can be made. On all 5 positions some seasonal changes in EMC are noticed: during each year EMC rises 0.3 to 0.5 mass percent during winter and drops 0.3 to 0.5 mass percent during summer. Also there seems to be a difference in between warmer areas in the repository (near working area and at the top) and colder areas (middle and at the bottom); this difference is about 0.8 mass percent.

For an empty repository the EMC can also be calculated. Now the yearly cycle in EMC is much larger: 0.9 mass percent. The average value is similar; also differences in between positions are in the same order of magnitude.

In order to compare to the current situation, also EMC is calculated based on measurements in the current repository. Locations M1A until M5A, M6D and M7D are assessed. The EMC is displayed in figure 24. The yearly EMC cycle depends on the location; it is in between 0.9 and 1,5 mass percent. The average value is comparable to the new repository.

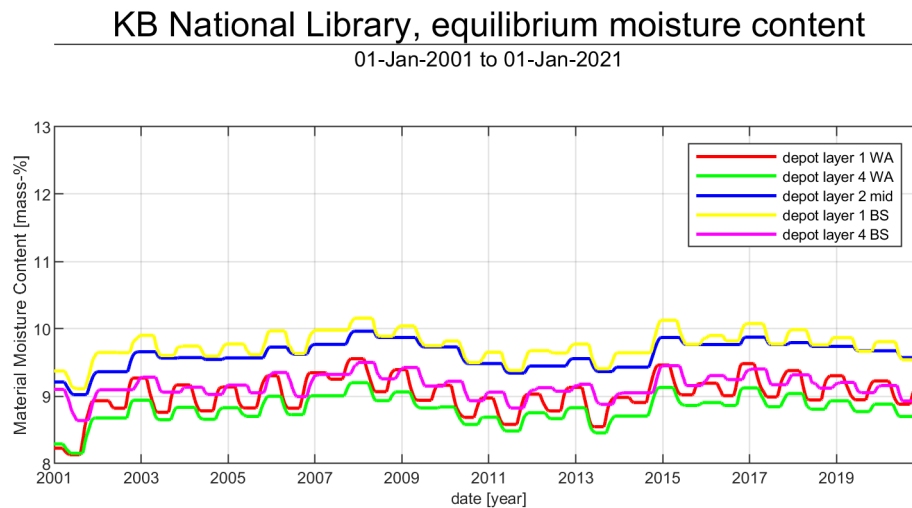


Figure 22: calculated EMC on 5 different positions in the repository, situation entirely filled

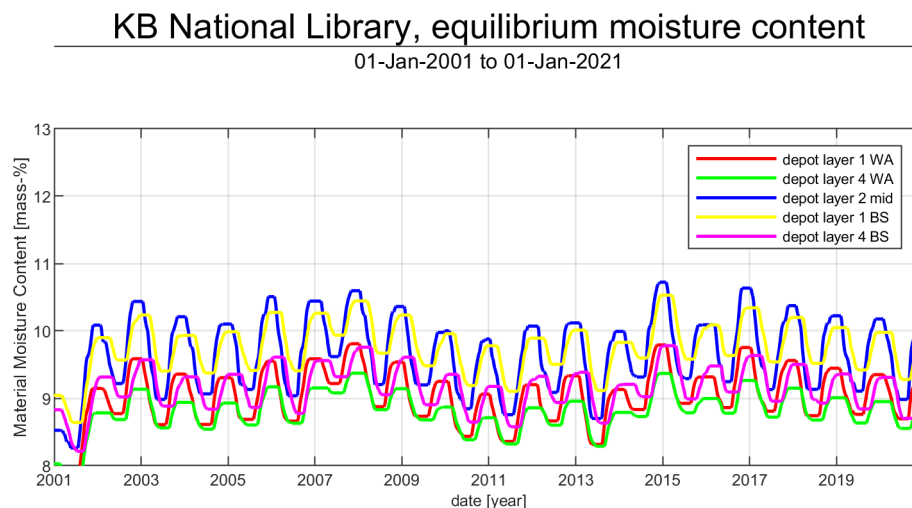


Figure 23: calculated EMC on 5 different positions in the repository, situation entirely empty

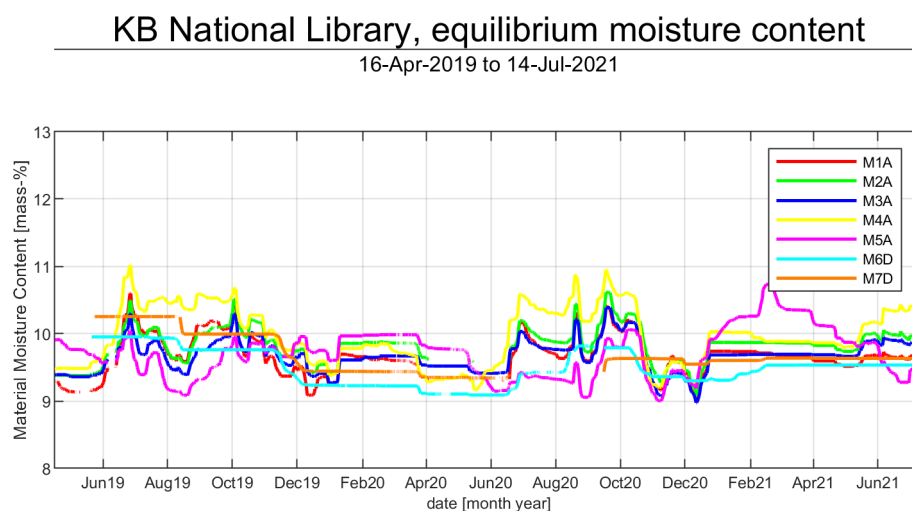


Figure 23: calculated EMC based on measurements in KB National Library

Although the average EMC is in between 9.5 and 10, some peaks can be seen especially in summer. Values slowly go up and reach close to 11 mass percent. The new repository provides for slightly drier conditions, while fluctuations are 5 times smaller. This is beneficial for safekeeping the objects for a longer period.

7.3 Variants

The following variants are calculated, based on the new basic model for round 2 (var2_1):

- Var2_2: Light construction (steel based instead of concrete based)
- Var2_3: Conditioning of working area (45 – 55 %RH)
- Var2_4: R-value to 20 m²K/W (for walls and roof)
- Dynamic façade
 - Var2_5: ventilated cavity when $T > 10\text{ °C}$ and $T_{\text{cavity}} > T_{\text{outside}}$
 - Var2_6: ventilated cavity when $T > 2\text{ °C}$ and $T_{\text{cavity}} > T_{\text{outside}}$
- Var2_7: Dynamic façade (2_5) and conditioning of working area (2_3)
- Var2_8: Insulation in between working area and repository
- Var2_9: Combination of conditioning working area, insulation and dynamic façade
- Var2_10: Less air exchange by clever crates control

7.3.1 Light construction (steel instead of concrete)

Currently the British Library is designing a new high-density storage building. The design differs considerably from the design of Büron. The construction used is a lightweight building using a steel framework and light paneling. The model is therefor used to check what the indoor climate would be when light constructions are used instead of concrete. Less thermal mass would lead to less temperature stability, one would expect.

Table 35: Results of new variant lightweight construction, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	0.14	-0.55	-0.85	-0.95	-0.65	-0.46	-0.47
Maximum [°C]	2.36	2.94	5.43	4.70	5.54	3.61	2.51

Table 36: Results of new variant lightweight construction, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.6	20.5	17.0	1.11	1.68	0.64	40.8	52.2	46.6	5.45	5.15	0.55
Front area high	14.4	21.5	17.3	2.24	2.56	0.74	41.3	50.2	45.8	4.23	4.06	0.40
Middle	12.1	19.0	15.5	2.76	2.64	0.65	47.6	55.2	51.6	3.81	3.43	0.29
Back side low	10.1	19.4	14.9	3.44	3.17	1.02	47.3	58.3	53.1	5.28	4.63	0.57
Back side high	10.9	21.8	16.3	4.13	3.88	1.12	43.6	52.9	48.6	4.52	3.94	0.48

Table 35 and 36 describe the differences between the basic model and the lightweight model. Except for positions very close to the heated working area, all results are slightly worse. Stratification is higher, minimum values are lower, maximum values are higher and changes – either slow or fast – are larger, both in temperature and relative humidity. The differences however are small.

It seems that a lightweight construction can also offer a good solution. The main point of attention comes from other fields, such as fire safety and the actual air tightness over many years. Concrete seems to be a more stable and time proof solution.

7.3.2 Conditioning of the working area RH

The working area is connected directly to the depot area; retrieving and returning books will enforce an air flow in between working area and depot. While the RH in the working area was free floating in the basic model, now the RH is kept in between 45 and 55 %RH by using a small air handling system in this working area.

Table 37: Results of new variant conditioning of working area, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.28	0.07	-0.35	-0.42	-0.34	-0.24	-0.36
Maximum [°C]	2.38	2.16	4.66	3.86	5.04	2.52	2.05

Table 38: Results of new variant conditioning of working area, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	19.8	16.8	1.33	1.72	0.50	42.1	49.9	46.1	3.77	3.54	0.38
Front area high	14.7	21.0	17.2	2.15	2.37	0.58	41.8	47.7	44.8	2.80	2.72	0.27
Middle	12.4	18.7	15.5	2.66	2.50	0.55	47.8	52.4	50.2	2.25	2.11	0.17
Back side low	10.8	19.2	15.1	3.38	3.07	0.83	48.4	53.4	51.0	2.49	2.21	0.22
Back side high	11.4	21.2	16.3	4.00	3.69	0.90	44.8	49.5	47.3	2.33	2.07	0.23

Tables 37 and 38 show that for temperature no differences are encountered. For relative humidity, nearly all values are lower. The average RH is about 1.5 %RH lower, while maximum values are 2.5 %RH lower. Also fluctuations are smaller, both seasonal and short.

It can be concluded that controlling the RH in the working area is beneficial for the RH within the repository. But it must also be stated that this requires additional effort (and energy): 7 kg/hour humidification is needed and 14 kg/hour dehumidification; on average 5,370 kg humidification is needed each year and 11,000 kg additional dehumidification. Moreover, controlling the RH can also be optimized by specifying a proper setpoint strategy that matches the repository needs.

7.3.3 Extreme insulation

Many examples of nearly passive storage buildings can be found that use extreme insulation thicknesses. To calculate the effect on the KB repository, the insulation value is increased to 20 m²K/W. This is more than twice the original value.

To obtain the desired relative humidity, the amount of dehumidification (by the low oxygen system) needed to be reduced by 25 %.

Table 39: Results of new variant extreme insulation, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.28	0.48	0.61	0.56	0.45	0.17	-0.01
Maximum [°C]	1.41	2.02	4.25	3.51	4.60	2.33	2.00

Table 40: Results of new variant extreme insulation, on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	16.3	19.0	17.1	0.69	0.96	0.28	43.7	53.6	48.8	4.81	4.50	0.44
Front area high	16.6	20.1	17.9	1.12	1.31	0.30	42.0	50.9	46.6	4.31	4.01	0.38
Middle	14.8	18.0	16.3	1.36	1.33	0.27	47.6	55.3	51.6	3.84	3.52	0.29
Back side low	14.0	18.2	16.1	1.73	1.62	0.39	47.4	56.3	52.1	4.40	3.96	0.38
Back side high	15.2	20.2	17.6	2.07	1.98	0.43	43.1	51.0	47.4	3.88	3.48	0.33

Table 39 and 40 show that by using additional insulation, the stratification is reduced but is always present (it does not go to nearly zero in winter / spring).

All minimum temperatures rise, while all maximum temperatures drop. On average temperature rises by 0.8 °C, due to the influence on internal heat sources. Short and long term fluctuations are nearly half their original values.

In terms of RH, nothing much happens with the average values or with minimum and maximum. Differences are small and can go either up or down, depending on position. Seasonal and short fluctuations increase about 10 %, except for very close to the working area.

7.3.4 A dynamic façade

A dynamic façade is a façade with a variable insulation value. This is provided by using a cavity which can be either closed or open. When the cavity is closed, the thermal insulation of the outer construction part is fully used. With an open cavity, additional ventilation of cavity air occurs thus shortening the thermal insulation; the effective insulation value decreases. The outdoor climate is allowed to pass through the cavity.

In this simulation, the air cavity is ventilated when 2 criteria are met:

- An outdoor air temperature of 10 °C or above
- An outdoor air temperature which is lower than the cavity air temperature

These conditions lead to a 'free cooling' effect of the cavity air. The conditions are chosen in such a way that the depot is not heated too much (insulation is used when outdoor temperature is higher

than indoor temperature in the cavity) and not cooled too much (insulation is used when outdoor conditions are below 10 °C). It turns out, using these conditions, that the insulation is bypassed 32 % of time.

In practice the cavity will open during the night when air temperatures drop while cavity temperature is still high. This occurs in summer, but also during parts of spring and autumn.

Table 41: Results of new variant dynamic façade, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.10	-0.20	-0.92	-0.79	-0.98	-0.36	-1.82
Maximum [°C]	2.49	2.13	4.69	3.66	4.94	2.30	1.94

Table 42: Results of new variant dynamic façade on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	14.6	20.2	16.2	1.38	2.22	0.67	40.5	50.7	45.7	4.95	4.61	0.49
Front area high	13.9	21.3	16.4	2.13	3.06	0.80	40.9	49.2	45.2	4.04	3.77	0.36
Middle	11.5	19.5	14.4	2.63	3.62	0.89	47.7	54.8	51.5	3.66	3.11	0.26
Back side low	10.4	21.3	14.0	3.02	4.61	1.53	48.0	56.5	52.5	4.20	3.68	0.43
Back side high	10.6	22.0	14.7	3.50	4.92	1.41	45.8	53.9	50.1	4.00	3.50	0.39

Table 41 and 42 show that stratification in summer decreases a little, while it increases in winter. The total temperature drop is about 1.1 °C. Minimum temperature values go down about 0.4 to 1.0 °C, while maximum values rise 0.3 to 0.8 °C. Because of the free cooling effect that is used mainly during summer evenings, seasonal changes become somewhat asymmetrical: the winter drop in temperature becomes smaller, while the summer rise becomes higher. This has to do with the changed average: the average becomes much lower, while minimum and maximum do not change as much as the average.

In terms of relative humidity changes are small. The changes are only 0.1 to 1.5 %RH. Also here seasonal changes show increased asymmetric values.

The value of 10 °C is chosen because it is the average outdoor temperature in The Netherlands. But it can be any value. To make the result more extreme, the conditions for ‘free cooling’ of the cavity can be increased to for example:

- An outdoor air temperature of 2 °C or above
- An outdoor air temperature which is lower than the cavity air temperature

Now, about 65 % of time the insulation is bypassed. Cooling of the cavity, while bypassing the insulation occurs larger parts of the day (evening, night and morning) and also during larger parts of autumn and spring, even during mild periods in winter. Much more dehumidification is needed, however.

Table 43 and 44 show similar but more extreme results as previously: the average repository temperature drops 1.6 °C. Temperature is less stable, showing increased seasonal and short



fluctuations. On most positions RH goes down and seasonal fluctuations are smaller. Short fluctuations however go up.

Table 43: Results of new variant dynamic façade, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.10	-0.87	-2.29	-1.56	-2.42	-1.28	-1.82
Maximum [°C]	3.31	2.13	4.69	3.66	4.94	2.30	3.44

Table 44: Results of new variant dynamic façade on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	13.3	20.2	16.0	2.22	2.43	0.77	38.6	49.2	44.1	5.22	4.74	0.52
Front area high	12.1	21.3	16.0	3.39	3.37	0.94	39.6	47.9	43.9	4.00	3.72	0.37
Middle	8.5	19.5	13.9	4.67	4.12	1.16	47.2	53.5	50.6	3.25	2.79	0.26
Back side low	5.5	21.3	13.2	6.17	5.36	2.05	48.0	55.9	52.2	3.86	3.32	0.46
Back side high	6.2	22.0	13.9	6.46	5.65	1.86	45.6	53.3	49.8	3.79	3.35	0.44

7.3.5 Wall insulation between working area and repository

To lower chemical degradation, the average temperature of the repository needs to be lowered. This can also be achieved by adding insulation in between working area (which is heated) and repository. The same insulation thickness as in the outer walls is used, so an Rc-value of 8 m²K/W.

Table 45 and 46 show that stratification increases, but differences are very small. Only very close to the working area a large difference is noted: now the wall does not work as a heating device, thus minimizing the upward flow of warmer air.

The average temperature drops 0.3 °C, which is a small difference. The variation in temperature based on position decreases. Minimum and maximum temperatures drop, but fluctuations in temperature rise a bit.

Table 45: Results of new variant inner insulation, stratification

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.48	-0.26	-1.03	-0.88	-1.14	-0.43	-0.43
Maximum [°C]	1.49	2.29	4.73	3.91	5.02	2.53	2.06

Table 46: Results of new variant inner insulation on 5 locations

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	12.7	18.8	15.6	2.57	2.41	0.53	46.5	54.9	50.9	4.08	3.82	0.36
Front area high	12.2	20.6	16.3	3.59	3.33	0.68	45.4	51.4	48.5	2.91	2.74	0.23



Middle	11.7	18.6	15.2	3.09	2.79	0.58	48.9	55.7	52.5	3.37	3.07	0.25
Back side low	10.3	19.2	14.8	3.74	3.30	0.83	49.2	56.8	53.2	3.78	3.35	0.32
Back side high	10.5	21.1	15.9	4.57	4.09	0.93	46.2	52.5	49.7	3.23	2.72	0.27

For relative humidity, all values go up: minimum, maximum and average. The largest rise occurs close to the working area, while further away from it, differences are small. Seasonal and short fluctuations drop a bit.

The influence of the inner wall is not that large. The effect of insulation is much smaller than the effect of dynamic insulation in the walls. Apparently the influence through interzonal air flow is much larger than the influence of heat conduction through the inner wall.

7.3.6 Combination of dynamic façade and working area conditioning

It seems that a dynamic façade is a good solution, because it decreases average temperature and therefore reduces chemical degradation. Conditioning relative humidity in the working areas decreases relative humidity in the repository area. Both can be a good combination; this is investigated here.

Table 47: Results of new variant with combination

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.10	-0.20	-0.92	-0.79	-0.98	-0.36	-1.82
Maximum [°C]	2.49	2.13	4.69	3.66	4.94	2.30	1.94

Table 48: Results of new variant with combination

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	14.6	20.2	16.2	1.38	2.22	0.67	42.0	50.0	46.0	3.79	3.54	0.41
Front area high	13.9	21.3	16.4	2.13	3.06	0.80	42.5	48.3	45.4	2.80	2.66	0.27
Middle	11.5	19.5	14.4	2.63	3.62	0.89	49.3	53.9	51.7	2.37	2.04	0.19
Back side low	10.4	21.3	14.0	3.02	4.61	1.53	49.8	55.5	52.8	2.76	2.51	0.37
Back side high	10.6	22.0	14.7	3.50	4.92	1.41	47.1	53.0	50.4	2.70	2.53	0.36

Tables 47 and 48 show that summer stratification decreases and winter stratification increases. On average, the repository is 1.1 °C cooler, while the average RH is 0.1 %RH higher at 51.7 %RH. Seasonal changes in temperature are a bit higher and asymmetrical. In terms of RH seasonal changes are smaller, while also most short fluctuations are smaller.

7.3.7 Combination of conditioning working area, dynamic façade and insulated inner wall

When also the inner wall (in between working area and repository) is insulated, energy can be saved and the average temperature in the repository is expected to drop.

Table 49: Results of new variant with conditioned working area, dynamic façade and insulated wall

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.57	-0.19	-1.34	-1.15	-1.45	-0.37	-1.71
Maximum [°C]	1.46	2.12	4.65	3.64	4.81	2.23	1.76

Table 50: Results of new variant with conditioned working area, dynamic façade and insulated wall

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	11.9	19.5	14.7	2.41	3.31	0.83	47.6	53.2	50.5	2.71	2.48	0.25
Front area high	12.0	20.8	15.3	2.88	3.93	0.89	46.5	50.5	48.6	2.04	1.83	0.16
Middle	11.1	19.5	14.2	2.74	3.82	0.90	50.1	54.7	52.6	2.35	2.02	0.19
Back side low	9.9	21.3	13.8	3.21	4.78	1.53	50.5	55.9	53.3	2.60	2.37	0.36
Back side high	9.8	22.2	14.3	3.71	5.25	1.51	48.1	54.0	51.5	2.65	2.43	0.38

Tables 49 and 50 show that the average indoor temperature drops an additional 0.2 °C. The effect is largest close to the working area, but is still noticed at the back as well.

7.3.8 Less air exchange by clever crates control

The basic model is also tested for when crates are collated and transported in batches from working area to repository and vice versa. This limits the air exchange: an air lock can be made to prevent much air exchange.

Table 51 shows only minimal differences. Table 52 shows minimal differences as far as temperature is concerned. For RH, a 10 % drop in all fluctuations is noticed. The average, minimum and maximum values increase slightly, but less dehumidification by the air handling system is needed. The repository seems more airtight.

Table 51: Results of new variant with smart insertion of crates

	WA pallet	WA corr	M pallet	M corr	M crate	BS corr	BS crate
Minimum [°C]	-0.28	0.06	-0.36	-0.43	-0.35	-0.24	-0.36
Maximum [°C]	2.39	2.16	4.66	3.86	5.04	2.52	2.05

Table 52: Results of new variant with smart insertion of crates

	Temperature [°C]						Relative Humidity [%RH]					
	Min	Max	Av	S-	S+	Short	Min	Max	Av	S-	S+	Short
Front area low	15.1	19.8	16.8	1.34	1.72	0.50	43.3	52.7	48.2	4.57	4.26	0.43
Front area high	14.6	21.0	17.2	2.15	2.38	0.58	43.0	50.5	46.8	3.60	3.43	0.32
Middle	12.4	18.7	15.5	2.66	2.51	0.55	49.1	55.3	52.4	3.08	2.78	0.22
Back side low	10.8	19.2	15.1	3.38	3.07	0.83	49.7	56.5	53.3	3.46	3.01	0.28
Back side high	11.4	21.2	16.3	4.01	3.70	0.90	46.0	52.3	49.4	3.17	2.75	0.27



7.3.9 Energy requirements

Also the energy need for the various variants is calculated and displayed in table 53.

In terms of energy, the extremely insulated variant is beneficial: 20 % less heating capacity is needed and also dehumidification (by low oxygen) is reduced by 25 %. About 30 % is saved on annual heating costs and 35 % on dehumidification.

Both lightweight construction and dynamic façade with extreme settings require more heating power and energy.

Insulating the inner wall does minimize the heating power, but the total energy used is only 10 % lower.

Reducing the amount of air has a positive effect on the use of dehumidification and on the efficiency of the oxygen reducing system.

Table 53: Energy requirements for round 2 simulations

Variant	Capacity needed			Yearly usage		
	Heating	Humidification	Dehumidification	Heating	Humidification	Dehumidification Or dilution*
New basic	25 kW	-	0.16 kg/h*	69.9 MWh	-	1,403 kg*
Lightweight	30 kW	-	0.16 kg/h*	75.0 MWh	-	1,403 kg*
Conditioning	25 kW	7 kg/h	14 + 0.16 kg/h	69.9 MWh	5,370 kg	12,448 kg
Extreme insul.	20 kW	-	0.12 kg/h*	49.0 MWh	-	1,052 kg*
Dynamic façade	25 kW	-	0.21 kg/h*	77.0 MWh	-	1,824 kg*
Dynamic faç. 2	30 kW	-	0.24 kg/h*	79.9 MWh	-	2,104 kg*
Inner insulation	20 kW	-	0.16 kg/h*	63,3 MWh		1,403 kg*
Combination	25 kW	7 kg/h	13 + 0.16 kg/h	77.0 MWh	5,415 kg	12,693 kg
Dyn+Cond+ins	25 kW	7 kg/h	13 + 0.16 kg/h	64.6 MWh	5,510 kg	12,633 kg
Crate control	25 kW	-	0.12 kg/h	69.9 MWh	-	1,052 kg*

* = assumed dehumidification by dilution, caused by low oxygen system

8 Conclusions

8.1 Goal

The main goal is to passively store the physical collection of the KB National Library in a new repository. This is done by following the seasons in terms of temperature, in which the average yearly temperature is around or below 15 °C. Temperature has a minimum value of 10 °C or above and a maximum value of 22 °C or below. Relative humidity needs to be in between a minimum of 40 %RH and a maximum of 55 %RH.

Allowed seasonal changes can be as large as 5 %RH change in relative humidity per 30 days and 2 °C in temperature per 30 days. Short fluctuations need to be small.

Compared to the current situation, chemical degradation will be much lower. An increase in lifetime expectancy of at least 60 % seems possible. Risks on mechanical and biological degradation will also be minimized.

8.2 Starting point

Starting point is the repository in Büron, Switzerland. This repository has very few climate systems and has a high-density storage. Both build-up of the constructions and use of an automated (robotized) retrieval system are used. All physical collections of KB National Library are being put in this new repository, including special collections, art collections and various other objects. In terms of dimensions the building is already adapted to fit the KB wishes and collections.

8.3 Method

In this report, simulation software is used to calculate the indoor climate of the new repository based on the outdoor climate at the building site. Various versions of the Büron situation were assessed, leading to milestones and points of further attention for the design of the building. In a future report, the model is also used for determining the best collection logistics and to find out what an actual book experiences.

8.4 Milestones

- The repository part of the building does not need an Rc value higher than 8 m²K/W. This will minimize seasonal fluctuations enough. More insulation will lead to a higher average indoor temperature, which is not wanted.
- The robots lead to heat production within the repository. Measurements in Büron show that this has a significant negative impact on the average temperature (it rises more than 2.0 °C). Design of and choice for a type of robot is vital.
- Some temperature stratification in the repository will occur; it is sufficiently low in winter but can be significant in summer (several °C). It is advised to reduce stratification to a maximum of 3 °C; a solution is needed to create additional air mixing.



- For fire safety a low oxygen system will be installed. This system needs to cater for a good mixing of internal air. Moreover, since this is an air handling system and more mixing is needed, it can also be used to reduce stratification. Air needs to be supplied to the top level of the repository and extracted in at least all four corners at floor level.
- At some point dehumidification may be needed (initially: excess moisture from constructing, in the long run: because of the equilibrium with the Dutch outdoor climate); it would be advisable to reserve some space for additional dehumidification within the recirculation system (in terms of amount of air flow and space and energy needed for a small mobile dehumidifier).
- In between office area and repository an inner wall is placed. The effect of insulation of this inner wall and the effect of controlling temperature and RH near the picking stations is very minor compared to the impact of air flow in between both zones. When a good solution can be found to minimize air flow, this would be preferred to all other solutions.
- The repository may be built using concrete or using a lighter system. Thermal buffering of concrete is marginal when compared to thermal buffering of the collections (that represent a very large thermal mass). Only in case of an empty building concrete has a positive effect. When a dynamic façade is chosen to reduce the average indoor temperature, some thermal mass is needed within this dynamic façade.
- A dynamic façade may be used to reduce the average temperature. However, the best solution would be to reduce internal heat gains (by the robots), so a much simpler and cheaper façade can be used.
- Highest priority is to construct the repository as airtight as possible. Doors and service hatches for the robots need to be constructed without air leakages. Also transporting containers in between repository and picking stations deserves utmost attention. A smart system, e.g. an air lock, will reduce the effort needed for the low oxygen system and will also reduce fluctuations and lower the average temperature.
- Facades and roof need to have a light color to be able to reflect as much solar radiation as possible (both visible, infrared and ultraviolet). It minimizes the generation of heat at the building envelope, which will also reach the repository. Additionally, also shading can be used by placing solar panels on top of the roof (note: efficiency of solar panels increases when temperature is kept low; even with the use of solar panels a light roof is still advised).
- The repository will be built on an artificial mound. The effect of subsidence, thus creating an air gap in between ground floor and soil, is marginal. It has virtually no effect on the indoor climate.

8.5 Wishlist for the robot(s)

- As little as possible heat production
- Placement of power transformers outside the repository when possible
- Possibility to completely shut off robots when not needed
- Smart method of transferring containers in between repository and picking stations
- Note: the use of robots at KB National Library is different from the use in robotized commercial storage buildings: the new repository will be filled with empty containers first



(3666 a day during 3 months). During the ingest period, which lasts 2 years, on average 371 empty containers a day will be swapped for containers filled with books. On a yearly basis about 75.000 containers will be accessed, resulting in 300 containers each day. Because of the slow rate of filling, after 6 months 100 containers will be accessed, increasing to 200 after 12 months and 300 after 24 months.

8.6 Wishlist for the building

- Systems for low oxygen should not be placed in the repository but in the working area (on behalf of reducing risks for the collection and for routing of maintenance staff)
- The system for recirculation of repository air also needs to inject additional nitrogen to make sure oxygen levels remain around 13 %
- Ventilation of the repository is unwanted, but recirculation is vital to minimize stratification
- A slight overpressure of the repository is wished for, realized by adding nitrogen
- To be able to cope with a higher relative humidity, the recirculation system needs to be designed in such a way that a simple mobile dehumidification device can be placed and powered within the system
- Air tightness of the repository has the utmost priority
- Also the air blockage in between repository and picking stations has high priority
- Picking station require another (cooler) indoor climate than offices. The indoor climate at the picking stations must be controlled separately from the offices
- Monitoring of the indoor climate (temperature and relative humidity) in the repository at various positions (at least 27: in front – at the middle – at the back; left – middle – right and bottom – middle – top) is desired (directly after completing the construction of the racks)