Naturally Ventilated Theatre

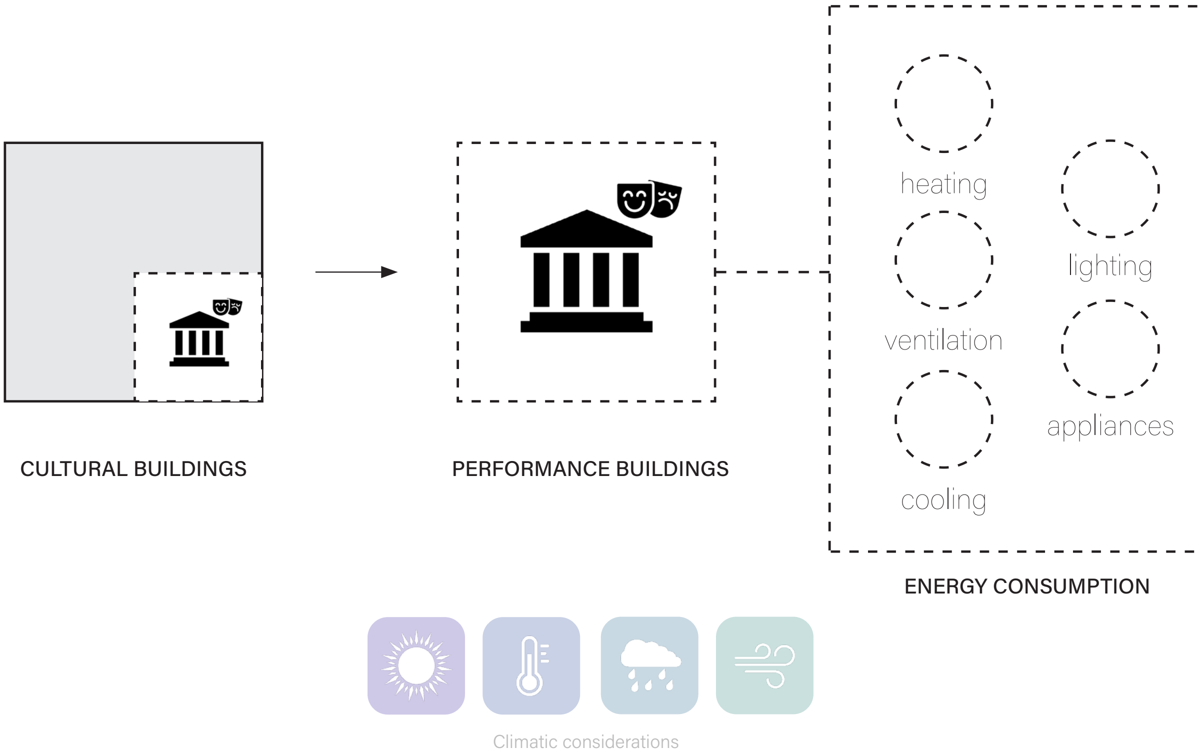
An approach to naturally ventilate a theatre in Central European Climate using the stack- and solar chimney effect

Research Book

P2

Architectural Engineering Graduation Studio
Mats Kolmas
4562135

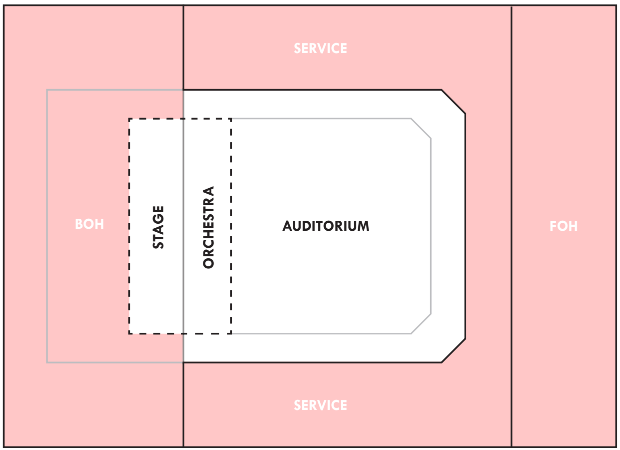
PRELIMINARY RESEARCH



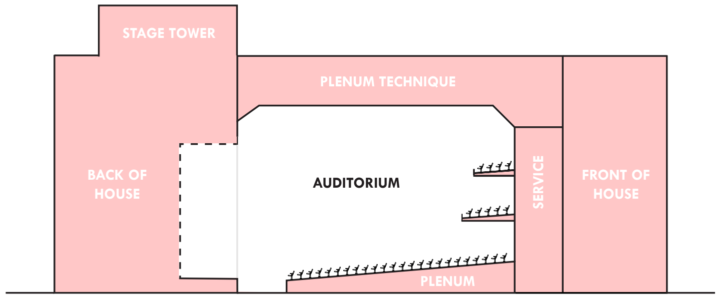
NATURAL VENTILATION OF A THEATRE HALL

In Central European Climate

ventilation cooling heating



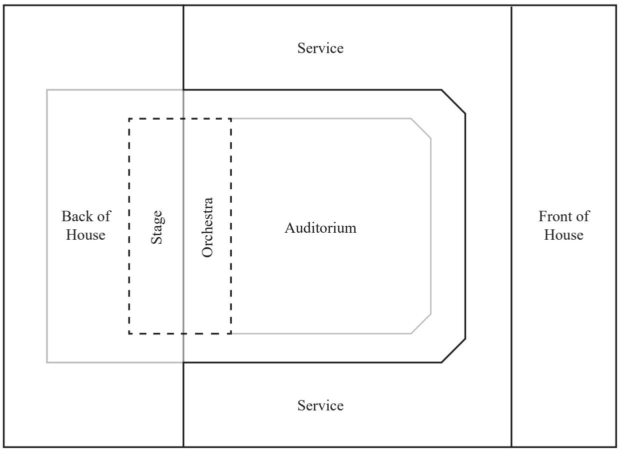
PLAN

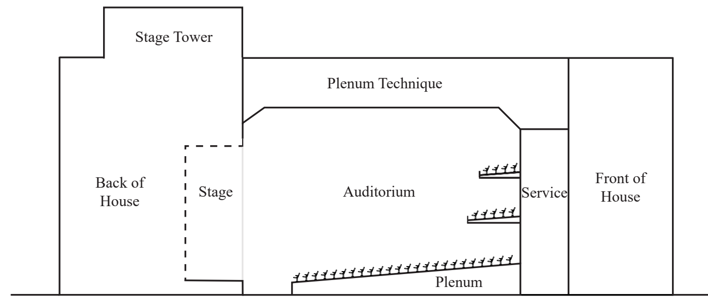


SECTION

NORMAL THEATRE LAYOUT

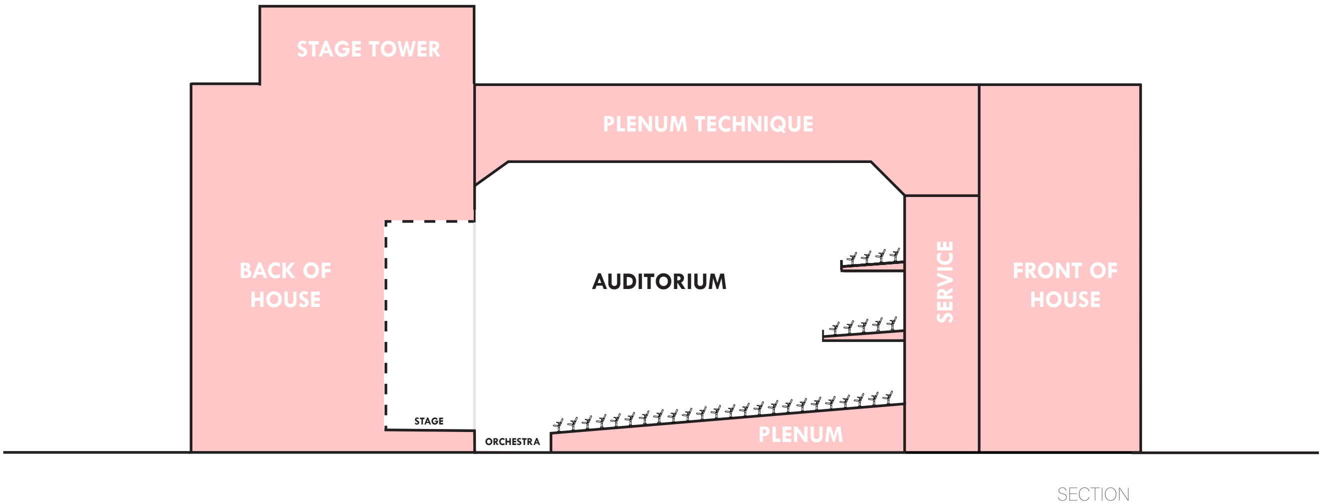
PROGRAM	CAPACITY	AREA	HEIGHT	VOLUME
CONCERTS, OPERAS, THEATRE	1.200 PEOPLE	1.350 M^2	13.5 METER	18.225 M^2





NORMAL THEATRE LAYOUT

PROGRAM	CAPACITY	AREA	HEIGHT	VOLUME
CONCERTS, OPERAS, THEATRE	1.200 PEOPLE	1.350 M^2	13.5 METER	18.225 M^2



NORMAL THEATRE LAYOUT

PROGRAM
CONCERTS, OPERAS, THEATRE

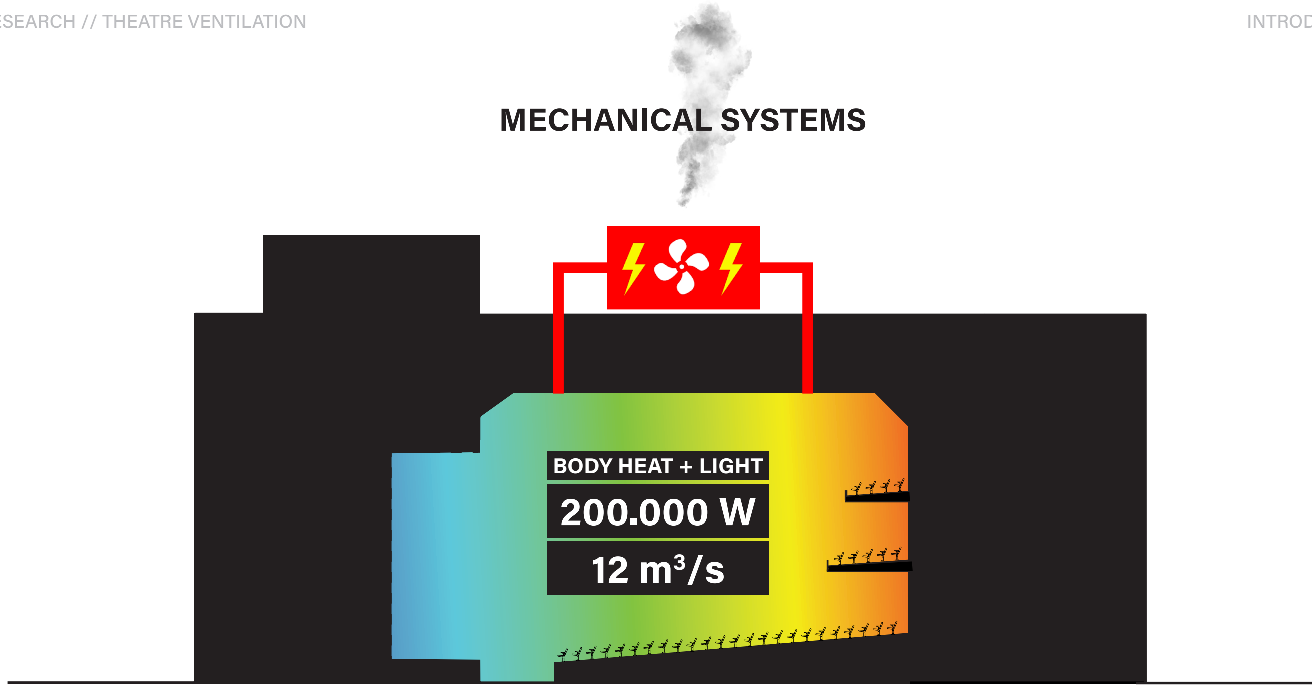
CAPACITY
1.200 PEOPLE

AREA
1.350 M^2

HEIGHT
13.5 METER

VOLUME
18.225 M^2

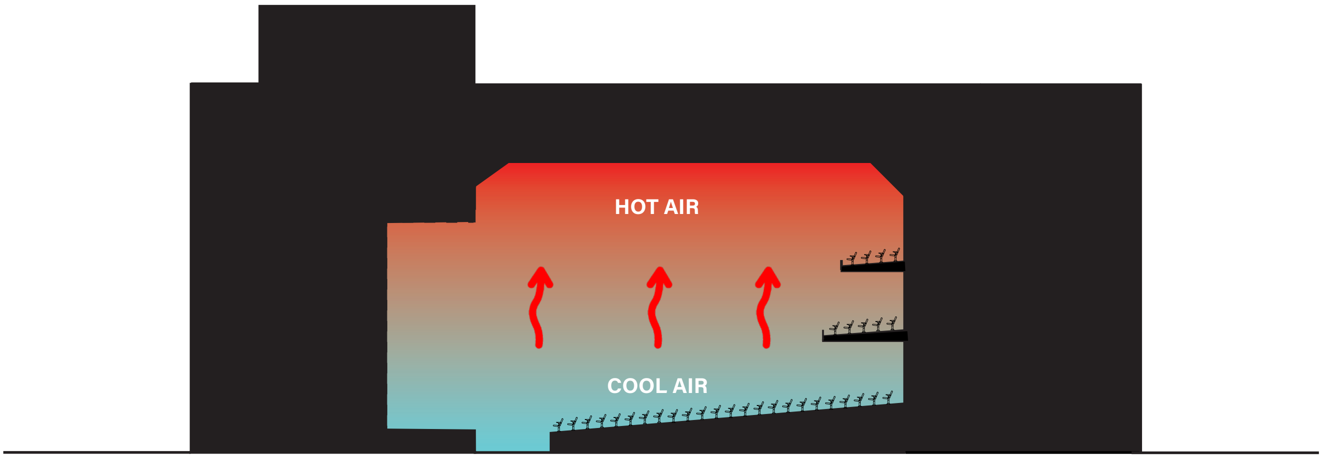
MECHANICAL SYSTEMS



CURRENT SITUATION

The mechanical supply and extraction of air in a theatre.
Placed on the roof actively using unnecessary energy for human comfort

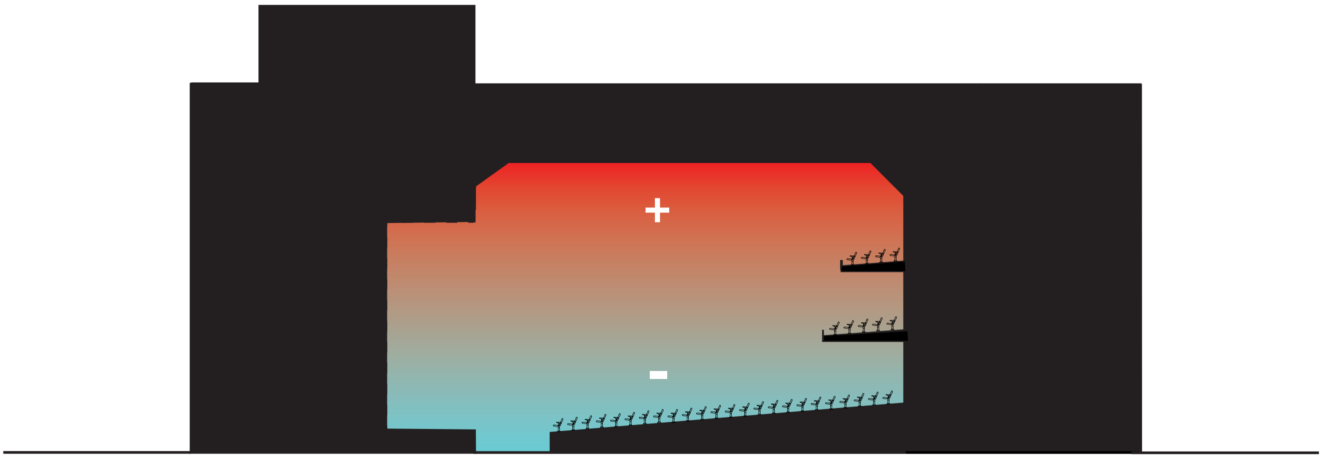
NATURAL VENTILATION BY BUOYANCY



PROPOSED METHOD

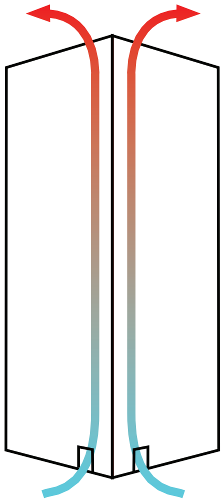
Using natural ventilation caused by buoyancy due to heat rise and create of circulation

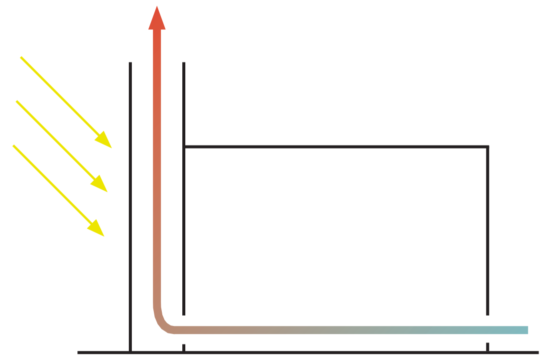
NATURAL VENTILATION BY BUOYANCY



PROPOSED METHOD

Using natural ventilation caused by buoyancy due to heat rise and create of circulation



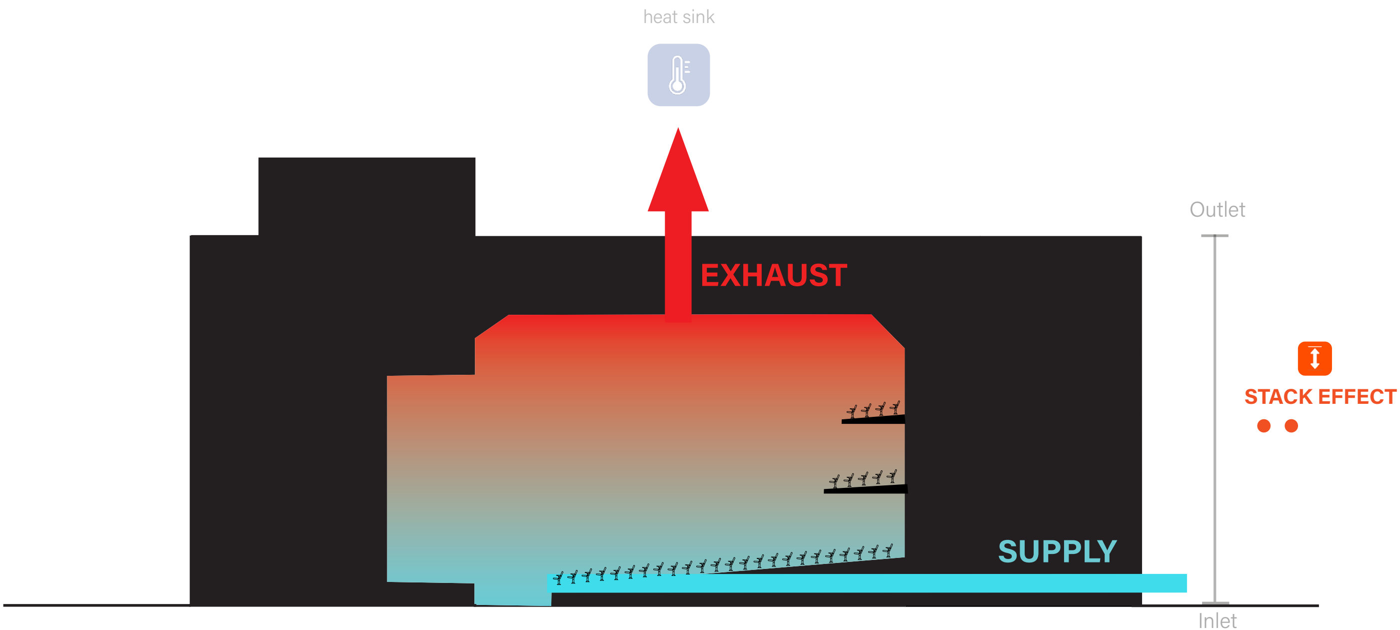


STACK EFFECT

The rising of hot air through a building, creating a natural loop, inhaling colder air through the bottom.

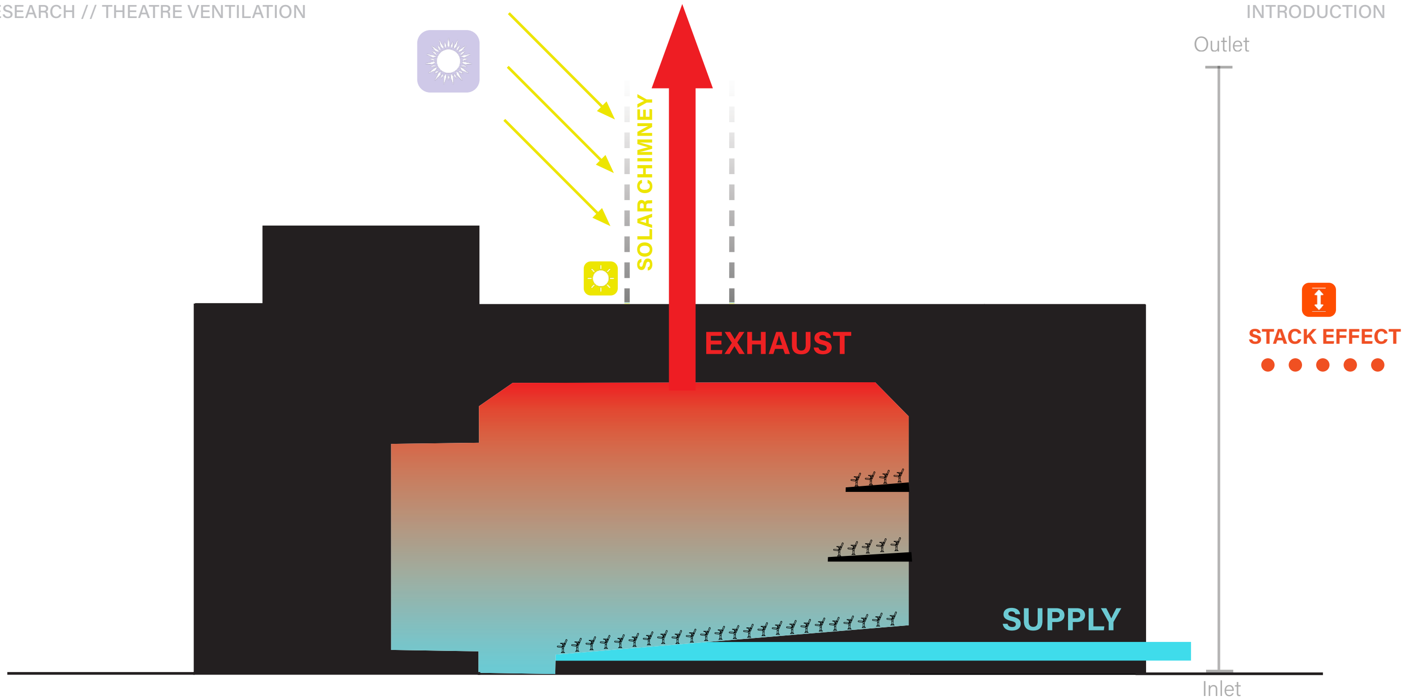
SOLAR CHIMNEY

Air gets heated by solar rays heating up the air inside a chimney, creating natural movement of air.



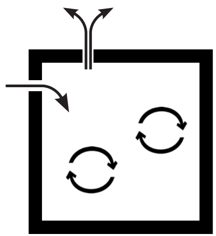
BASIC SYSTEM

Supplying hot air in below, and exhausting hot air above



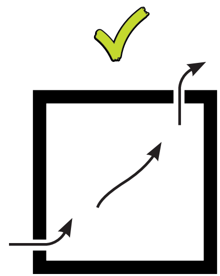
BASIC SYSTEM

Supplying hot air in below, and exhausting hot air above



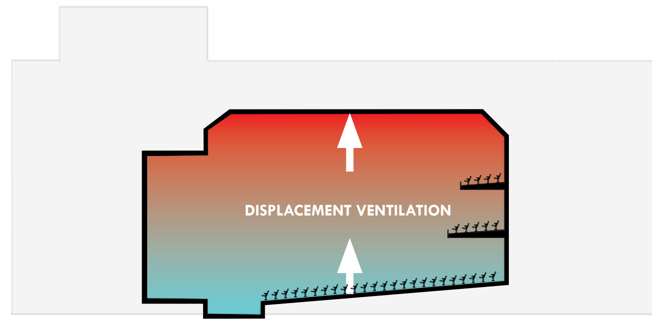
MIXING VENTILATION

Traditional method of ventilation. It mixes the new incoming air with the existing air.



DISPLACEMENT VENTILATION

This ventilation method displaces the used air and provides fresh air from below.



1 VENTILATION METHOD

CONSIDERATIONS

PART 1: RETRIEVING INCOMING AIR

2 RETRIEVING AIR FROM OUTSIDE
3 CARDINAL INTAKE
4 AIR TEMPERATURE
5 PATH THROUGH BUILDING
6 INTO AUDITORIUM
7 BALCONIES
8 SIZE OF THE AIRINLET
9 REGULATE AIRFLOWS

PART 2: INSIDE THE THEATRE

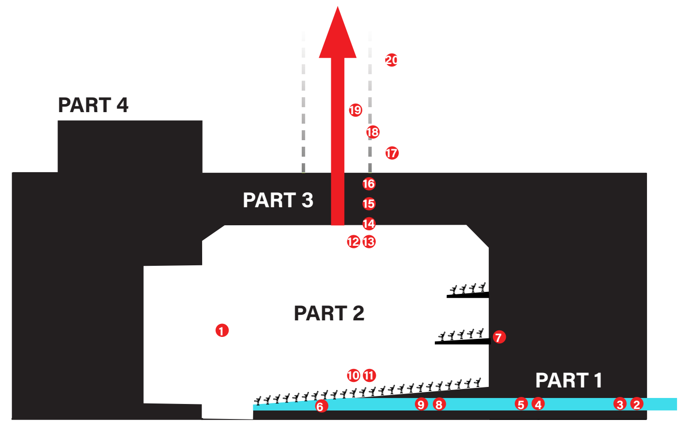
10 HEAT DISSIPATION PER SEASON
11 VENTILATION BY BUOYANCY
12 LESS OCCUPACY
13 AIR AT THE TOP OF THE AUDITORIUM
14 UPPER SIDE OF THE PLENUM

PART 3: THE EXHAUST

15 LOCATION OF THE CHIMNEYS
16 AMOUNT OF EXHAUST CHIMNEYS
17 LENGTH OF EXHAUST CHIMNEYS
18 MATERIAL EXHAUST CHIMNEYS
19 TEMPERATURE EXHAUST CHIMNEYS
20 SOUND
21 WIND AND RAIN

PART 4: ADDITIONAL MEASURES

22 RE-USING THE HEAT
23 NIGHT TIME COOLING
24 THERMAL MASS

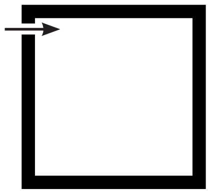


PART 1: RETRIEVING INCOMING AIR

PART 2: INSIDE THE THEATRE

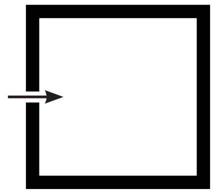
PART 3: THE EXHAUST

PART 4: ADDITIONAL MEASURES



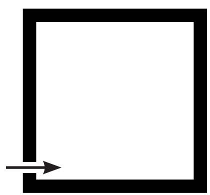
HIGH

Higher part of the building



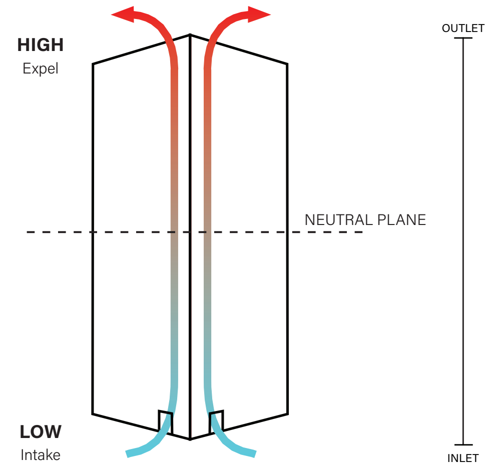
MIDDLE

Middle part of the building



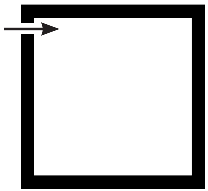
LOW

Lower part of the building



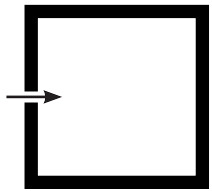
STACK EFFECT

❷ RETRIEVING AIR FROM OUTSIDE



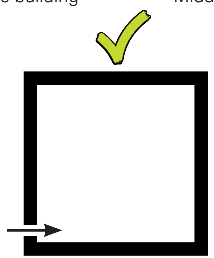
HIGH

Higher part of the building



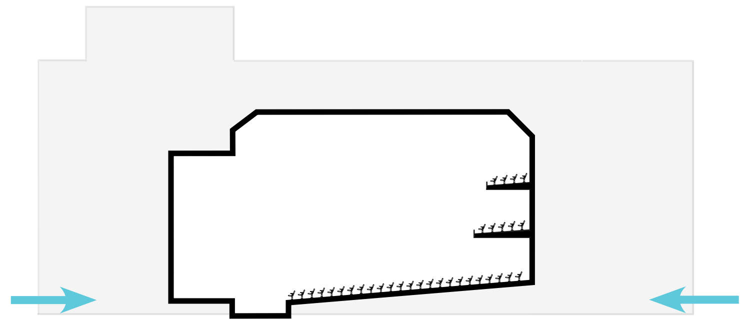
MIDDLE

Middle part of the building



LOW

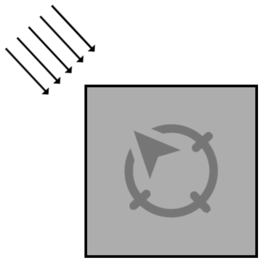
Lower part of the building



THEATRE

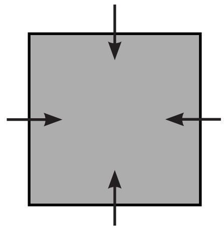
Lower levels. Biggest difference inlet and outlet.

2 RETRIEVING AIR FROM OUTSIDE



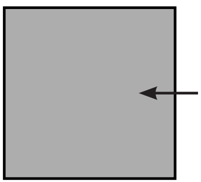
WIND DIRECTION

Primary wind direction, catching the blow of wind



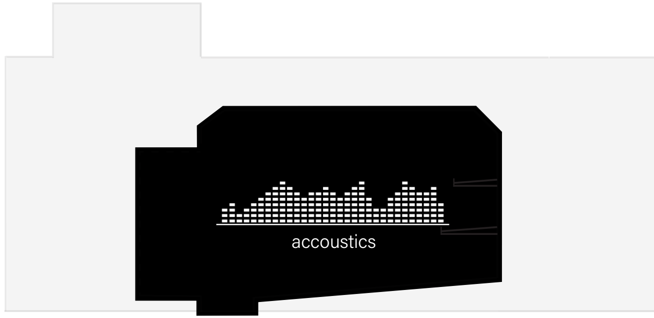
ALL SIDES

Every cardinal direction



ONE SIDE

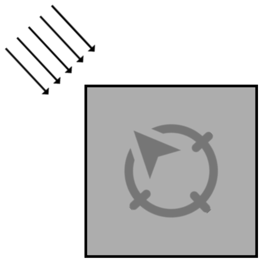
One cardinal side



BLACKBOX

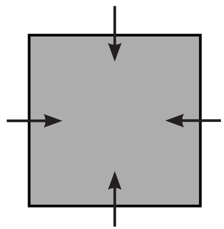
A theatre is basically a blackbox not allowing any sound or daylight in from the outside.

3 CARDINAL INTAKE



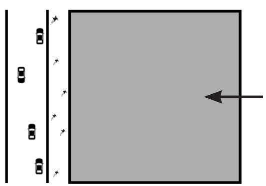
WIND DIRECTION

Primary wind direction, catching the blow of wind



ALL SIDES

Every cardinal direction



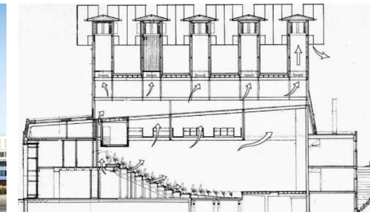
QUIET SIDE

Faced away from unwanted noise and pollution

References

Contact Theatre, Manchester

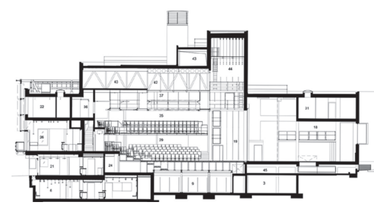
Everyman Theatre
Liverpool, England



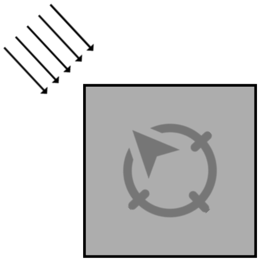
Wind direction. An open space towards the primary wind direction is necessary to allow wind to enter the building.

Everyman Theatre, Liverpool

The Contact Theatre
Manchester, England

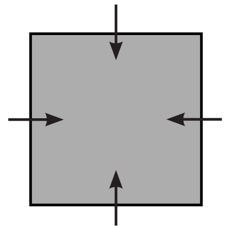


Quiet Side. The front side is a busy street of Manchester. The inlet is on the back of the building on a more quiet side street.



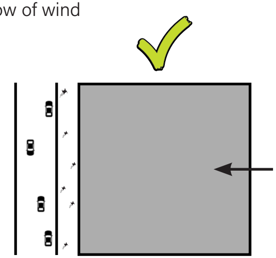
WIND DIRECTION

Primary wind direction, catching the blow of wind



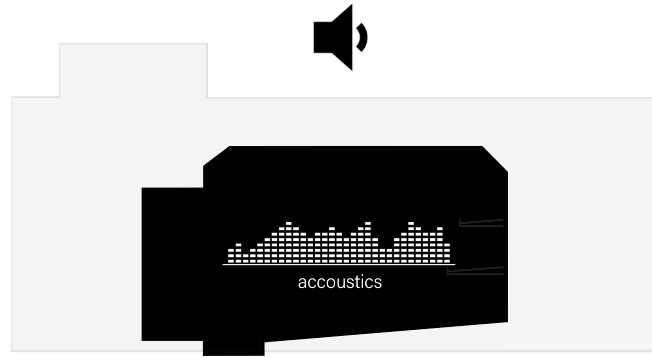
ALL SIDES

Every cardinal direction



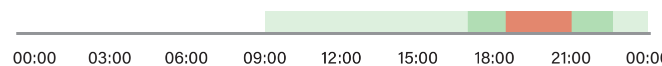
QUIET SIDE

Faced away from unwanted noise and pollution



REDUCE AMOUNT OF SOUND EXPOSURE

Least amount of sound entrances. Wind not necessary



WIND MIGHT BE FOUND UNRELIABLE IN URBAN AREAS

This should be considered per theatre

3 CARDINAL INTAKE

Monthly, Hourly Temperatures, Berlin, Germany

	January	February	March	April	May	June	July	August	Sept	October	Nov	Dec
1	1,5	-0,5	4,2	6,3	10,7	15,2	16,8	16,2	13,1	9,2	3,8	2,0
2	1,4	-0,6	4,0	5,9	10,3	14,7	16,3	15,8	12,7	8,9	3,7	1,9
3	1,4	-0,7	3,8	5,4	10,0	14,3	15,9	15,3	12,4	8,7	3,6	1,9
4	1,1	-1,0	3,7	5,0	9,8	13,7	15,5	15,0	12,2	8,5	3,5	2,1
5	1,2	-1,1	3,5	4,7	9,5	13,7	15,1	14,7	12,0	8,2	3,2	2,1
6	1,1	-1,1	3,3	4,7	10,3	14,4	15,4	14,6	12,1	7,9	3,1	2,1
7	1,1	-1,2	3,1	5,2	11,5	15,3	16,3	15,3	12,2	7,9	3,0	2,0
8	1,2	-1,2	3,3	6,6	12,8	16,3	17,2	16,4	13,1	8,2	2,9	2,1
9	1,3	-0,7	4,0	7,8	14,0	17,2	18,2	17,6	14,2	9,0	3,2	2,1
10	1,5	-0,2	4,9	8,9	15,1	18,1	19,5	18,7	15,2	10,0	3,7	2,2
11	2,0	0,6	5,8	9,8	16,1	19,1	20,4	19,8	16,1	10,7	4,5	2,4
12	2,6	1,2	6,9	10,4	16,7	19,8	20,9	20,4	17,1	11,6	5,4	2,8
13	2,9	1,7	7,4	11,0	17,2	20,6	21,8	21,2	17,9	12,4	6,1	3,2
14	3,1	2,0	7,7	11,6	17,7	21,1	22,3	21,7	18,5	12,9	6,4	3,3
15	3,1	2,1	8,0	11,6	17,7	21,2	22,9	22,1	18,6	13,0	6,4	3,4
16	2,9	2,1	8,1	11,7	18,0	21,2	23,0	22,1	18,4	13,0	6,1	3,3
17	2,7	1,7	7,8	11,6	18,0	20,9	22,8	22,0	18,0	12,4	5,7	3,0
18	2,4	1,2	7,3	11,1	17,2	20,2	22,4	21,8	17,2	11,6	5,3	2,8
19	2,2	1,0	6,5	10,2	16,6	19,5	21,6	21,0	16,4	11,2	4,9	2,6
20	1,9	0,8	6,1	9,3	15,4	18,7	20,6	20,0	15,6	10,8	4,7	2,4
21	1,8	0,5	5,6	8,7	14,1	17,5	19,4	19,0	15,0	10,3	4,5	2,3
22	1,6	0,3	5,5	7,9	13,4	17,0	18,7	18,2	14,3	9,9	4,3	2,3
23	1,5	0,1	4,9	7,3	12,4	16,4	17,9	17,5	13,7	9,7	4,2	2,2
24	1,4	-0,1	4,6	6,8	11,9	15,7	17,4	17,0	13,3	9,4	3,9	2,1

	Autumn	Winter	Spring	Summer
17	12,0	2,4	12,5	21,9
18	11,4	2,1	11,9	21,4
19	10,8	1,9	11,1	20,7
20	10,4	1,7	10,3	19,8
21	9,9	1,6	9,5	18,6
22	9,5	1,4	8,9	18,0

Seasonal Temperatures, Berlin, Germany

→

	Summer	Winter	Inbetween
17	21,9	2,4	12,2
18	21,4	2,1	11,6
19	20,7	1,9	11,0
20	19,8	1,7	10,3
21	18,6	1,6	9,7
22	18,0	1,4	9,2

Seasonal Temperatures, Berlin, Germany

SEASONAL DIFFERENCES

SUMMER 18 - 22 °C

PRECOOL

WINTER 1,4 - 2,4 °C

PREHEAT

INBETWEEN 9,2 - 12,2 °C

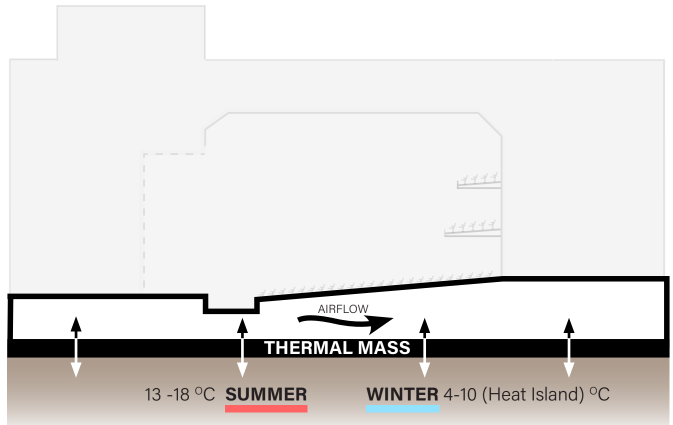
MINIMAL ADJUSTMENTS

4 AIR TEMPERATURE

SUMMER 18 - 22 °C

WINTER 1,4 - 2,4 °C

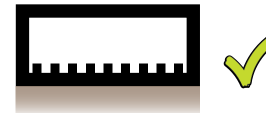
INBETWEEN 9,2 - 12,2 °C



GROUND COUPLING

Coupled thermal mass will naturally heat up the incoming air in winter and cool down in summer by making use of the temperature of the ground.

THERMAL MASS



EXPOSED CONCRETE

Situated as a maze for the air

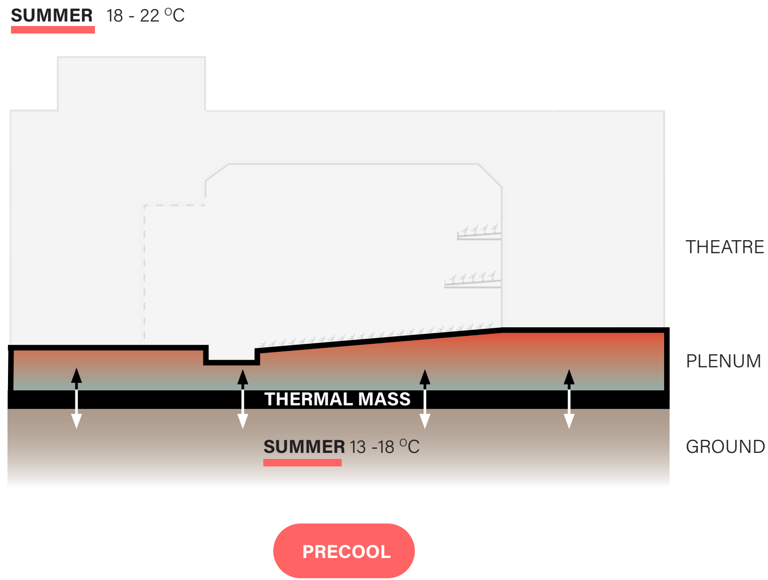
WATER

Collected from rainwater

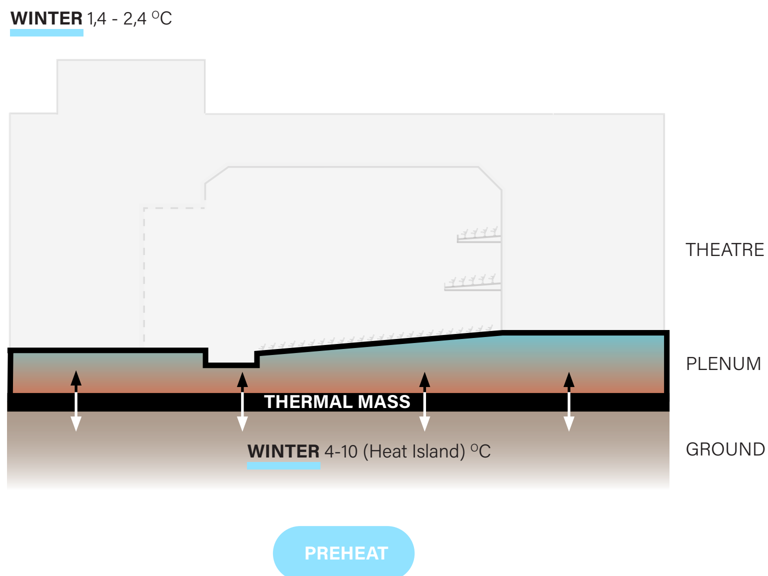
OTHER HIGH THERMAL MASS

Fryfat

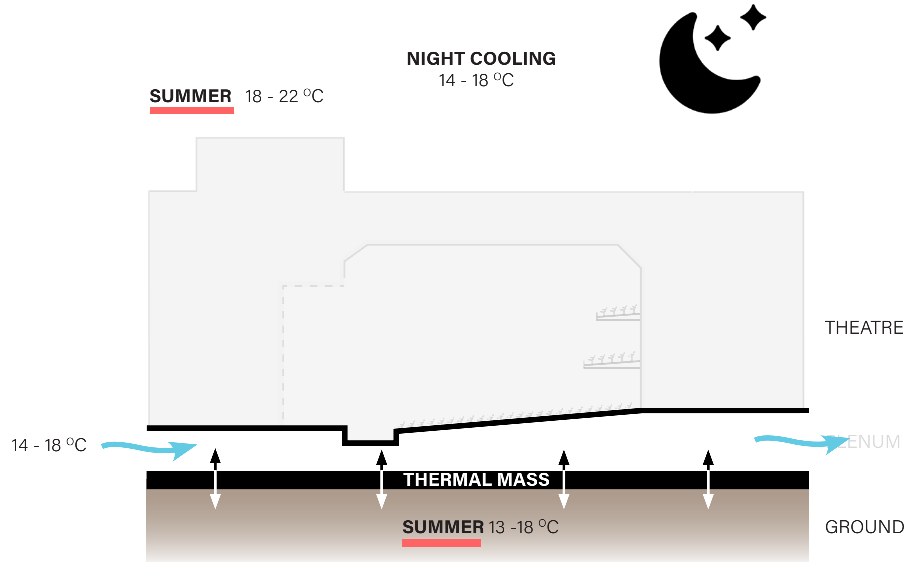
4 AIR TEMPERATURE



4 **AIR TEMPERATURE**



4 **AIR TEMPERATURE**



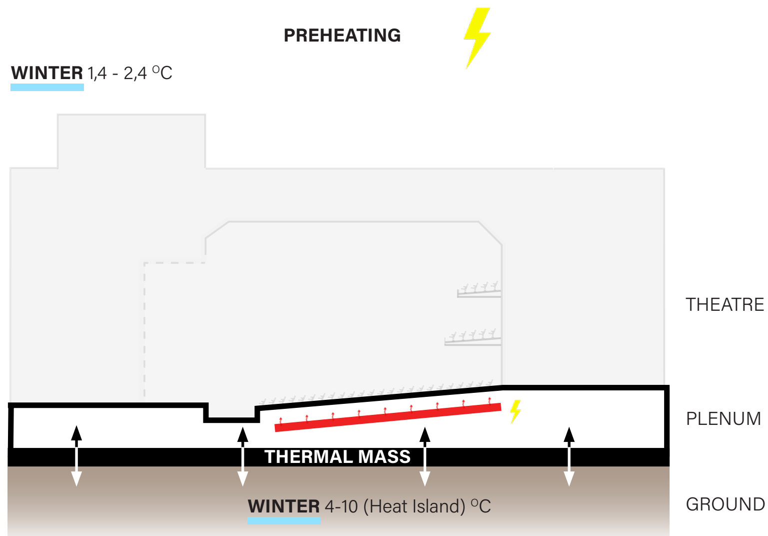
PRECOOL

EXTRA ADJUSTMENT

Might need extra cooling on extreme hot days

< limited

4 AIR TEMPERATURE

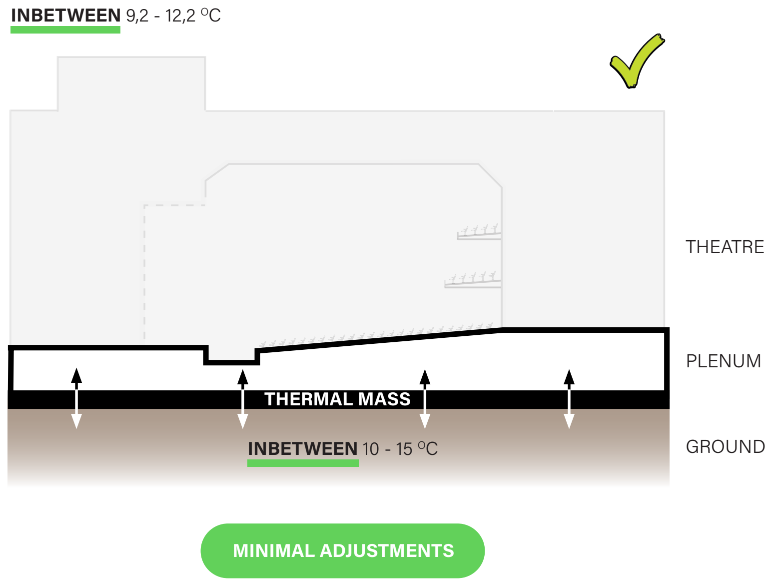


PREHEAT

EXTRA ADJUSTMENT

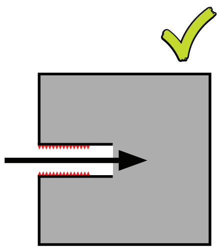
Preheat the incoming air.
Thermal mass not enough.

4 AIR TEMPERATURE



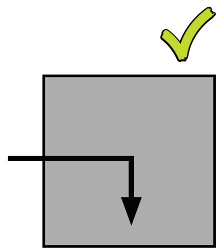
4 **AIR TEMPERATURE**

ADVICES



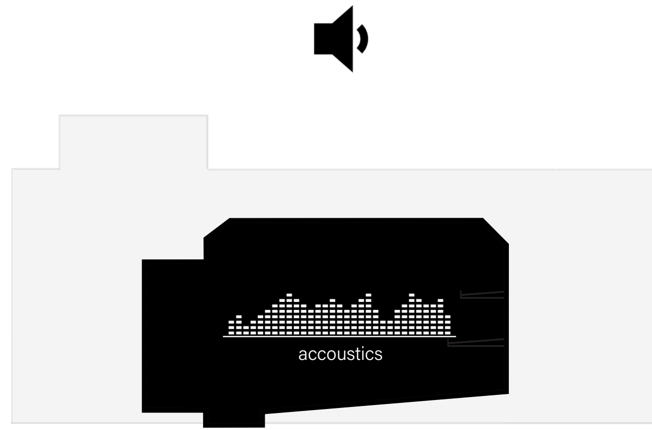
ACCOUSTIC ATTENUATORS

To lower the possible noise dis-
turbance



90 DEGREE TURN

As the natural ventilation facilitates a direct connection, turns in the air tubes reduce possible noise disturbance from guts of wind or traffic

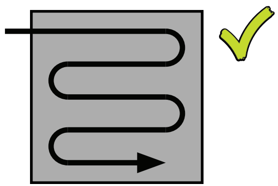


BLACKBOX

A theatre is basically a blackbox not allowing any sound or daylight in from the outside.

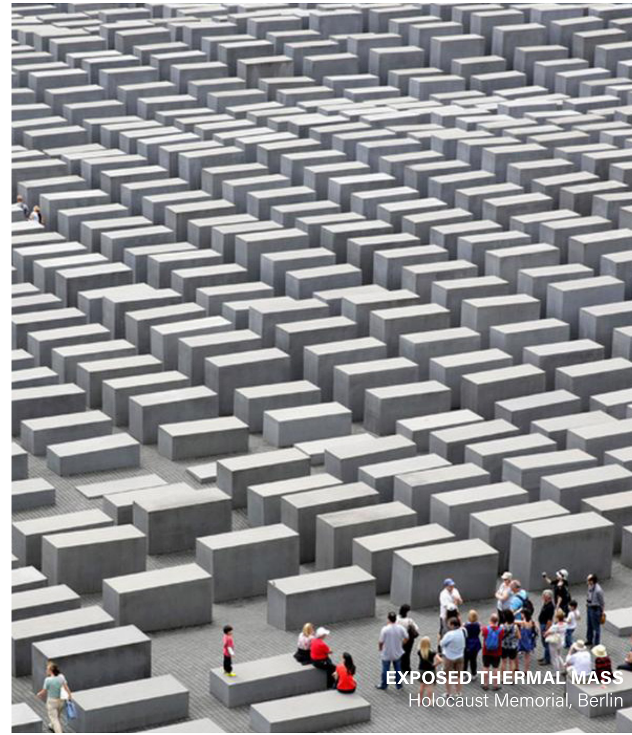
5 PATH THROUGH BUILDING

ADVICES



MAXIMIZE EXPOSURE

The longer the path past the thermal mass, the more it is able to exchange its temperature



EXPOSED THERMAL MASS
Holocaust Memorial, Berlin

5 PATH THROUGH BUILDING

LENGTH OF UNDERGROUND DUCTS

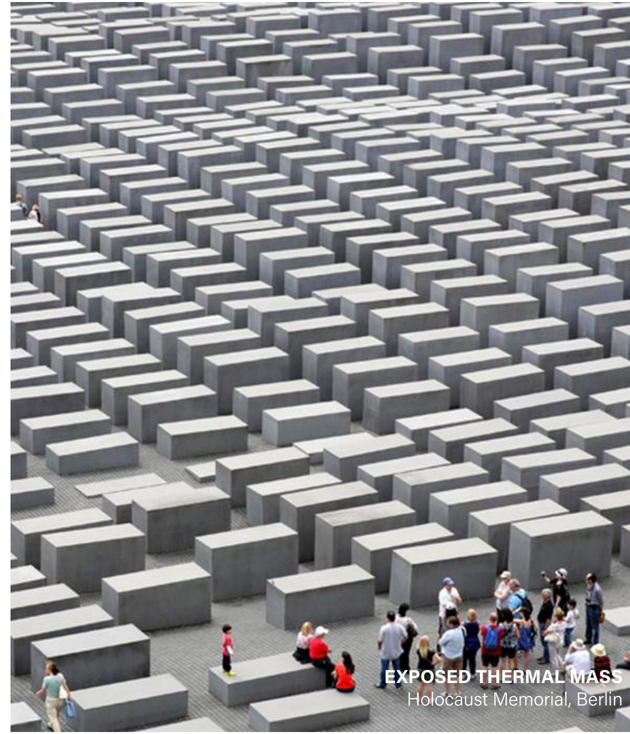
$$l = \frac{\left(T_{out} - T_{in}\right)\left(\frac{1}{\alpha_i} + \frac{d}{\lambda}\right) v\, r\, \rho c_l}{2\left(T_{ground} - T_{in}\right)}$$

l = length of the necessary ducts (m)	
T_{out} = temperature of the outgoing air (°C)	20 °C
T_{in} = temperature of the ingoing air (°C)	24 °C
α_i = the heat transfer coefficient between the surface of the duct and the air	10 m²K/W
d/λ = thermal conductivity (m²/K/W)	0,02 m²K/W
T_{ground} = temperature of the ground (°C)	14 °C
pc_lair = specific heat air = 1200 J/m3K	1200 J/m³K
v = velocity (m/s)	1 m/s
r = radius (m)	3,91 m

T_{in} → T_{out}

24 °C → 20 °C

$l =$ **72 meter**



5 PATH THROUGH BUILDING

LENGTH OF UNDERGROUND DUCTS

$$l = \frac{\left(T_{out} - T_{in}\right)\left(\frac{1}{\alpha_i} + \frac{d}{\lambda}\right) v\, r\, \rho c_l}{2\left(T_{ground} - T_{in}\right)}$$

l = length of the necessary ducts (m)	
T_{out} = temperature of the outgoing air (°C)	20 °C
T_{in} = temperature of the ingoing air (°C)	24 °C
α_i = the heat transfer coefficient between the surface of the duct and the air	10 m²K/W
d/λ = thermal conductivity (m²/K/W)	0,02 m²K/W
T_{ground} = temperature of the ground (°C)	14 °C
pc_lair = specific heat air = 1200 J/m3K	1200 J/m³K
v = velocity (m/s)	1 m/s
r = radius (m)	3,91 m

T_{in} → T_{out}

24 °C → 20 °C

$l =$ **72 meter**

COOLING CAPACITY

$$Q = mCp\Delta T$$

Q = cooling capacity (W)	
Cp = specific heat air = 1200 J/m³K	1200 J/m³K
m = mass flow of air (m³/s)	12 m³/s
dT = temperature difference	4 °C

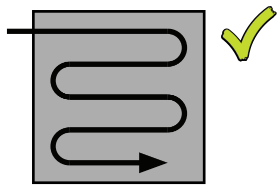
$$Q = 57{,}6\ \text{kW}$$

Substract

HEAT PRODUCTION **200.000 W**

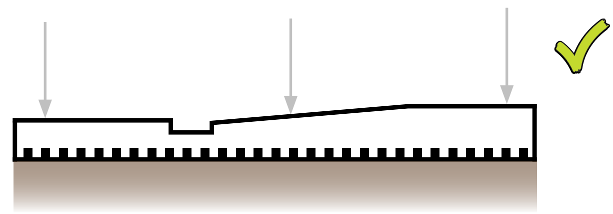
COOLING CAPACITY **57.600 W** –

COOLING LOAD



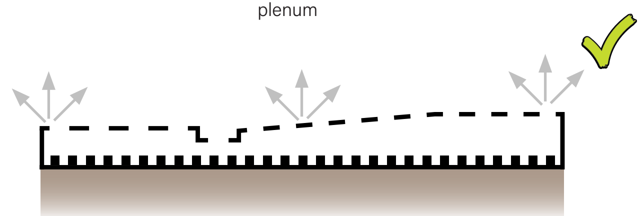
MAXIMIZE EXPOSURE

The longer the path past the thermal mass, the more it is able to exchange its temperature



HIDDEN

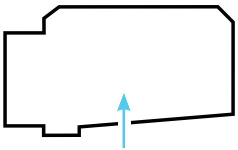
Hide the thermal mass in the plenum



INTEGRATE

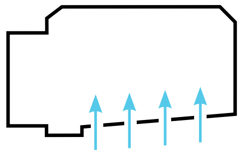
Seek to contribute to an architectural element

5 PATH THROUGH BUILDING



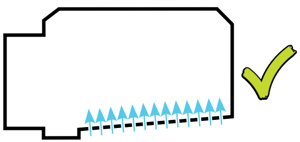
SINGLE PLACE

One location of air inlet



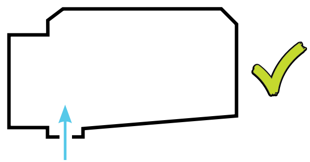
MULTIPLE PLACES

Multiple locations of air inlet



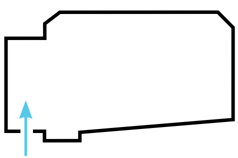
POROUS

Equal distribution



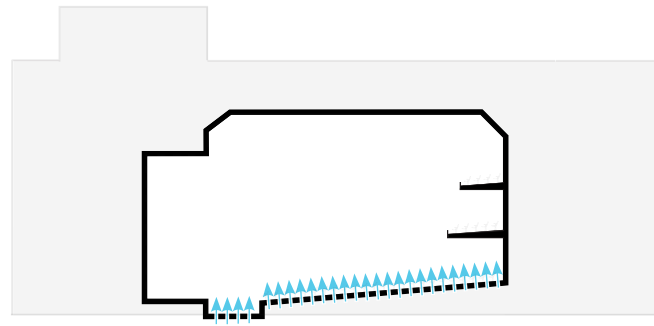
ORCESTRA

Air inlet in orchestra pit



STAGE

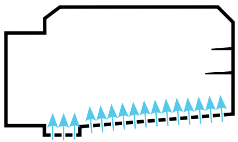
Air inlet in stage



INSERT AIR DISTRIBUTED OVER SEATING AREA

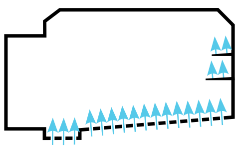
Grills integrated in between seating

6 INTO AUDITORIUM



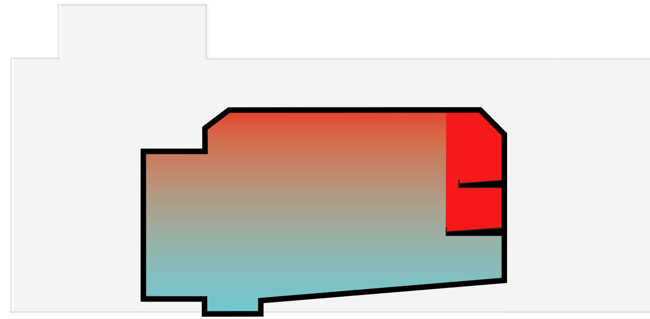
ONLY GROUNDLEVEL

Only ground level ventilation



+ BALCONIES

Both groundlevel as balconies

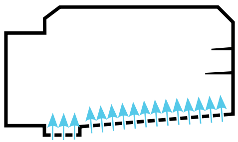


PREVIOUS RESEARCH:

The auditorium modelling also highlighted the problem of insufficient air movement around the upper level gallery seating. 'When we modelled the air flow, we found that it by-passed the galleries altogether'

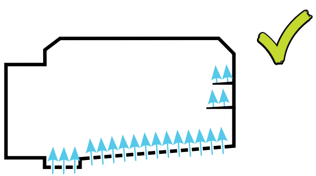
Purcell, Architect, The Contact Theatre

7 INTO BALCONIES



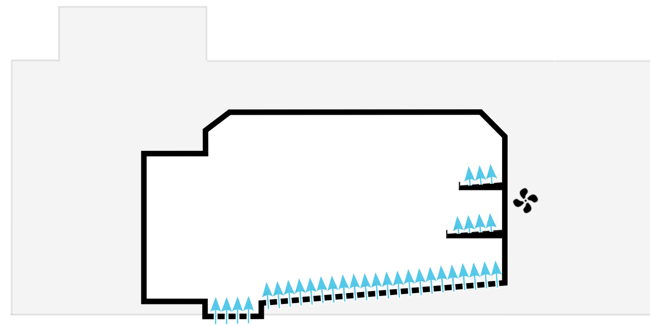
ONLY GROUNDLEVEL

Only ground level ventilation



+ BALCONIES

Both groundlevel as balconies



INSERT AIR DISTRIBUTED OVER SEATING AREA

Porous distribution

7 INTO BALCONIES

SIZING IN- AND OUTLET

WORST CASE SCENARIO

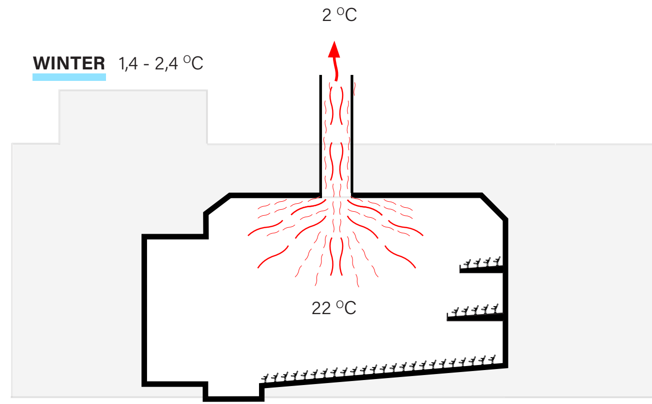
SUMMER 18 - 22 °C

	January	February	March	April	May	June	July	August	September	October	November	December
1	1,5	-0,5	4,2	6,3	10,7	15,2	16,8	16,2	13,1	9,2	3,8	2,0
2	1,4	-0,6	4,0	5,9	10,3	14,7	16,3	15,8	12,7	8,9	3,7	1,9
3	1,4	-0,7	3,8	5,4	10,0	14,3	15,9	15,3	12,4	8,7	3,6	1,9
4	1,1	-1,0	3,7	5,0	9,8	13,7	15,5	15,0	12,2	8,5	3,5	2,1
5	1,2	-1,1	3,5	4,7	9,5	13,7	15,1	14,7	12,0	8,2	3,2	2,1
6	1,1	-1,1	3,3	4,7	10,3	14,4	15,4	14,6	12,1	7,9	3,1	2,1
7	1,1	-1,2	3,1	5,2	11,5	15,3	16,3	15,3	12,2	7,9	3,0	2,0
8	1,2	-1,2	3,3	6,6	12,8	16,3	17,2	16,4	13,1	8,2	2,9	2,1
9	1,3	-0,7	4,0	7,8	14,0	17,2	18,2	17,6	14,2	9,0	3,2	2,1
10	1,5	-0,2	4,9	8,9	15,1	18,1	19,5	18,7	15,2	10,0	3,7	2,2
11	2,0	0,6	5,8	9,8	16,1	19,1	20,4	19,8	16,1	10,7	4,5	2,4
12	2,6	1,2	6,9	10,4	16,7	19,8	20,9	20,4	17,1	11,6	5,4	2,8
13	2,9	1,7	7,4	11,0	17,2	20,6	21,8	21,2	17,9	12,4	6,1	3,2
14	3,1	2,0	7,7	11,6	17,7	21,1	22,3	21,7	18,5	12,9	6,4	3,3
15	3,1	2,1	8,0	11,6	17,7	21,2	22,9	22,1	18,6	13,0	6,4	3,4
16	2,9	2,1	8,1	11,7	18,0	21,2	23,0	22,1	18,4	13,0	6,1	3,3
17	2,7	1,7	7,8	11,6	18,0	20,9	22,8	22,0	18,0	12,4	5,7	3,0
18	2,4	1,2	7,3	11,1	17,2	20,2	22,4	21,8	17,2	11,6	5,3	2,8
19	2,2	1,0	6,5	10,2	16,6	19,5	21,6	21,0	16,4	11,2	4,9	2,6
20	1,9	0,8	6,1	9,3	15,4	18,7	20,6	20,0	15,6	10,8	4,7	2,4
21	1,8	0,5	5,6	8,7	14,1	17,5	19,4	19,0	15,0	10,3	4,5	2,3
22	1,6	0,3	5,5	7,9	13,4	17,0	18,7	18,2	14,3	9,9	4,3	2,3
23	1,5	0,1	4,9	7,3	12,4	16,4	17,9	17,5	13,7	9,7	4,2	2,2
24	1,4	-0,1	4,6	6,8	11,9	15,7	17,4	17,0	13,3	9,4	3,9	2,1

BASE TO WORST MOMENT

Summer

WINTER 1,4 - 2,4 °C



DISSIPATION IN WINTER

Porous distribution

8 SIZE OF THE AIRINLET

STACK DRIVEN VENTILATION

REQUIRED SIZE OF VENTILATION OPENINGS

$A_{in} = A_{out} = \sqrt{2} * A_e$

$$A_e \approx 5Qh^{-\frac{1}{2}}\Delta T^{-\frac{3}{2}}$$

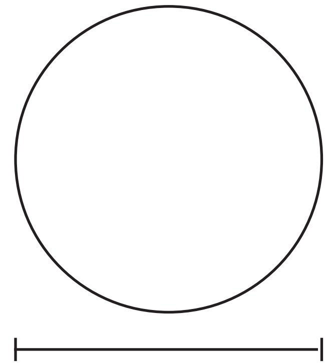
Ae= equivalent sizeventilationopenings[m2]
dT = averageraisein temperature [K]
Q= incomingheat [kW] (solar+ internalloads)
h = heightdifferenceair inlet-outlet [m]

SIZE OF THE INLET AND OUTLET OPENINGS

REQUIRED SIZE OF VENTILATION OPENINGS

$A_{in} = A_{out} = \sqrt{2} * A_e$

$$\frac{1}{A_e^2} = \left[\frac{1}{A_i^2} + \frac{1}{A_a^2}\right]$$



SIZING

Ventilation area

8 SIZE OF THE AIRINLET

STACK DRIVEN VENTILATION

REQUIRED SIZE OF VENTILATION OPENINGS

$A_{in} = A_{out} = \sqrt{2}*A_e$

$$A_e \approx 5Qh^{-\frac{1}{2}}\Delta T^{-\frac{3}{2}}$$

Ae= equivalent sizeventilationopenings[m2]
dT = averageraisein temperature [K]
Q= incomingheat [kW] (solar+ internalloads)
h = heightdifferenceair inlet-outlet [m]

3 °C
200.000 W
16 m

$$A_e \approx 48{,}11 \text{ m}^2$$

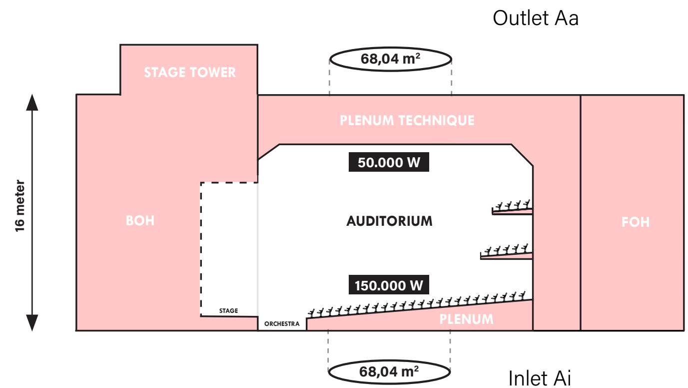
SIZE OF THE INLET AND OUTLET OPENINGS

REQUIRED SIZE OF VENTILATION OPENINGS

$A_{in} = A_{out} = \sqrt{2}*A_e$

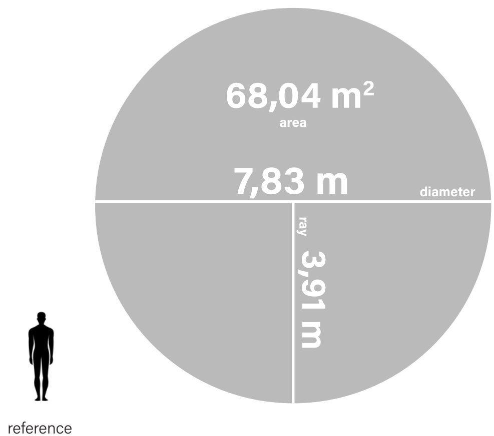
$$\frac{1}{A_e^2} = \left[\frac{1}{A_i^2} + \frac{1}{A_a^2}\right]$$

$$A_i = A_a = \sqrt{2}\,A_e = 68{,}04 \text{ m}^2$$



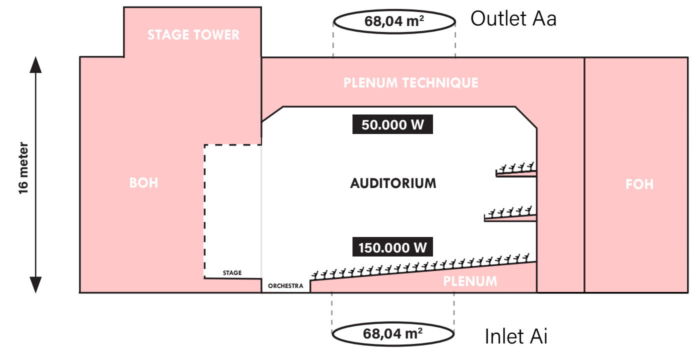
AREA OF AIR INLET AND OUTLET

Without Chimney



NO CHIMNEY

Size of the inlet and outlet



AREA OF AIR INLET AND OUTLET

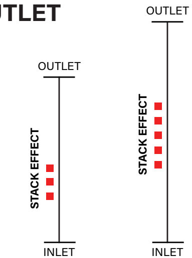
Without Chimney

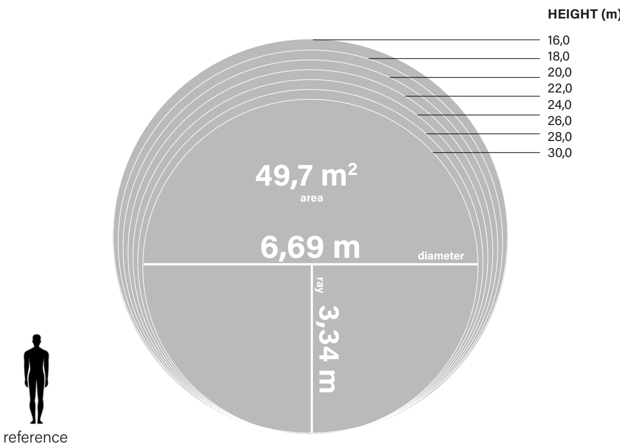
8 SIZE OF THE AIRINLET

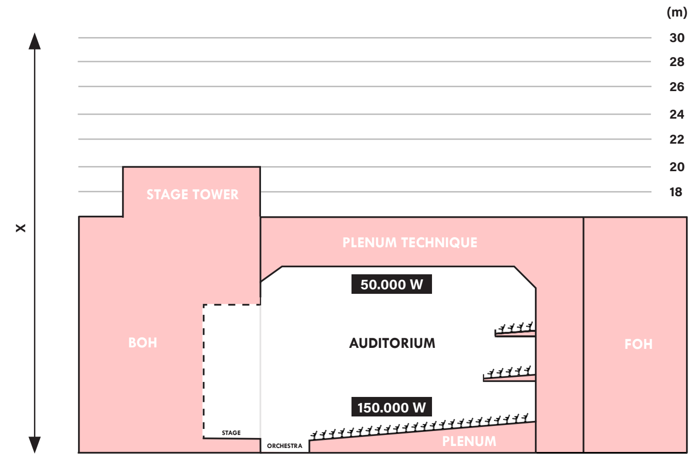
8 SIZE OF THE AIRINLET

VARYING HEIGTH BETWEEN IN- AND OUTLET

HEIGHT (m)	Ae (m²)	Ai (m²)	RAY	DIAMETER
16	48,1	68,0	3,91	7,83
18	45,4	64,2	3,80	7,60
20	43,0	60,9	3,70	7,40
22	41,0	58,0	3,61	7,23
24	39,3	55,6	3,54	7,07
26	37,7	53,4	3,47	6,93
28	36,4	51,4	3,40	6,80
30	35,1	49,7	3,34	6,69



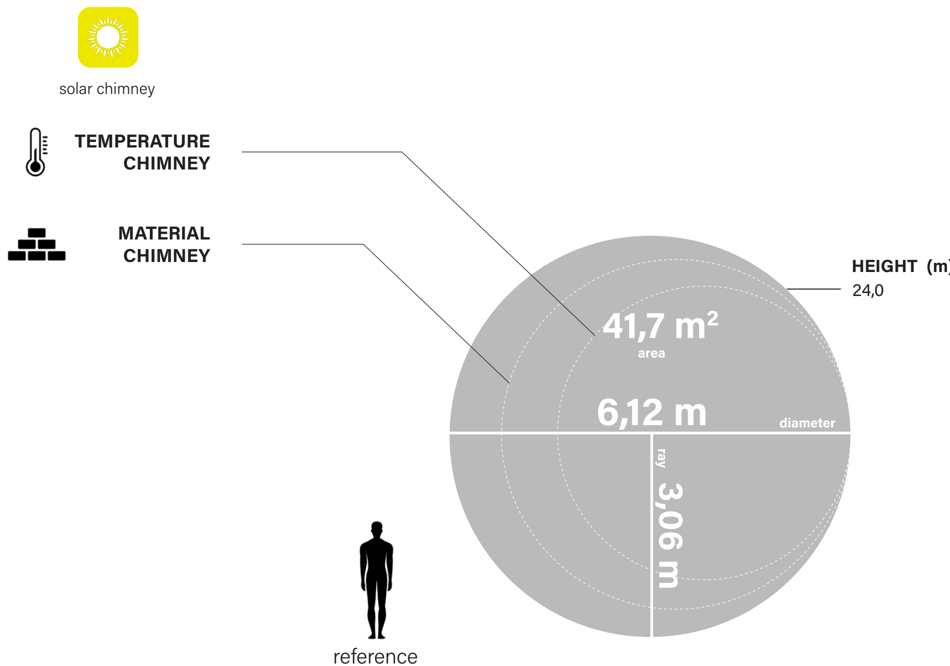


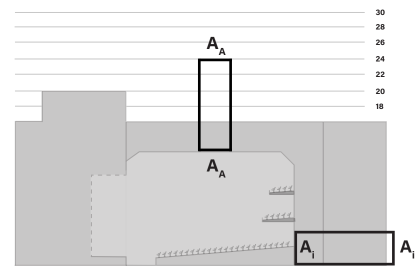


HEIGHT ABOVE THEATRE

Stack effect heights

8 SIZE OF THE AIRINLET



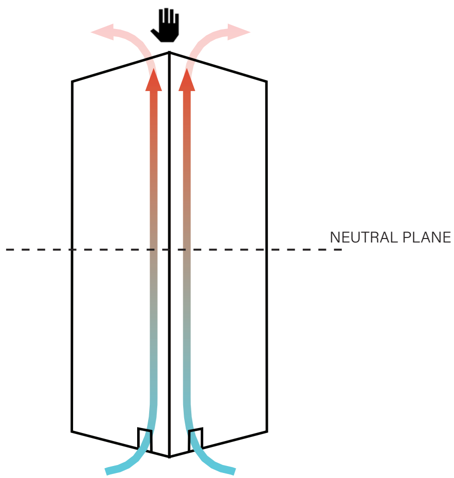


24 METERS

8 meters height increase

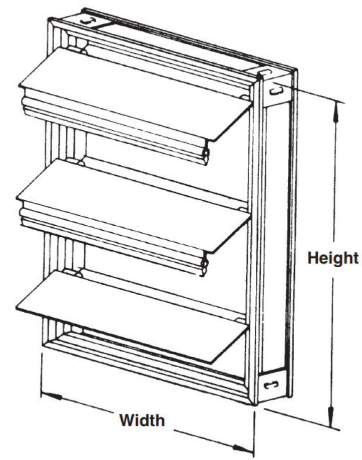
8 SIZE OF THE AIRINLET


1/4
1/4
1/4
1/4
Reference
EVERYMAN THEATRE, LIVERPOOL



STACK EFFECT

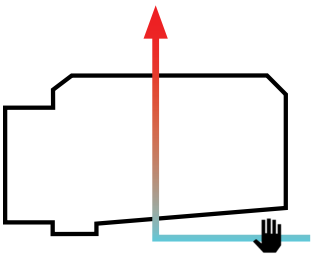
Most important to stop the air from flowing out, if you want to stop the stack effect. If the air cannot flow out, new air cannot enter



ACTUATOR CONTROLLED DAMPERS

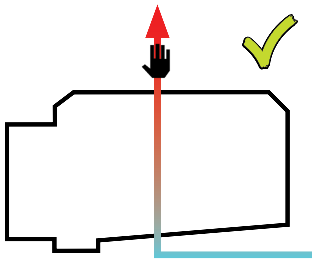
Installed into shafts or doorways may dampers play a role in the stopping of air. These can be controlled by sensors or the building manager.

9 REGULATE AIRFLOWS



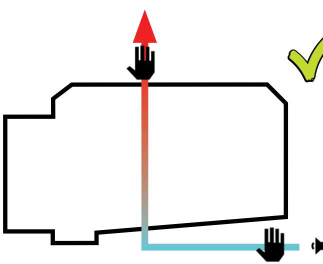
AT ENTRY

Regulate before entering the building



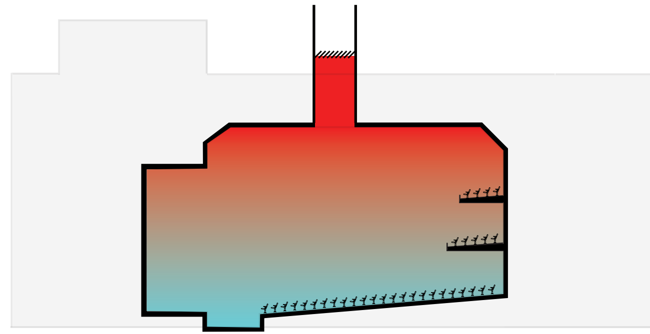
AT EXHAUST

Only ground level ventilation



AT ENTRY AND EXHAUST

Both groundlevel as balconies



UPPER DAMPERS

Lower dampers may be installed as an extra to stop unwanted noise or guts of wind to come in but are not as necessary

9 REGULATE AIRFLOWS

PART 1: RETRIEVING INCOMING AIR

PART 2: INSIDE THE THEATRE

PART 3: THE EXHAUST

PART 4: ADDITIONAL MEASURES

HEAT DISSIPATION

HEAT DISSIPATION AT GIVEN VENTILATION RATE

12 m³/s — MIN. VENTILATION ⟷ **200.000 W** — BODY HEAT + LIGHT

$$\Delta W = \rho c_{air} Q . f \Delta T \ [W]$$

dW = warmteafvoer door ventilatie in W
dcair = specifieke warmte lucht = 1200 J/m3K
Q = ventilatiehoeveelheid in m3/s
dT = gemiddelde temperatuurverschil tussen binnen en buiten
f = factor voor verschil tussen gemiddelde temperatuurverschil en Tuit-Tin

1200		
12 m/s		
1,9	20,1	11,3
1,5		

f = Tuit-Tin / delta T = (Tuit-Tbuiten) / (Tgem-Tbuiten)

	Summer	Winter	Inbetween
17	21,9	2,4	12,2
18	21,4	2,1	11,6
19	20,7	1,9	11,0
20	19,8	1,7	10,3
21	18,6	1,6	9,7
22	18,0	1,4	9,2
average (°C)	20,1	1,9	10,7
inside (19-25 °C)	22	22	22
difference (°C)	1,9	20,1	11,3

HEAT DISSIPATION PER SEASON

SUMMER 18 - 22 °C — **41 kW**

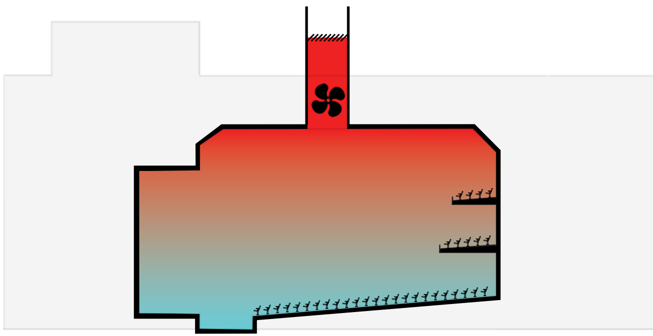
Note:
Need extra fan assistance to dissipate heat

WINTER 1,4 - 2,4 °C — **435 kW** ✓

INBETWEEN 9,2 - 12,2 °C — **244 kW** ✓

10 **HEAT DISSIPATION PER SEASON**

SUMMER 18 - 22 °C



LOW PRESSURE FAN

To initiate the air flow when the outdoor climate is too hot to do this.

HEAT DISSIPATION PER SEASON

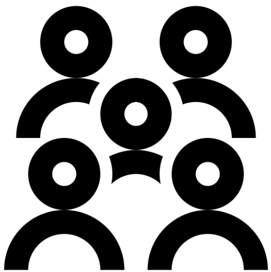
SUMMER 18 - 22 °C — **41 kW**

Note:
Need extra fan assistance to dissipate heat

WINTER 1,4 - 2,4 °C — **435 kW** ✓

INBETWEEN 9,2 - 12,2 °C — **244 kW** ✓

10 HEAT DISSIPATION PER SEASON



FULL OCCUPANCY

200.000 W

NATURAL VENTILATION DUE TO HEAT

TEMPERATUURVERSCHIL DOOR HITTE PRODUCTIE

$$\Delta T = \frac{0{,}0279 \cdot \Delta W^{\frac{2}{3}}}{h^{\frac{1}{3}} \cdot f^{\frac{2}{3}} . A_e^{\frac{2}{3}}} = 0{,}0279 \left(\frac{\Delta W^2}{h \cdot f^2 A_e^{\ 2}} \right)^{\frac{1}{3}}$$

dT = temperatuurverschil tussen binnen en buiten
dW = warmteafvoer door ventilatie
h = hoogteverschil tussen toevoeropening en afvoeropeningen in m
Ae = equivalente ventilatieopening in m2
f = Tuit-Tin / delta T = (Tuit-Tbuiten) / (Tgem-Tbuiten)

200.000 W
24 m
29,5 m²
1,5

$$\Delta T = \ 2{,}65\ ^{O}C$$

BIJKOMENDE VENTILATIEVOUD

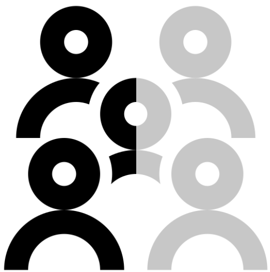
$$Q = C_D \times A_e \sqrt{2gh \times \Delta T / T_a} \quad [m^3/s]$$

Q = ventilatiehoeveelheid in m3/s
Cd = weerstandcoefficient, tussen 1 en 0,7
hg = zwaartekrachtconstrante = 9,8 m/s2
h = hoogteverschil tussen toevoeropening en afvoeropeningen in m
dT = gemiddelde temperatuurverschil tussen binnen en buiten
Ta = buitentemperatuur in K (circa 300 K)
Ae = equivalente ventilatieopening in m²

0,85
9,8 m/s²
24 m
3 °C
296 K
29,5 m²

Q= **51,42 m³/s** > **12 m³/s** ✓

11 VENTILATION BY BUOYANCY



HALF OF THE OCCUPANCY

100.000 W

NATURAL VENTILATION DUE TO HEAT

TEMPERATUURVERSCHIL DOOR HITTE PRODUCTIE

$$\Delta T = \frac{0{,}0279 \cdot \Delta W^{\frac{2}{3}}}{h^{\frac{1}{3}} \cdot f^{\frac{2}{3}} . A_e^{\frac{2}{3}}} = 0{,}0279\left(\frac{\Delta W^2}{h \cdot f^2 A_e^{\ 2}}\right)^{\frac{1}{3}}$$

dT = temperatuurverschil tussen binnen en buiten
dW = warmteafvoer door ventilatie
h = hoogteverschil tussen toevoeropening en afvoeropeningen in m
Ae = equivalente ventilatieopening in m2
f = Tuit-Tin / delta T = (Tuit-Tbuiten) / (Tgem-Tbuiten)

100.000 W
24 m
29,5 m²
1,5

$$\Delta T = \ 1{,}68\ ^{O}C$$

BIJKOMENDE VENTILATIEVOUD

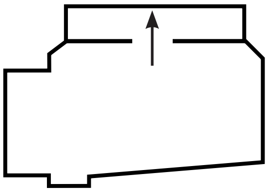
$$Q = C_D \times A_e \sqrt{2gh \times \Delta T / T_a} \quad [m^3/s]$$

Q = ventilatiehoeveelheid in m3/s
Cd = weerstandcoefficient, tussen 1 en 0,7
hg = zwaartekrachtconstrante = 9,8 m/s2
h = hoogteverschil tussen toevoeropening en afvoeropeningen in m
dT = gemiddelde temperatuurverschil tussen binnen en buiten
Ta = buitentemperatuur in K (circa 300 K)
Ae = equivalente ventilatieopening in m²

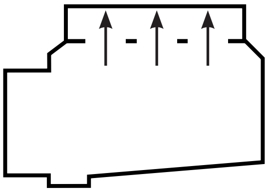
0,85
9,8 m/s²
24 m
3 °C
296 K
29,5 m²

Q= **40,81 m³/s** > **12 m³/s**

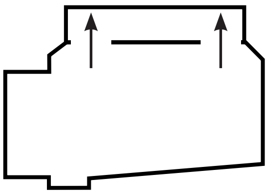
12 CONSIDERATION 12: LESS OCCUPACY



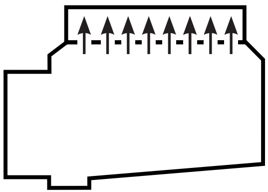
ONE CENTRAL
One in the centre



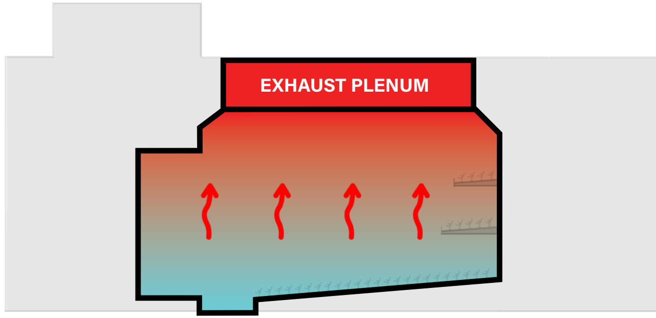
MULTIPLE
Multiple large ones



SIDES
In the corners of the theatre

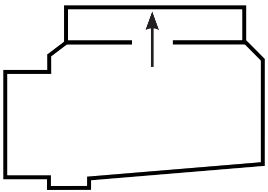


POROUS
Many small ones



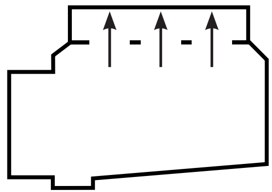
THEATRE
Lower levels. Biggest difference inlet and outlet.

13 AIR AT THE TOP OF THE AUDITORIUM



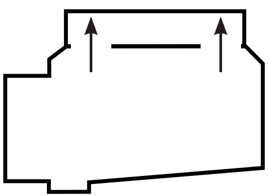
ONE CENTRAL

One in the centre



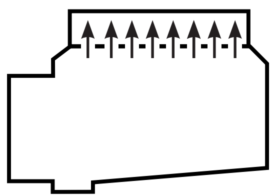
MULTIPLE

Multiple large ones



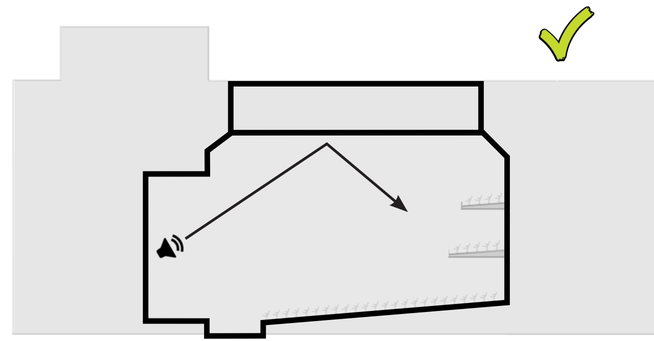
SIDES

In the corners of the theatre



POROUS

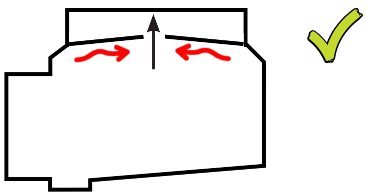
Many small ones



ACCOUSTICS

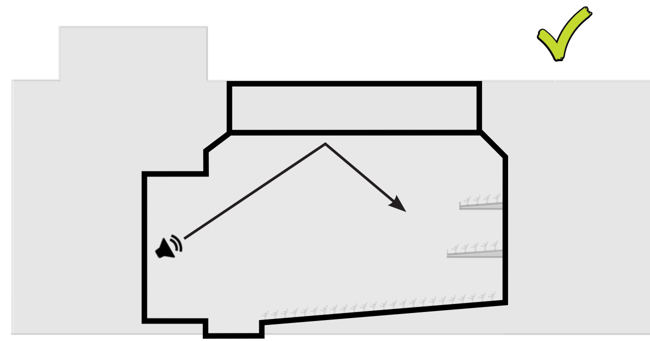
Dependent on the space specifically. What is possible.
Cannot do wrong.

13 AIR AT THE TOP OF THE AUDITORIUM



SLOPED TO HIGHEST POINT

To not created accumulations of hot air



ACCOUSTICS

Dependent on the space specifically. What is possible.
Cannot do wrong.

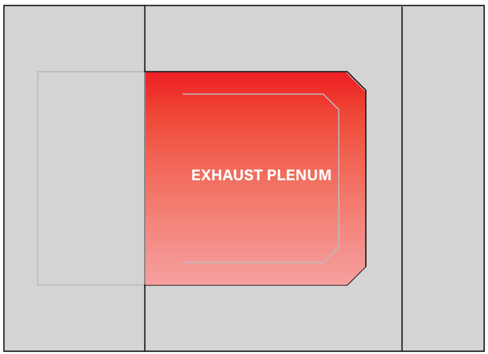
14 UPPERSIDE OF THE PLENUM

PART 1: RETRIEVING INCOMING AIR

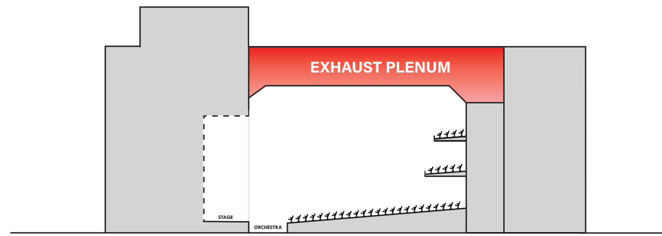
PART 2: INSIDE THE THEATRE

PART 3: THE EXHAUST

PART 4: ADDITIONAL MEASURES

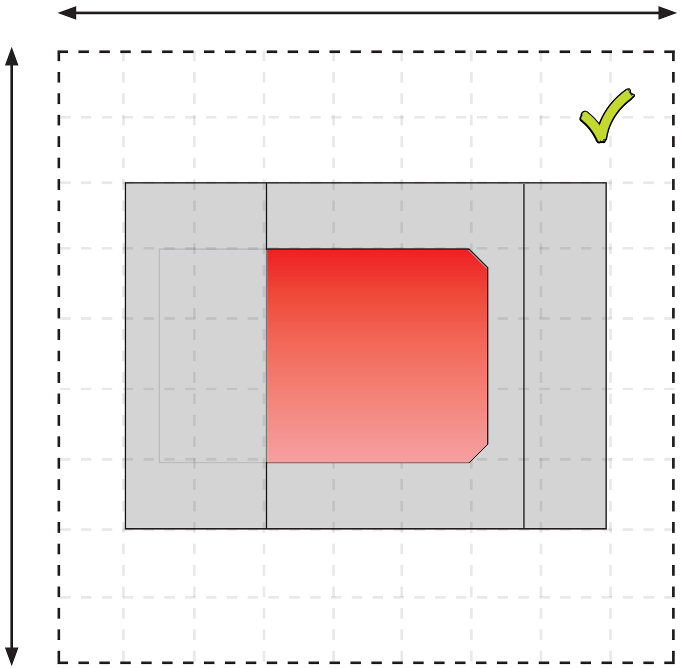


PLAN



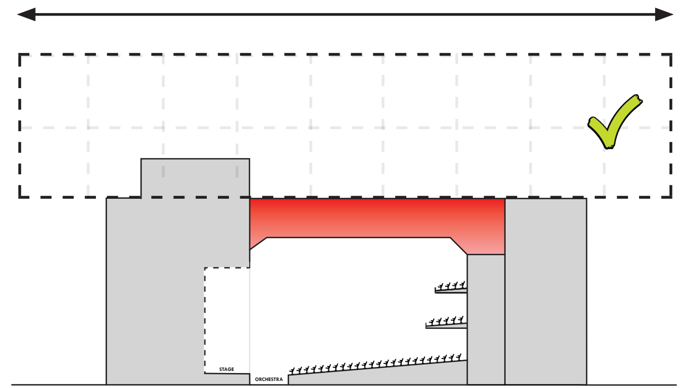
SECTION

15 LOCATION OF THE CHIMNEYS



PLAN

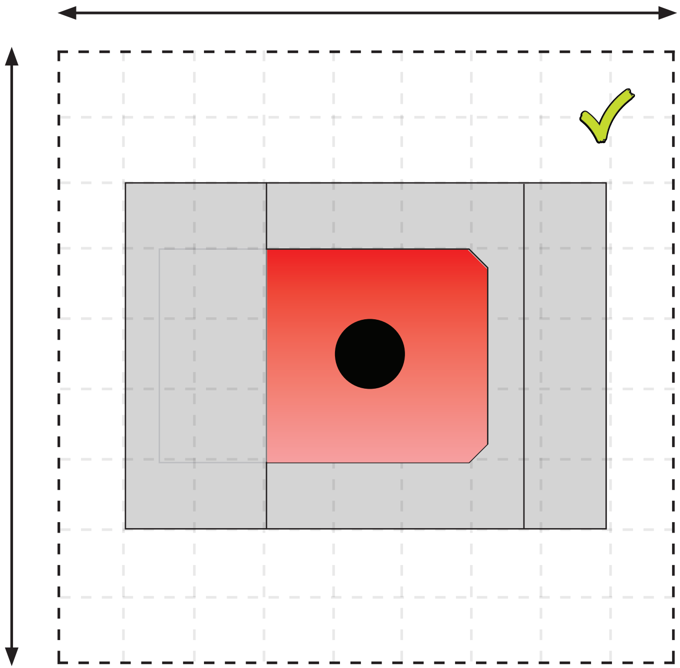
Anywhere in the proximity of the auditorium.
Exact location not important.



SECTION

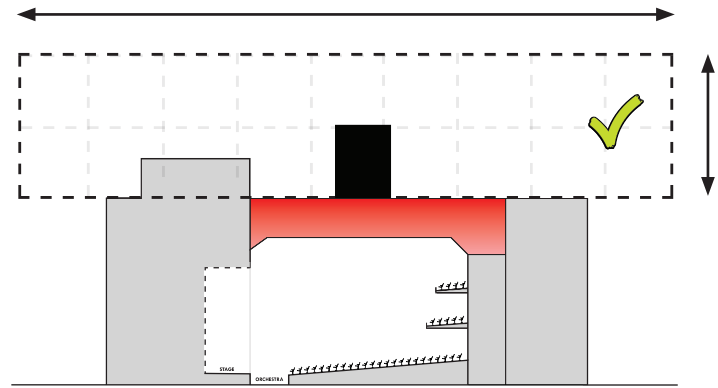
The inlet into the chimney needs to be
above the exhaust plenum

15 LOCATION OF THE CHIMNEYS



PLAN

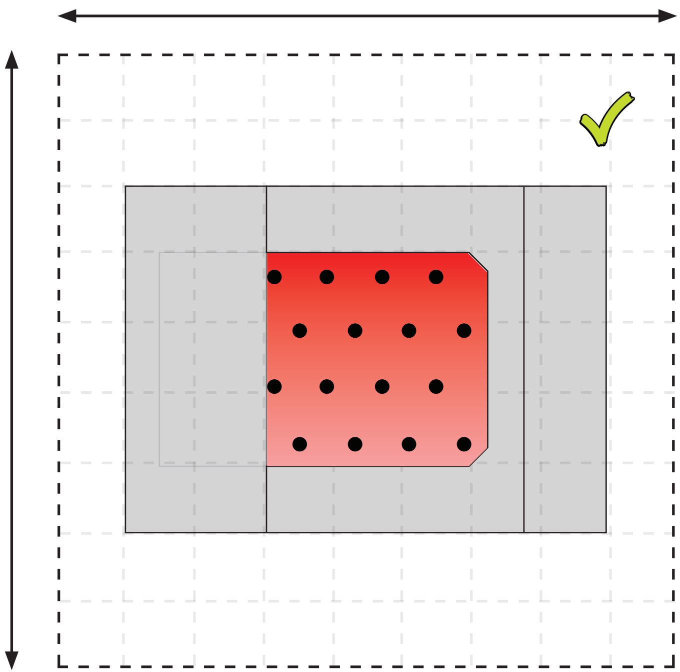
1



SECTION

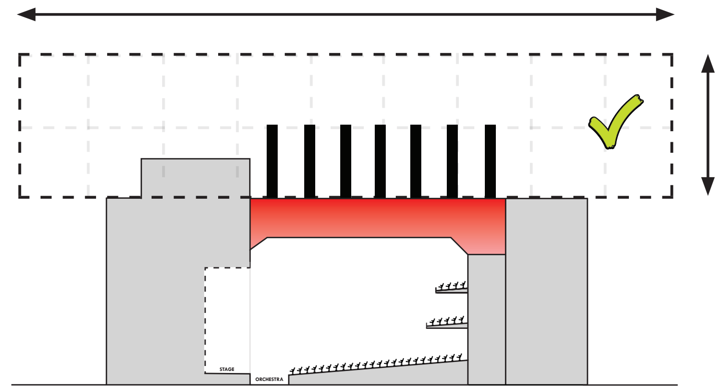
1

16 AMOUNT OF CHIMNEYS



PLAN

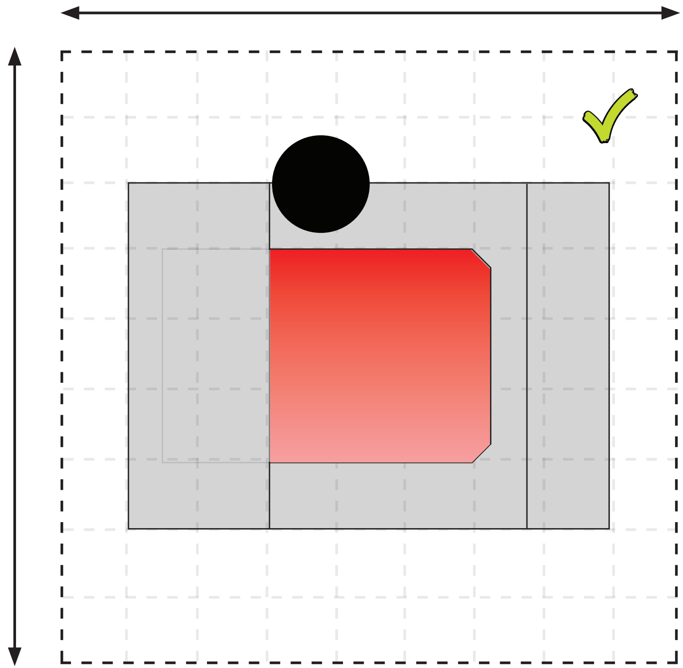
16



SECTION

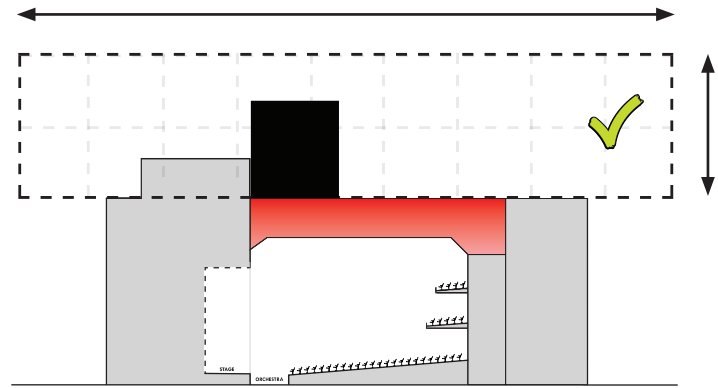
16

16 AMOUNT OF CHIMNEYS



PLAN

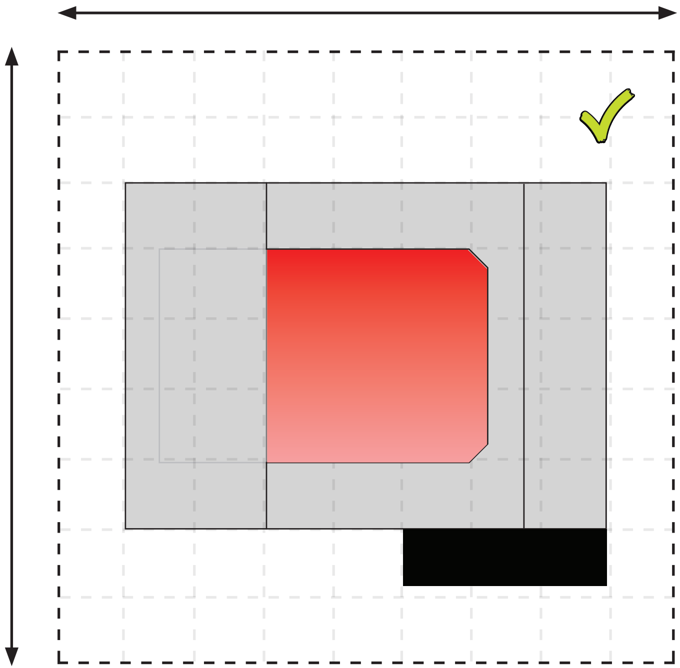
1 Decentralized



SECTION

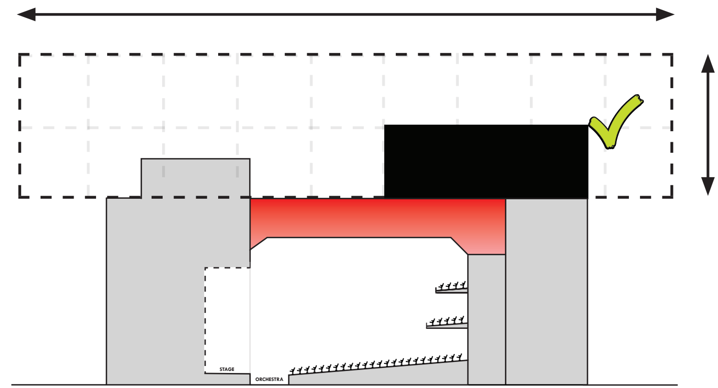
1 Decentralized

16 AMOUNT OF CHIMNEYS



PLAN

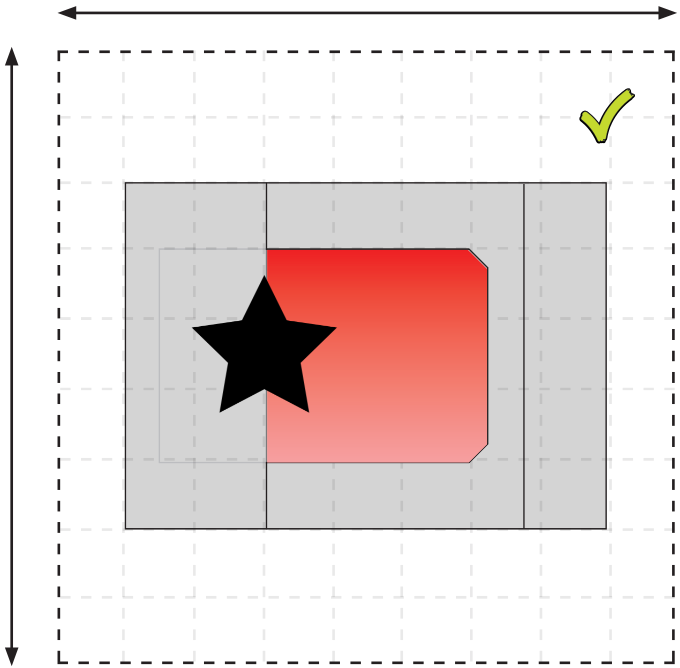
1 Decentralized



SECTION

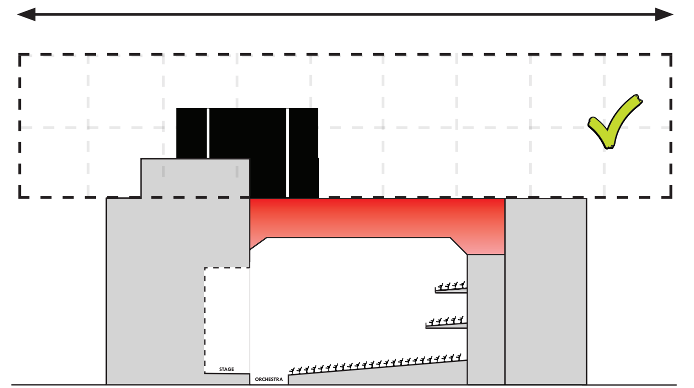
1 Decentralized

16 AMOUNT OF CHIMNEYS



PLAN

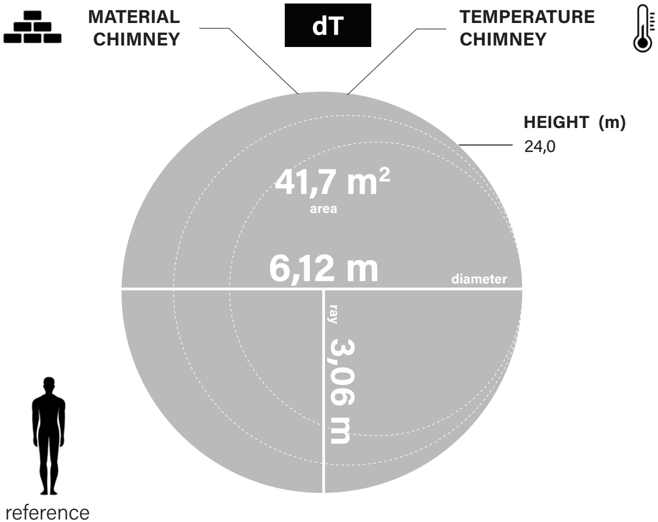
Odd shape



SECTION

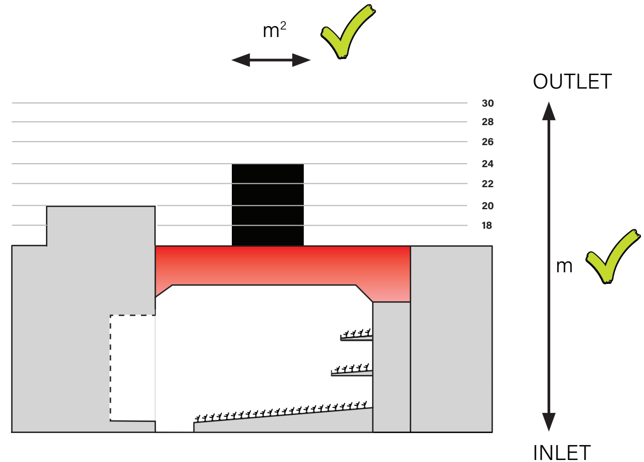
Odd shape

16 AMOUNT OF CHIMNEYS



24 METERS

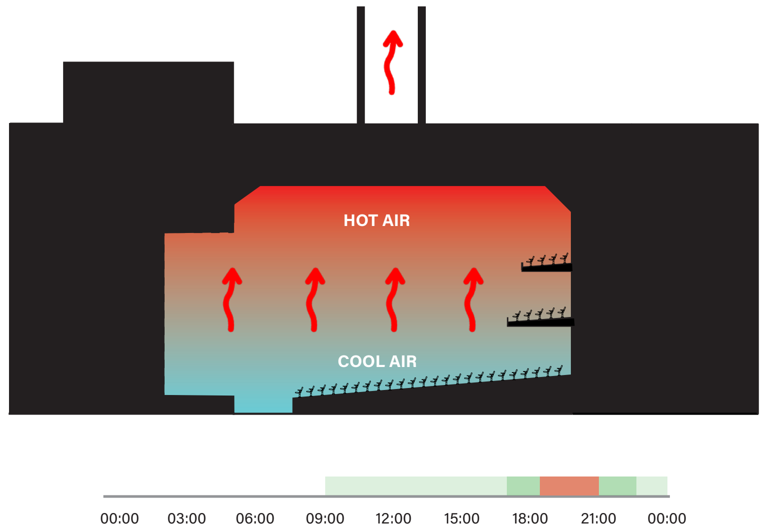
8 meters height increase



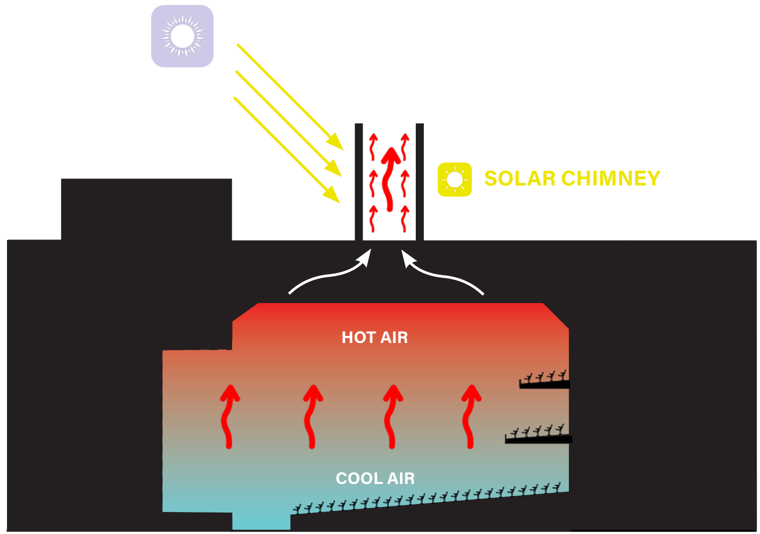
SECTION

Enough m^2 and height

17 LENGTH OF EXHAUST CHIMNEYS



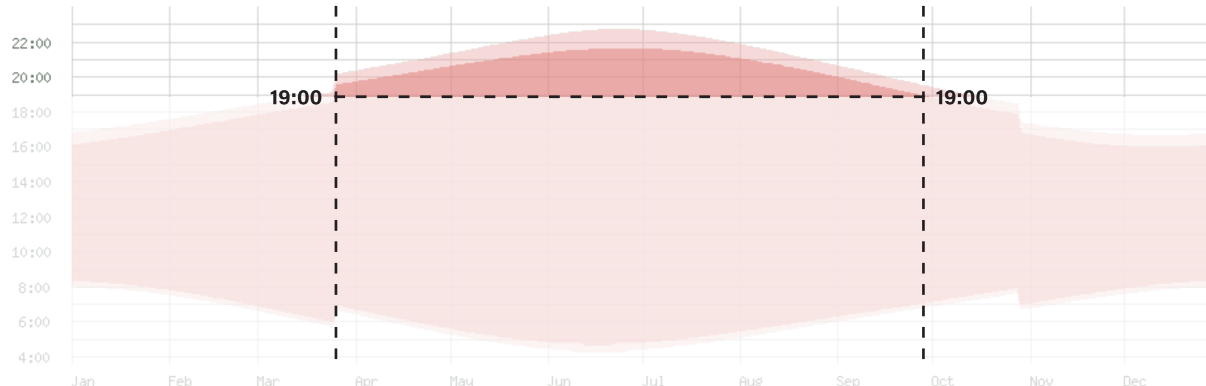
18 MATERIAL EXHAUST CHIMNEYS



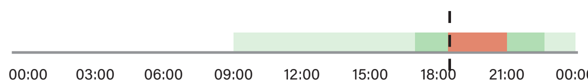
SUN ENHANCES HEAT INSIDE A CHIMNEY

This stimulates the speed of the air rise inside the chimney

18 MATERIAL EXHAUST CHIMNEYS



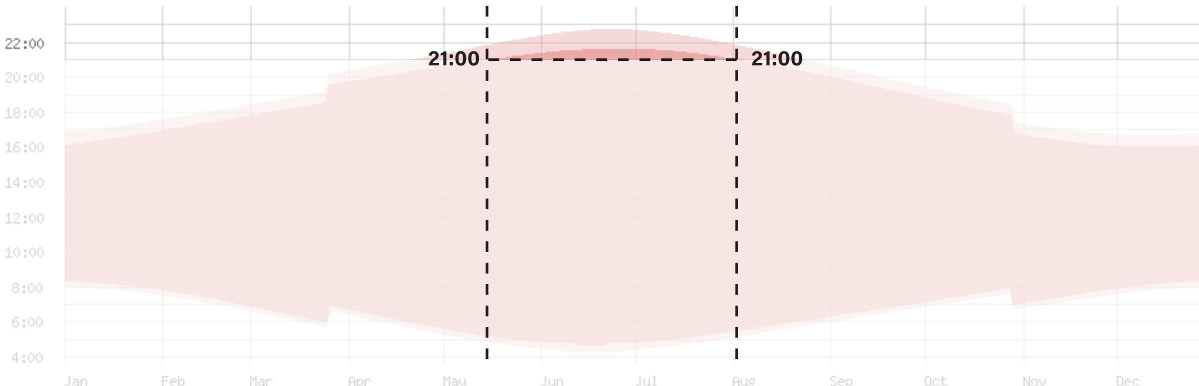
Sun hours in Berlin, Germany



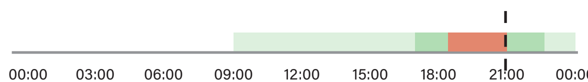
MEAGER SUN EXPOSURE DURING SHOWS

To not created accumulations of hot air

18 MATERIAL EXHAUST CHIMNEYS



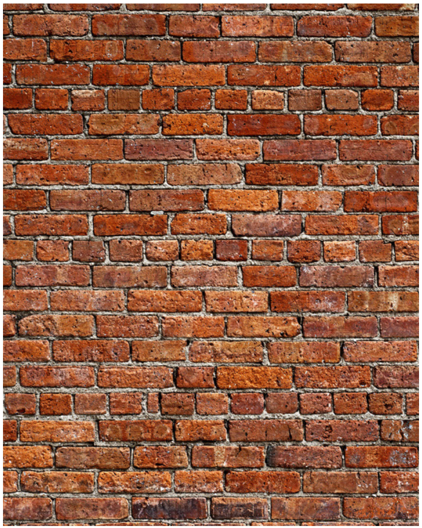
Sun hours in Berlin, Germany



MEAGER SUN EXPOSURE DURING SHOWS

To not created accumulations of hot air

18 MATERIAL EXHAUST CHIMNEYS



STONE / BRICK / CONCRETE

High thermal mass

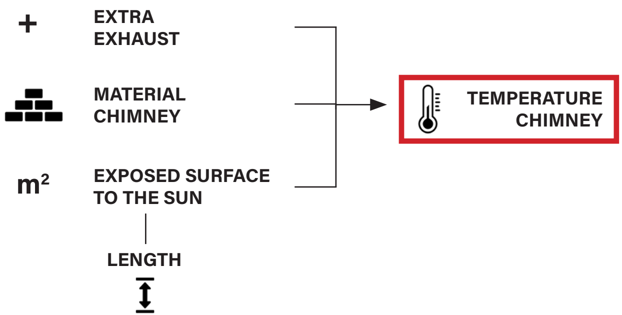
PHASE CHANGE MATERIALS (PCM'S)

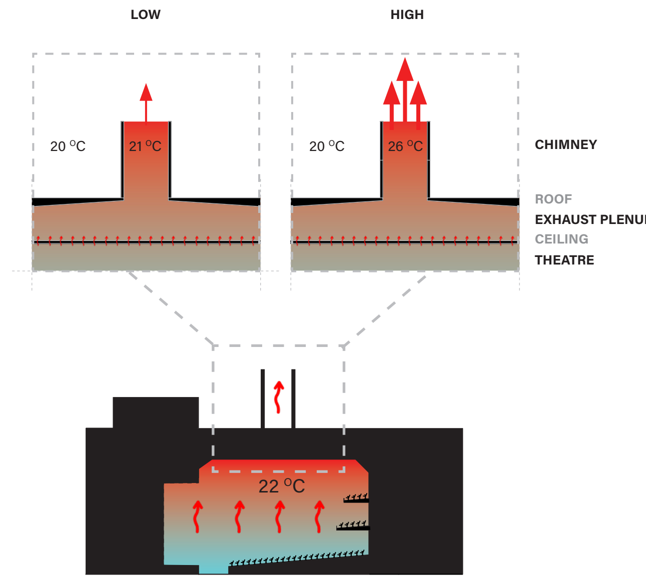
Change Phase at certain temperature range. Keep significant amount of energy

STEEL

High thermal conductivity

18 MATERIAL EXHAUST CHIMNEYS



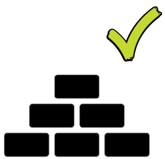


ENLARGED SECTION

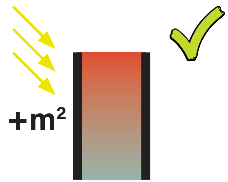
Auditorium, Plenum and Chimney

19 TEMPERATURE OF EXHAUST CHIMNEYS

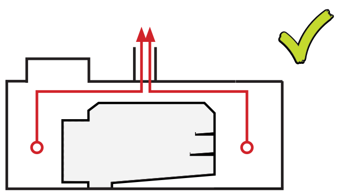
TEMPERATURE AMPLIFIERS



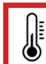
MATERIAL CHIMNEY

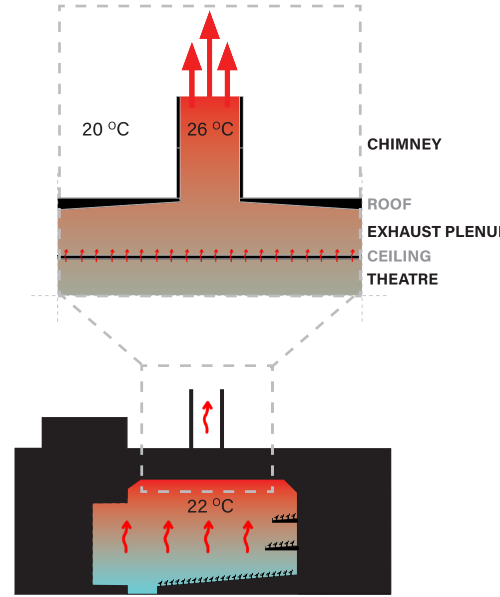


EXPOSED SURFACE TO THE SUN



OTHER EXHAUSTS


TEMPERATURE CHIMNEY



ENLARGED SECTION
Auditorium, Plenum and Chimney

19 TEMPERATURE OF EXHAUST CHIMNEYS

TEMPERATURE RISE IN CHIMNEY

$$\Delta T = \frac{0{,}0279 \cdot \Delta W^{\frac{2}{3}}}{h^{\frac{1}{3}} \cdot f^{\frac{2}{3}} . A_e^{\frac{2}{3}}} = 0{,}0279 \left(\frac{\Delta W^2}{h \cdot f^2 A_e^{\,2}} \right)^{\frac{1}{3}}$$

dT = temperatuurverschil tussen binnen en buiten
dW = warmteafvoer door ventilatie
h = hoogteverschil tussen toevoeropening en afvoeropeningen in m
Ae = equivalente ventilatieopening in m2
f = Tuit-Tin / delta T = (Tuit-Tbuiten) / (Tgem-Tbuiten)

ΔW = Internal heat production (W) → **200.000 W**

+

SOLAR HEAT

Solar heat gain (W) = $A_{exposed}$ (m^2) * Solar radiation (W/m^2)

+

ADDITIONAL EXHAUSTS

W = Exhaust of the rest of the builidng

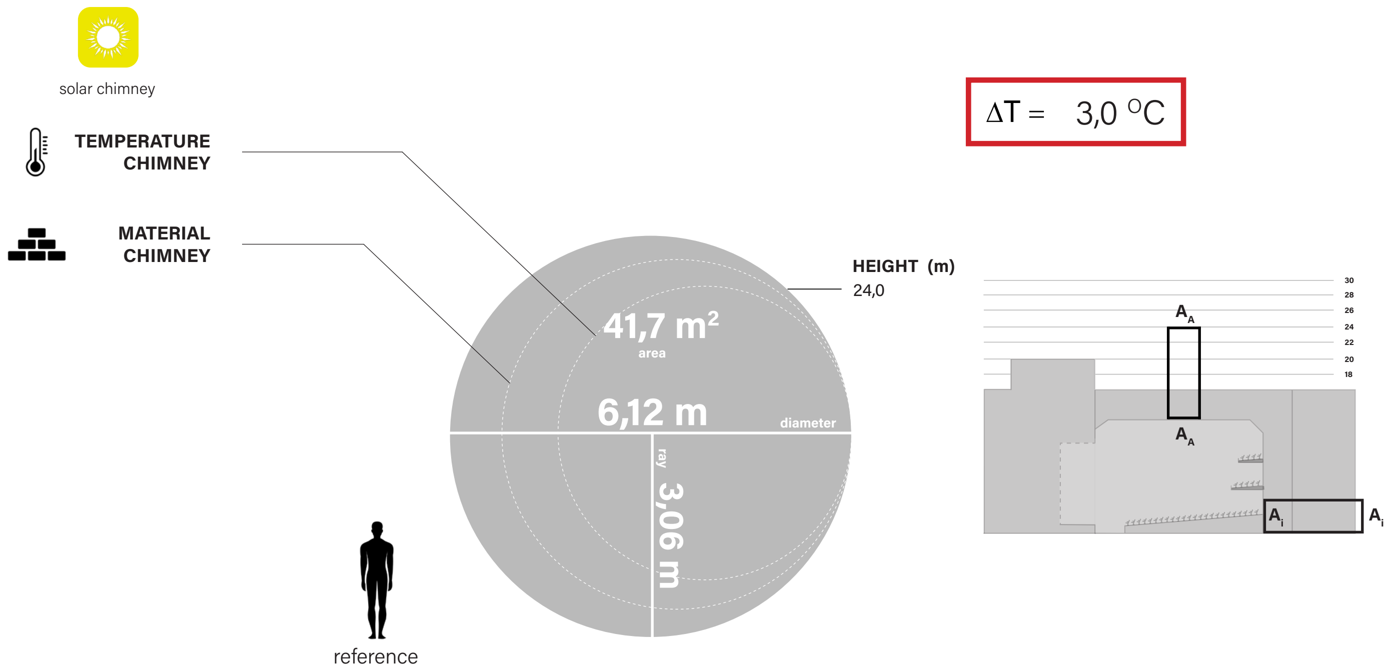
ΔW = Internal heat production (W)+ Solar heat gain (W) + Additional Exhaust (W)

SOLAR HEAT RADIATION

Month	1	2	3	4	5	6	7	8	9	10	11	12
Radiation	149	223	369	418	418	459	448	403	346	275	251	118

Average hourly monthly solar heat radiation (W/m^2)

19 TEMPERATURE OF EXHAUST CHIMNEYS



24 METERS

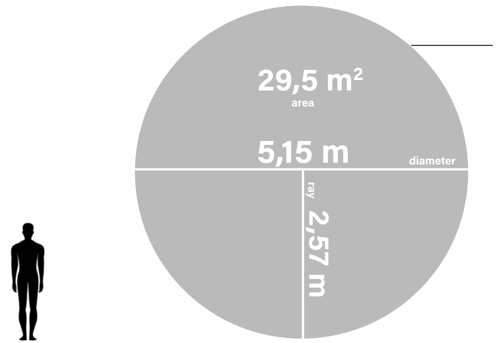
8 meters height increase

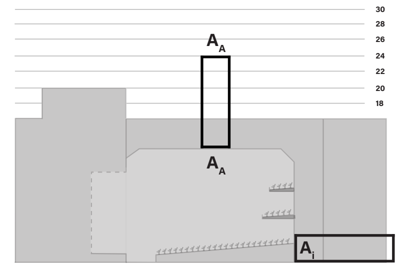
19 TEMPERATURE OF EXHAUST CHIMNEYS

solar chimney

stack effect

$\Delta T = \quad 6{,}0\ ^{O}C$





24 METERS

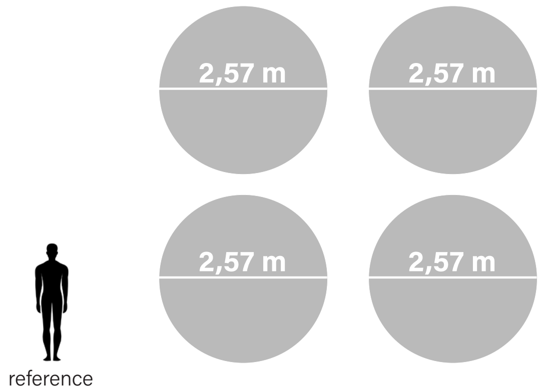
8 meters height increase

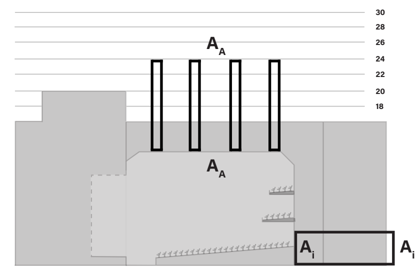
19 TEMPERATURE OF EXHAUST CHIMNEYS

solar chimney

stack effect

$\Delta T = 3{,}0\ ^{O}C$

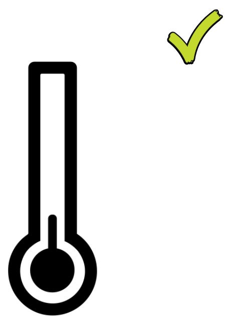




24 METERS

8 meters height increase

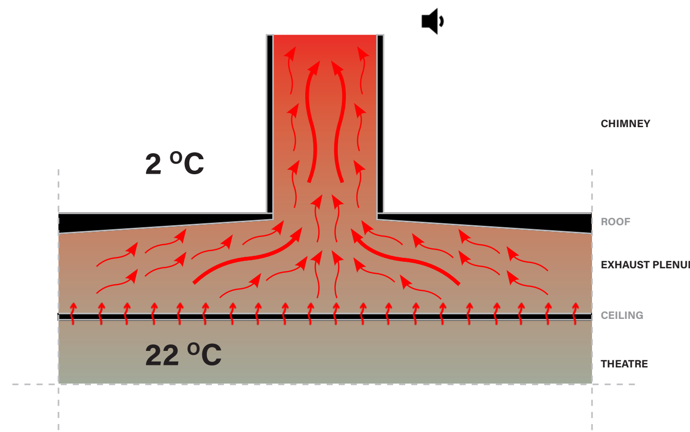
19 TEMPERATURE OF EXHAUST CHIMNEYS



LOW AMBIENT TEMPERATURE

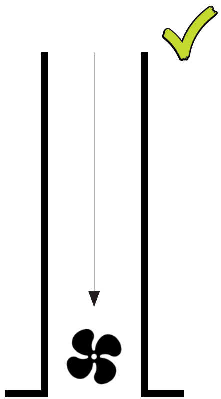
Easy heat dissipation

WINTER 1,4 - 2,4 ^{O}C



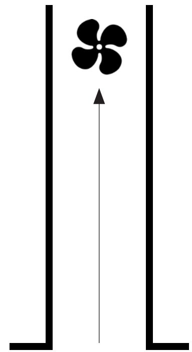
HIGH CLIMATIC COOLING EFFECT

Easy heat dissipation



LOWEST PART

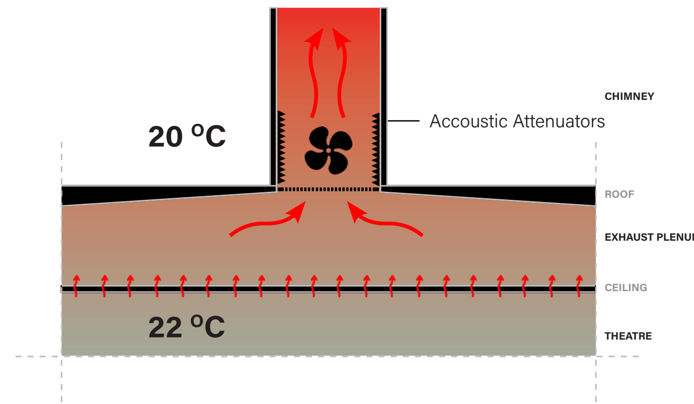
In the chimney



HIGHEST PART

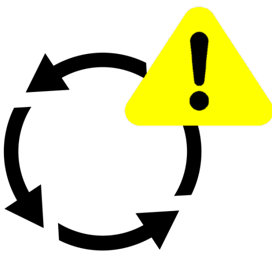
In the chimney

SUMMER 18 - 22 ^{o}C



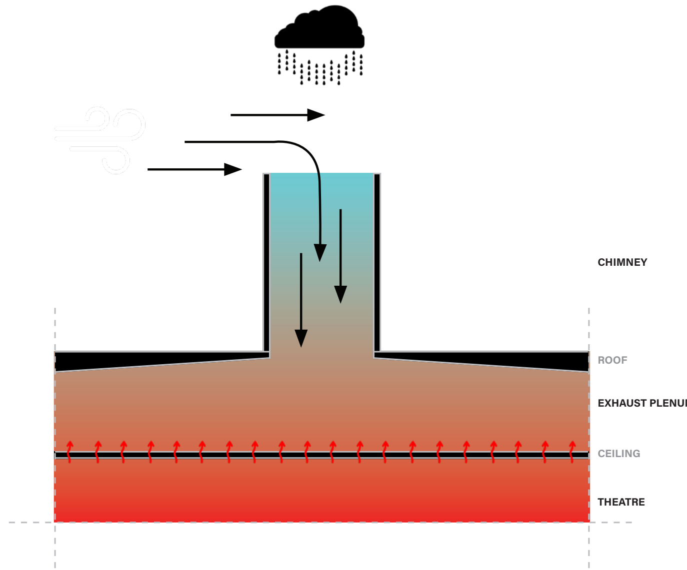
LOW CLIMATIC COOLING EFFECT

Easy heat dissipation



REVERSING AIRFLOWS

Because of wind flows



WIND AND RAIN

Unwanted

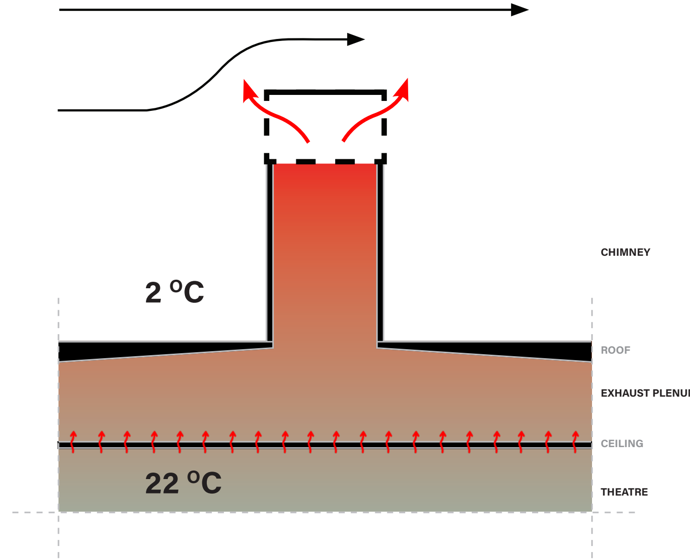
WIND AND RAIN

EXPRESSIVE

Architectural Expression

INTEGER

Architectural Expression

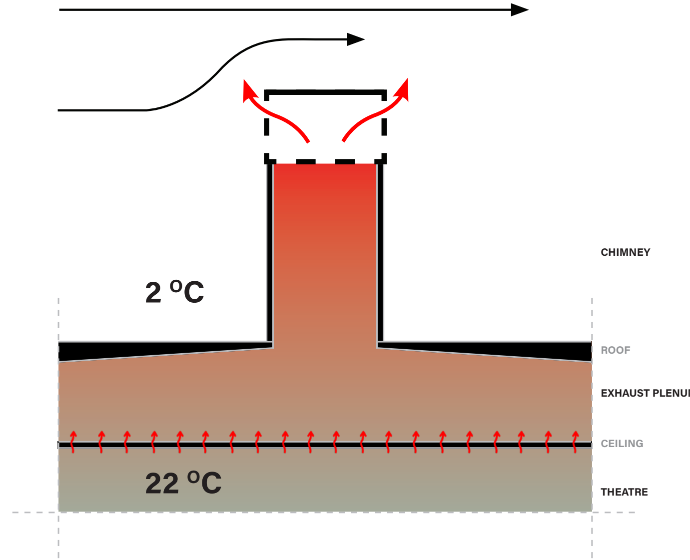


HIGH CLIMATIC COOLING EFFECT

Easy heat dissipation

WIND AND RAIN

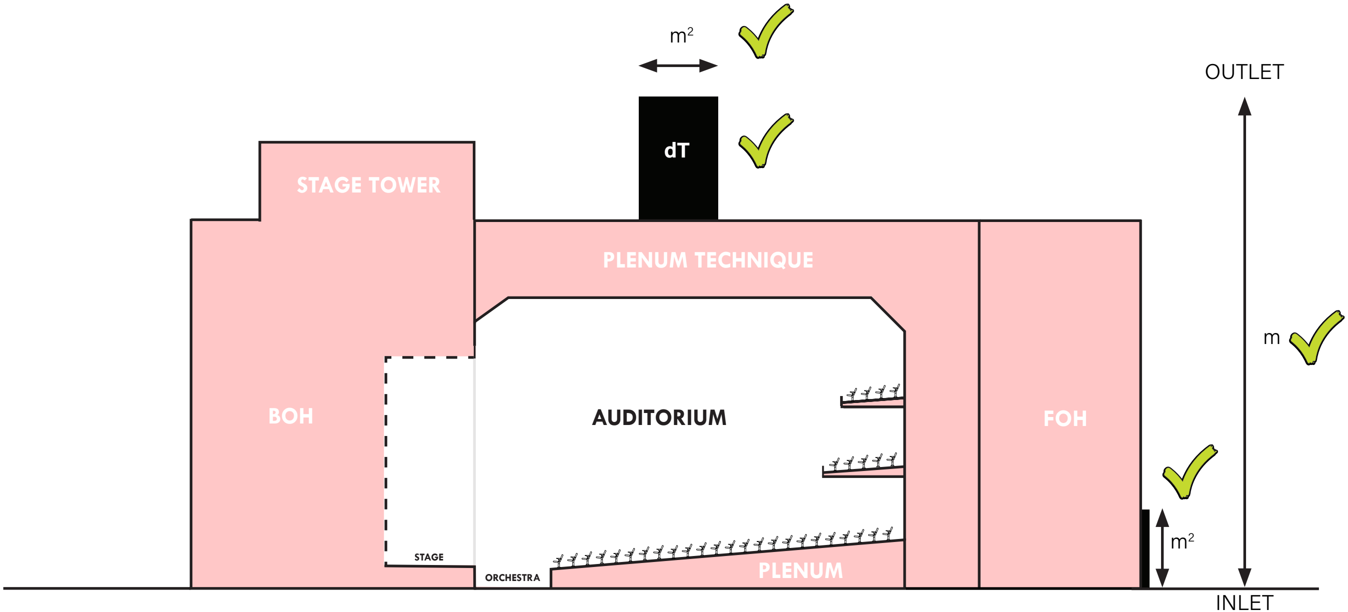
EXAMPLES



HIGH CLIMATIC COOLING EFFECT

Easy heat dissipation

FLEXIBILITY

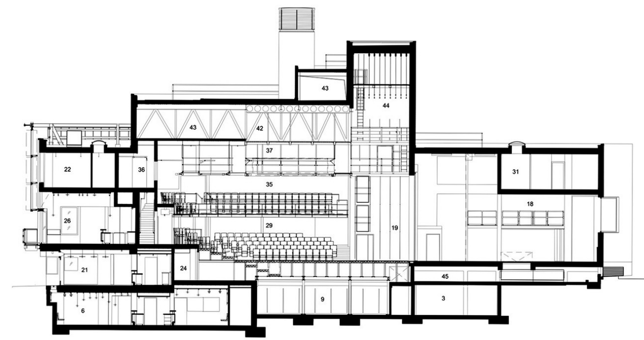


PART 1: RETRIEVING INCOMING AIR
2 CONSIDERATION 2: RETRIEVING AIR FROM OUTSIDE
3 CONSIDERATION 3: CARDINAL INTAKE
4 CONSIDERATION 4: AIR TEMPERATURE
5 CONSIDERATION 5: PATH THROUGH BUILDING
6 CONSIDERATION 6: INTO AUDITORIUM
7 CONSIDERATION 7: BALCONIES
8 CONSIDERATION 8: SIZE OF THE AIRINLET
9 CONSIDERATION 9: REGULATION INCOMING AIR

PART 2: INSIDE THE THEATRE
10 CONSIDERATION 10: HEAT DISSIPATION PER SEASON
11 CONSIDERATION 11: VENTILATION BY BUOYANCY
12 CONSIDERATION 12: LESS OCCUPACY
13 CONSIDERATION 13: AIR AT THE TOP OF THE AUDITORIUM
14 CONSIDERATION 14: UPPER SIDE OF THE PLENUM

PART 3: THE EXHAUST
15 CONSIDERATION 15: LOCATION OF THE CHIMNEYS
16 CONSIDERATION 16: AMOUNT OF EXHAUST CHIMNEYS
17 CONSIDERATION 17: LENGTH OF EXHAUST CHIMNEYS
18 CONSIDERATION 18: MATERIAL EXHAUST CHIMNEYS
19 CONSIDERATION 19: SOUND
20 CONSIDERATION 20: WIND AND RAIN

APPLICATION

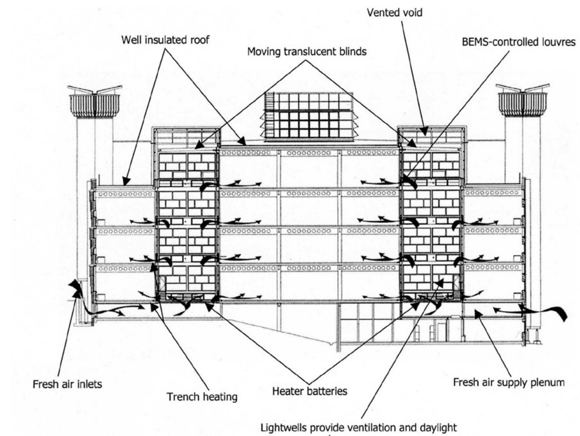


Everyman Theatre
Liverpool, England

CHIMNEY

On top of building

APPLICATION

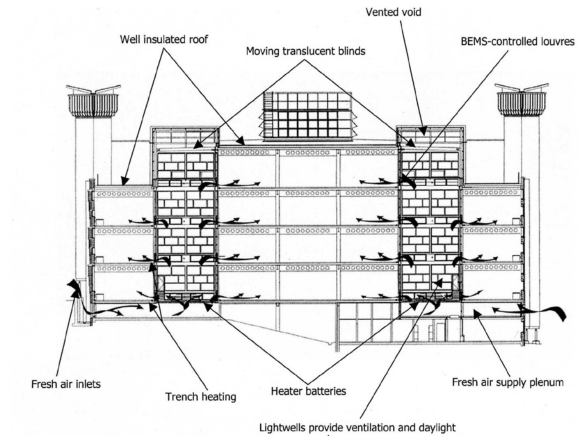


The Contact Theatre
Manchester, England

CHIMNEY

On top of building

APPLICATION



Lanchester Library
Coventry, Engeland

CHIMNEY

On top of building

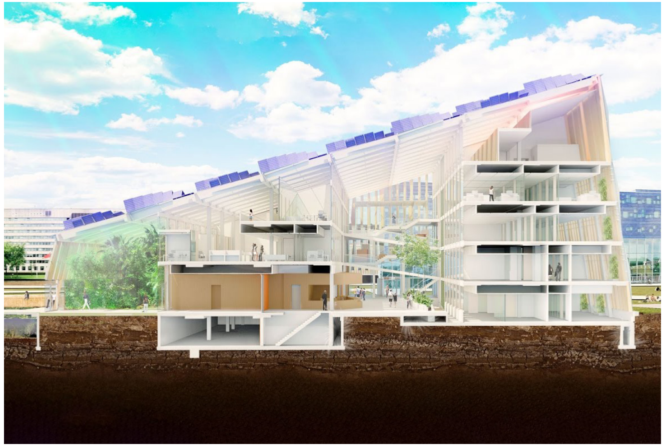
APPLICATION

Hexagone Balard, Ministry of Defence
Paris, France

INTEGRAL PART

Of the building

APPLICATION



INTEGRAL PART

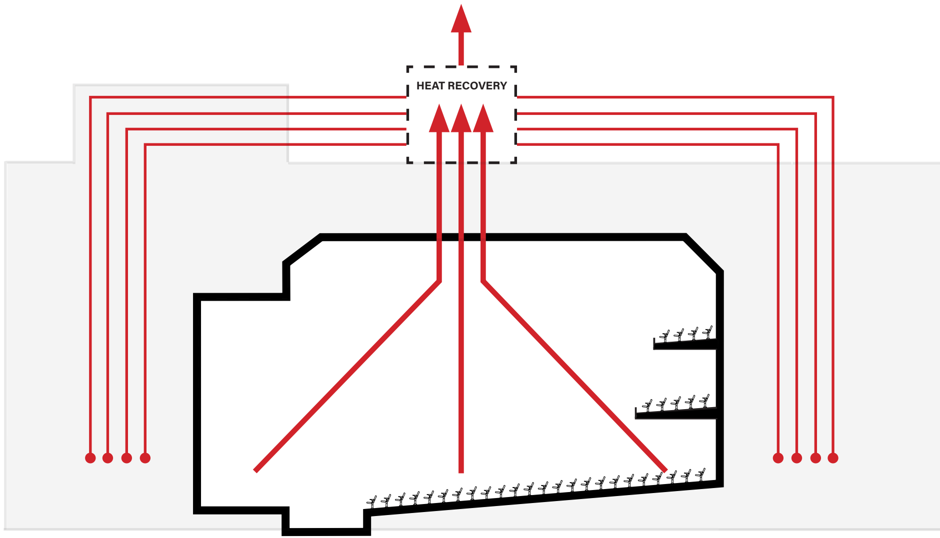
Of the building design

PART 1: RETRIEVING INCOMING AIR

PART 2: INSIDE THE THEATRE

PART 3: THE EXHAUST

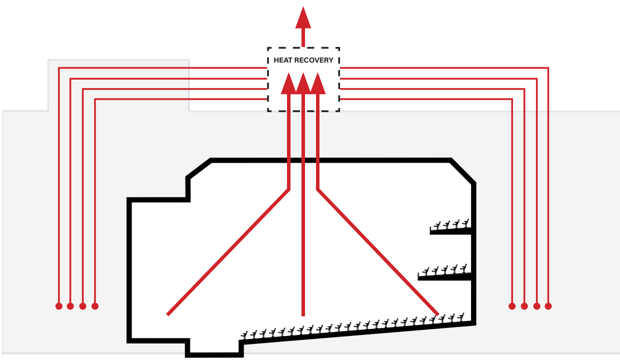
PART 4: ADDITIONAL MEASURES



HEAT RECOVERY

As all the heat naturally centralizes in one or multiple locations, these spaces offer good space for heat recovery of the heated air. This can be used to heat other parts of the building.

22 RE-USING THE HEAT

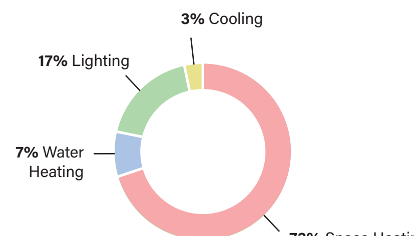


HEAT RECOVERY

As all the heat naturally centralizes in one or multiple locations, these spaces offer good space for heat recovery of the heated air. This can be used to heat other parts of the building.

CENTRAL EUROPEAN REGION

Location of Berlin

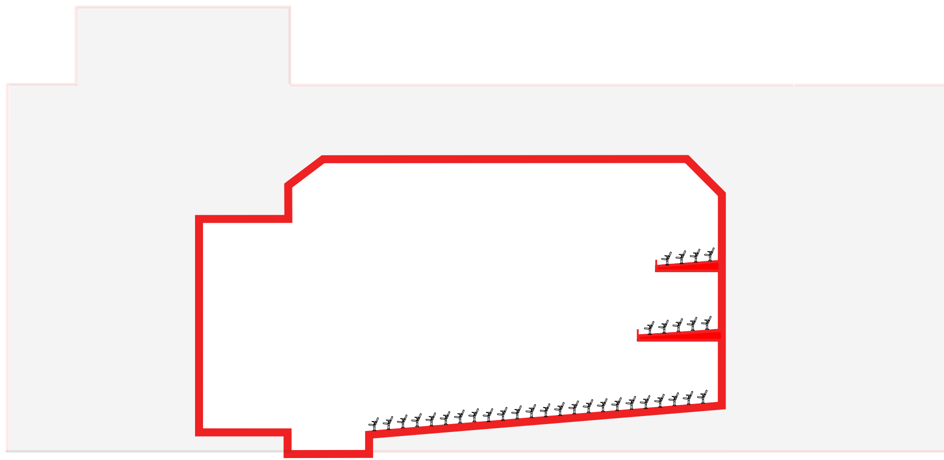


AVERAGE ENERGY CONSUMPTION

Non-residential

22 RE-USING THE HEAT

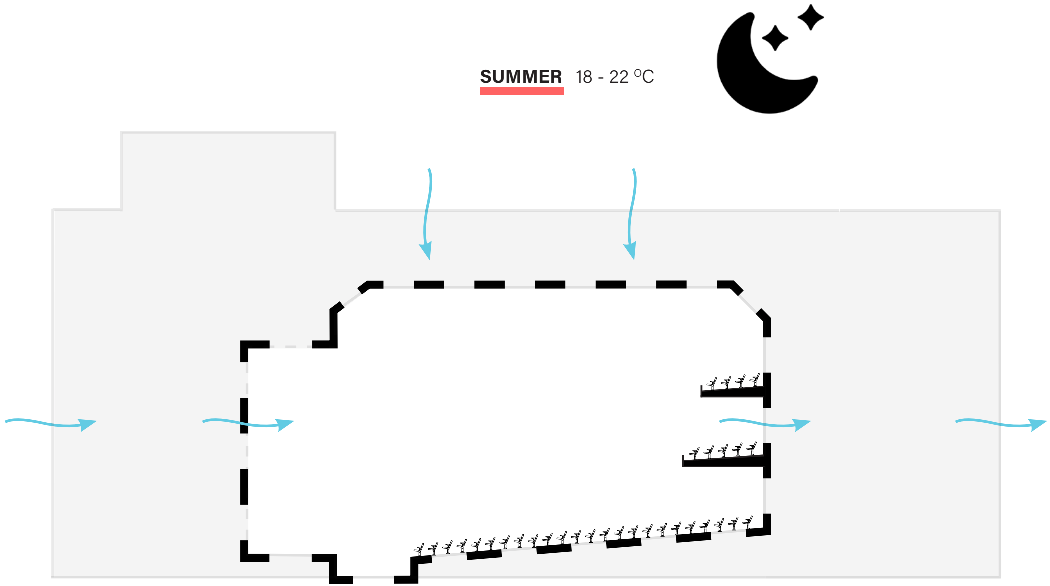
SUMMER 18 - 22 ^{O}C



THERMAL MASS
< 2 -3 ^{O}C in summer

High thermal mass of the theatre results in slower heating of the space as the high thermal mass slowly heats up due to daytime temperatures. This is especially effective with night ventilation.

23 THERMAL MASS



NIGHT TIME VENTILATION

In summer we can cool the thermal mass of the structure by the colder outside temperatures.

24 NIGHT TIME VENTILATION

CONSIDERATIONS

PART 1: RETRIEVING INCOMING AIR

- 2 RETRIEVING AIR FROM OUTSIDE ✓
- 3 CARDINAL INTAKE ✓
- 4 AIR TEMPERATURE ✓
- 5 PATH THROUGH BUILDING ✓
- 6 INTO AUDITORIUM ✓
- 7 BALCONIES ✓
- 8 SIZE OF THE AIRINLET ✓
- 9 REGULATE AIRFLOWS ✓

PART 2: INSIDE THE THEATRE

- 10 HEAT DISSIPATION PER SEASON ✓
- 11 VENTILATION BY BUOYANCY ✓
- 12 LESS OCCUPACY ✓
- 13 AIR AT THE TOP OF THE AUDITORIUM ✓
- 14 UPPER SIDE OF THE PLENUM ✓

PART 3: THE EXHAUST

- 15 LOCATION OF THE CHIMNEYS ✓
- 16 AMOUNT OF EXHAUST CHIMNEYS ✓
- 17 LENGTH OF EXHAUST CHIMNEYS ✓
- 18 MATERIAL EXHAUST CHIMNEYS ✓
- 19 TEMPERATURE EXHAUST CHIMNEYS ✓
- 20 SOUND ✓
- 21 WIND AND RAIN ✓

PART 4: ADDITIONAL MEASURES

- 22 RE-USING THE HEAT ✓
- 23 NIGHT TIME COOLING ✓
- 24 THERMAL MASS ✓

✓ **Naturally Ventilated Theatre**

✓ **Mechanically Assisted**

→ **Hybrid**