
adaptive fabric façade for a high-rise in paris
p5 presentation | July 2017
antigoni lampadiari-matsa | 4516907

# 1

# problem statement + research framework

# problem statement

long construction time

heavy equipment

a lot of manpower

glass ⇢ heavy material ⇢ dominant in all kinds of buildings

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glass → heavy material → dominant in all kinds of buildings

→ need for lightweight materials

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long construction time

heavy equipment

a lot of manpower

glass → heavy material → dominant in all kinds of buildings

need for lightweight materials

fabrics/membranes → **possible solution**


why fabric??

# why fabric??

lightweight

flexible / foldable

high tensile and tear strength

variety of transparency levels

recyclability

## why fabric??

lightweight

flexible / foldable

high tensile and tear strength

variety of transparency levels

recyclability

## façade requirements

daylight levels

glare control

solar heat gain

thermal insulation

ventilation

water management

sound and pollution control

# research question

*How can an **adaptive**, **lightweight** and **flexible fabric** façade be designed, a façade that will be responsible for meeting the requirements and improving the **indoor comfort** in terms of **thermal** and **acoustical** insulation, as well as **shading** and **sun control** in a **high-rise** in Paris?*

# sub - questions

» Which are the main **problems of high-rises** that should be tackled? Which among them occur in the **chosen location**?

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» Which is the most **effective façade design** that meets all the requirements?

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» Which are the **most suitable fabrics/textiles** as a solution to the above problems? Do they meet the **building envelope requirements**?

» Which is the most **effective façade design** that meets all the requirements?

» How can the desired **adaptivity** be achieved? With what kind of **mechanisms**?

# methodology

categories of fabrics + properties

PCMs / PV films

coatings

## 1.literature survey

recycling

high-rises

unitised element façade

climate

preliminary design concepts

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## 1.literature survey

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preliminary design concepts

selection of certain design concepts

selection of fabrics

## 2.analysis and conclusions

selection of a case study

# methodology

categories of fabrics + properties

PCMs / PV films

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unitised element façade

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preliminary design concepts

selection of certain design concepts

selection of fabrics

## 2.analysis and conclusions

selection of a case study

further development of concepts

simulations

physical models / calculations

acoustic test

## 3.design phase

drawings + details

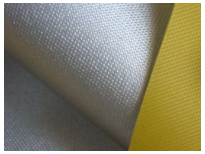
selection of final model

# 2

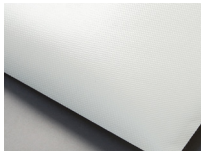
# materials

# table of materials

PVC-coated polyester

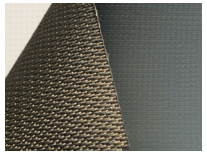


PVC-Birdair



PTFE

PTFE-coated glass-fibre



PTFE/ETFE/PVDF coated with fluoropolymer

THV coated polyester/ETFE

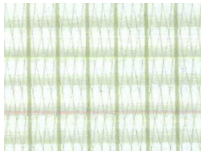
Silicone-coated glass-fibre

PTFE laminated glass-fibre mesh

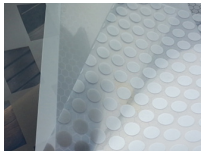
coated PTFE

uncoated PTFE

PVC/PTFE-coated aramid fibre



ETFE



TENSOTHERM™ with nanogel ® (layers with PTFE fiberglass)

Texlon® ETFE Vector Foiltech

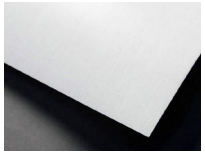
PLA

PU coated nylon

PVDF (Polyvnlylidene fluoride)

Silicone leather

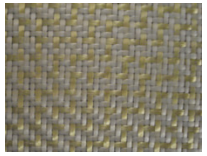
Tenara fabric (Architen Landrell) - ePTFE (fluoropolymer composite)



KEVLAR® PARA-ARAMID (DuPont™)

NOMEX® PARA-ARAMID (DuPont™)

VECTRAN® liquid crystal polymer (Kuraray™)



ZYLON® PBO (Toyobo™)

TECHNORA® (Teijin™)

UHMWPE (Honeywell™)

# comparison criteria

PTFE/ETFE/PVDF

PVC-coated polyester

PVC-Birdair

PTFE



PTFE laminated glass-fibre mesh

coated PTFE

uncoated PTFE

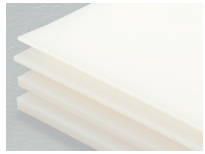


PVC/PTFE-coated aramid fibre



ETFE

PVDF (Polyvnlylidene fluoride)



Silicone leather



Tenara fabric (Architen Landrell) - ePTFE (fluoropolymer composite)

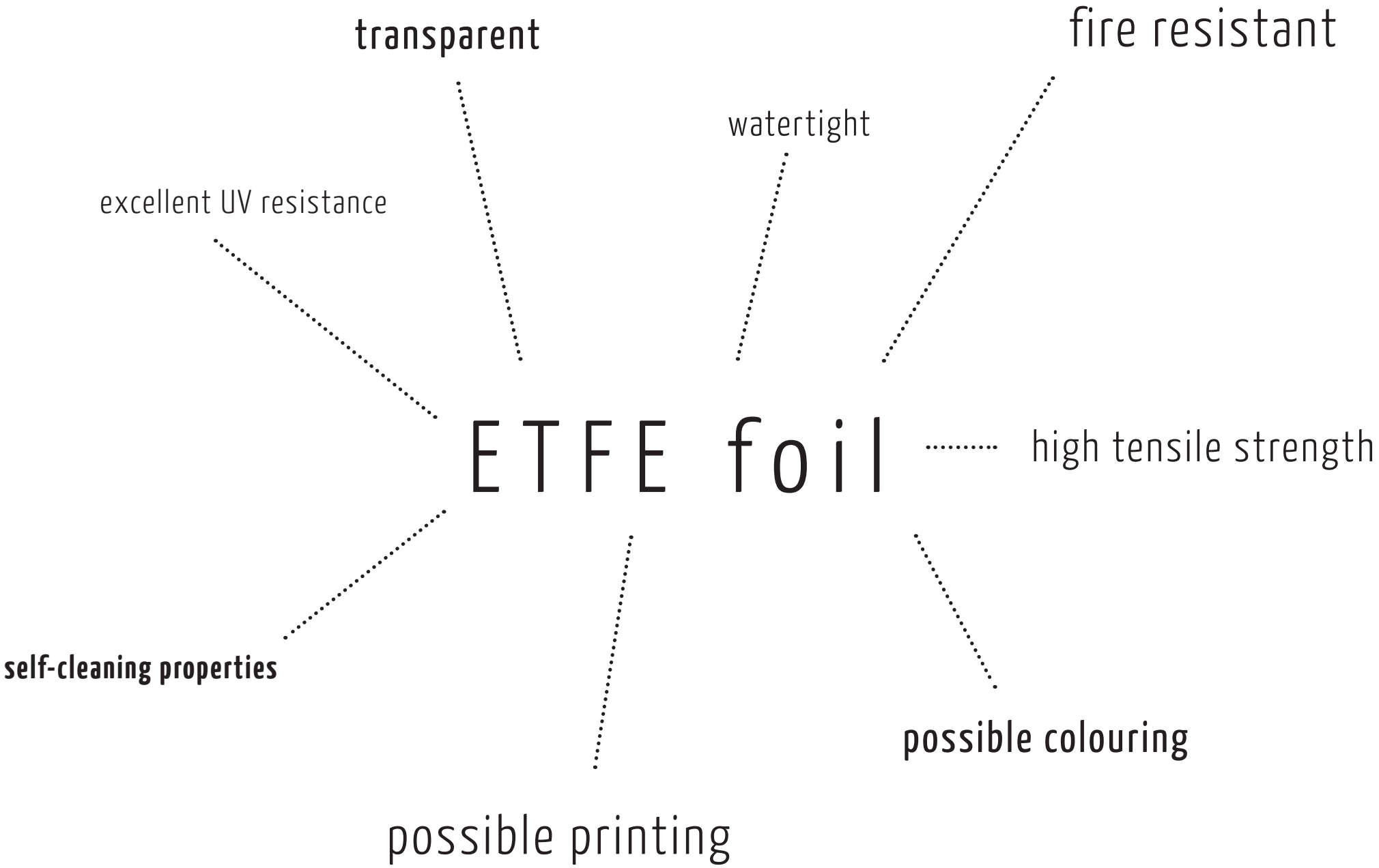
KEVLAR® PARA-ARAMID (DuPont™)



- » tensile strength
- » UV-resistance
- » reaction to fire
- » light transmittance
- » sensitivity to soiling
- » resistance to external factors
- » necessity of a top coat
- » price
- » levels of transparency / translucency
- » service life
- » possibility of recycling

# summary of comparison

| excellent UV resistance | good UV resistance | fire resistance | transparency | self-cleaning properties | possible printing | recyclable | high price |
|---|---|---|---|---|---|---|---|
| coated & uncoated PTFE | PVC-coated polyester | PVDF | ETFE | ETFE | ETFE | ETFE | Silicone-coated glassfibre |
| PTFE-coated glassfibre | Silicone-coated glassfibre | NOMEX® PARA-ARAMID (DuPont™) | PVC Birdair | PTFE-coated glassfibre | PTFE-coated glassfibre | PVDF | coated & uncoated PTFE |
| PTFE/ETFE/PVDF coated with fluoropolymer | PTFE laminated glassfibre mesh | PTFE | Texlon ETFE Vector Foiltech | PTFE/ETFE/PVDF coated with fluoropolymer | PVDF | PVC-coated polyester | PVC/PTFE-coated aramid fibre |
| ETFE | TENSOTHERM™ with nanogel ® (layers with PTFE fiberglass) | Silicone-coated glassfibre | PV coated nylon | THV coated polyester/ETFE | | Silicone-coated glassfibre | Tenara fabric (ePTFE) |
| THV coated polyester/ETFE | PLA | PVC/PTFE-coated aramid fibre | PVDF | PTFE laminated glassfibre mesh | | | |
| Texlon ETFE Vector Foiltech | Silicone leather | Tenara fabric (ePTFE) | **translucent** | | | | |
| PVDF | Tenara fabric (ePTFE) | | coated & uncoated PTFE | **opaque** | | | |
| NOMEX® PARA-ARAMID (DuPont™) | UHMWPE | | Silicone-coated glassfibre | PVC/PTFE-coated aramid fibre | | | |
| | | | THV coated polyester/ETFE | PLA | | | |
| | | | PTFE-coated glassfibre | Silicone leather | | | |
| | | | PVC-coated polyester | | | | |
| | | | TENSOTHERM™ with nanogel ® (layers with PTFE fiberglass) | | | | |
| | | | Tenara fabric (ePTFE) | | | | |


transparent
fire resistant
watertight
excellent UV resistance
ETFE foil
high tensile strength
self-cleaning properties
possible printing
possible colouring

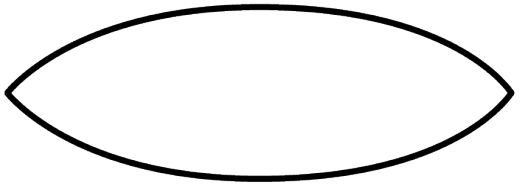
3

# design concepts

# design concepts

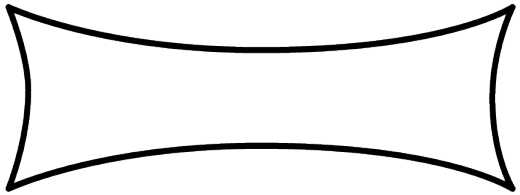
## inflatable (cushions)

[pressure difference]

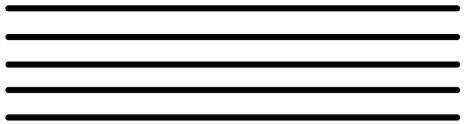


## deflateable (vacuum system)

[pressure difference]

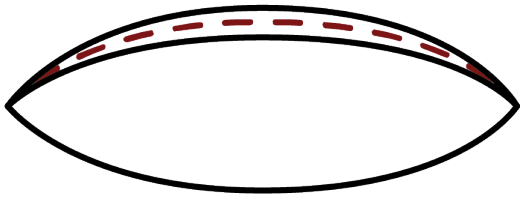


## multi-layer system

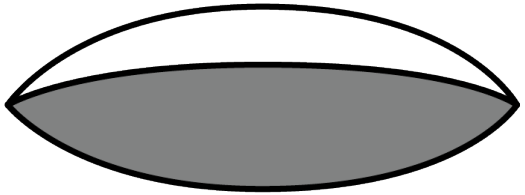


horizontal sections

## PV flexibles



## silica-aerogel

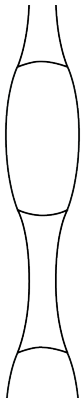


## PCMs

vertical sections

# design concepts

1 a



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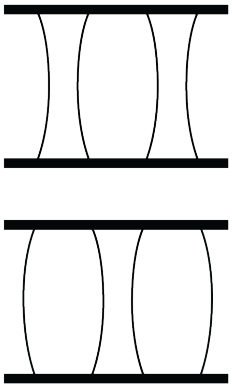

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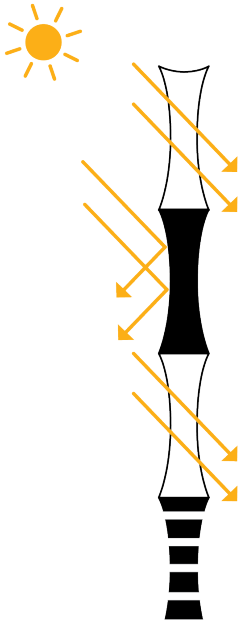

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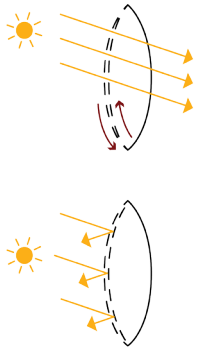

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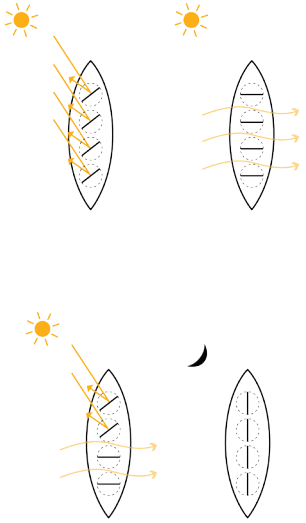

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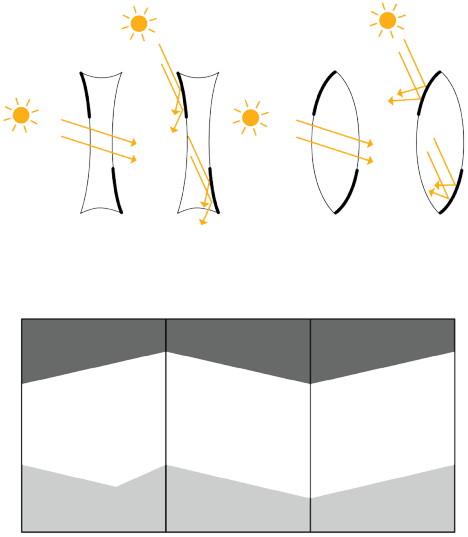

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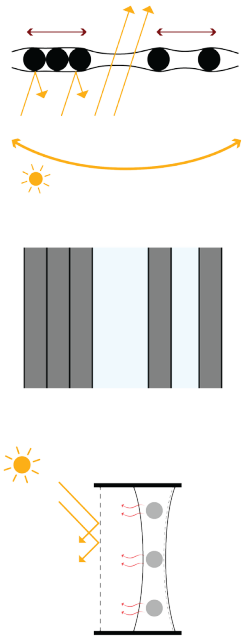

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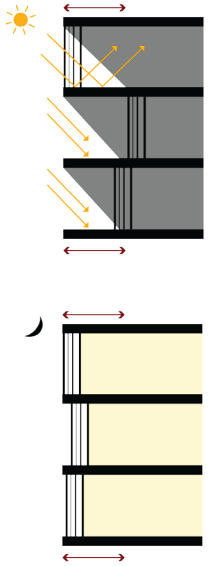

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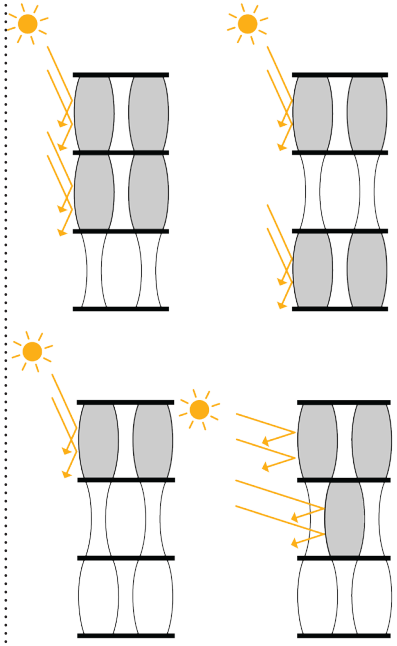

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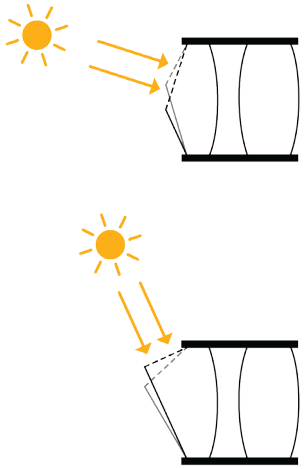
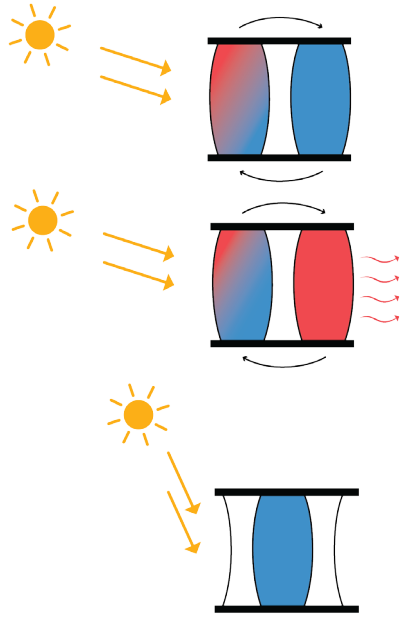


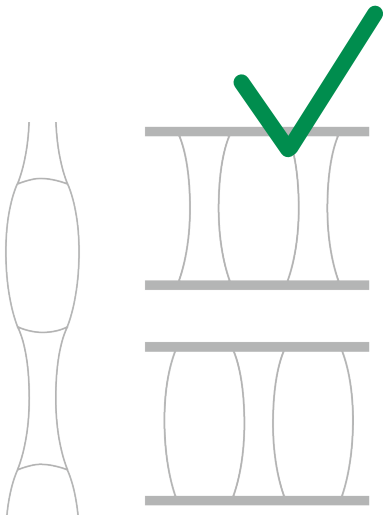
1 0



# design concepts

1 a

1 b



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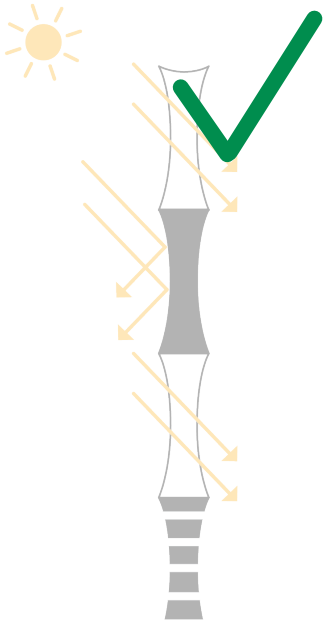

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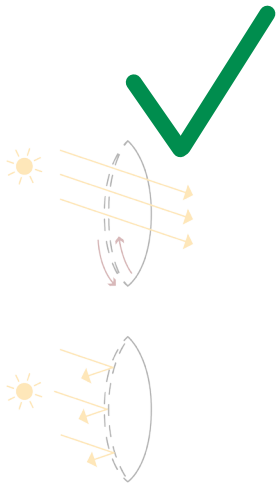

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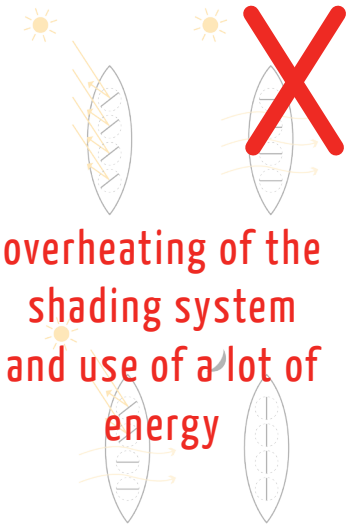
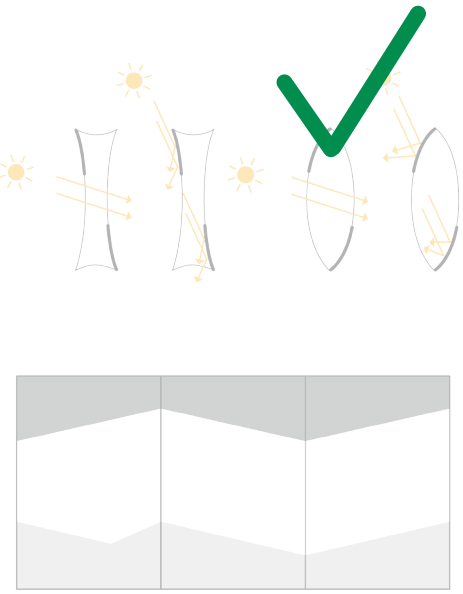


overheating of the shading system and use of a lot of energy

5



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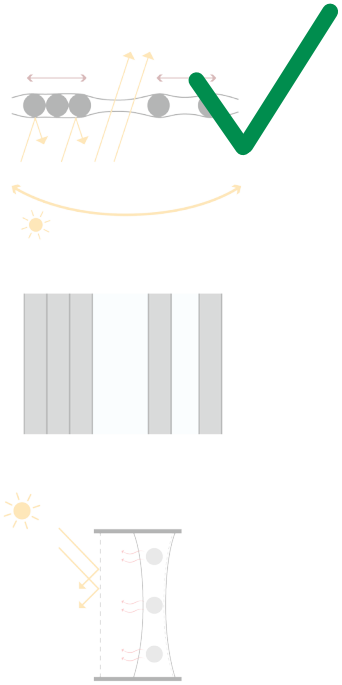
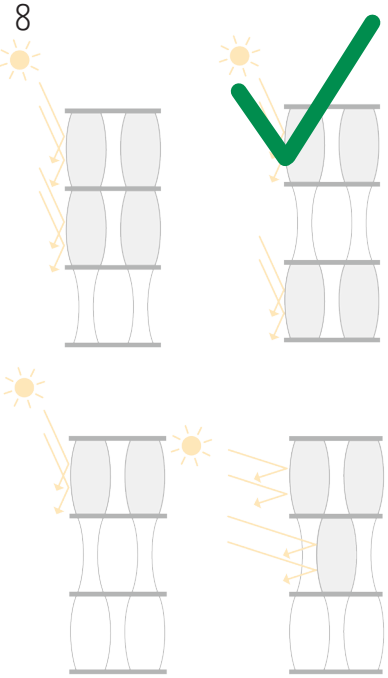


7

creation of useless space and use of energy

8



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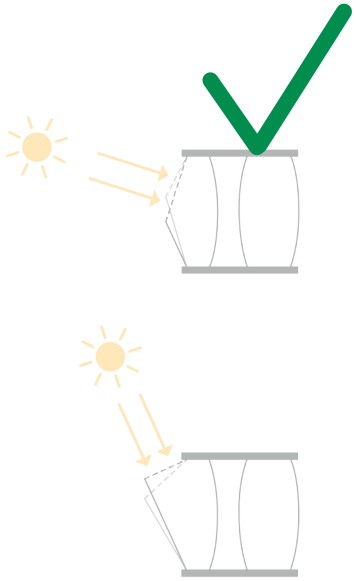


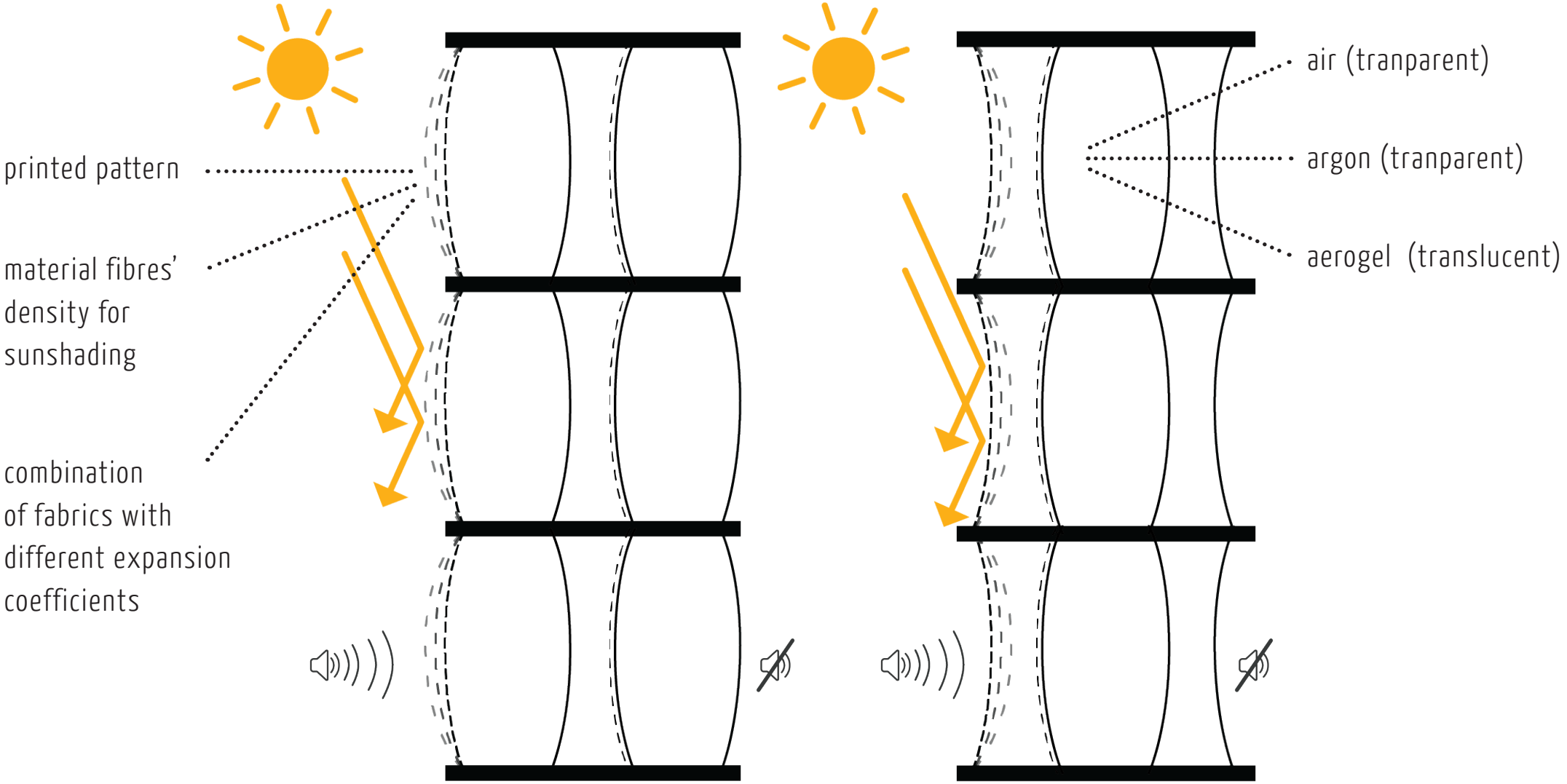
10

water not really compatible with fabrics / leaks

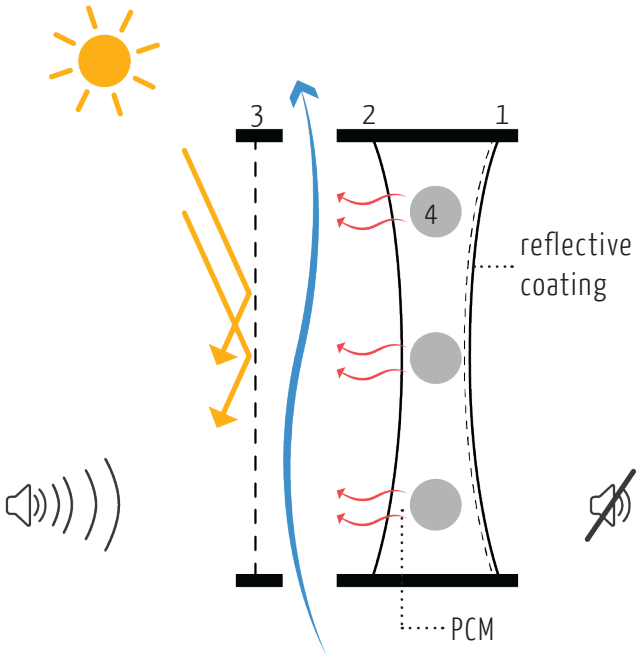
# design concepts

1.

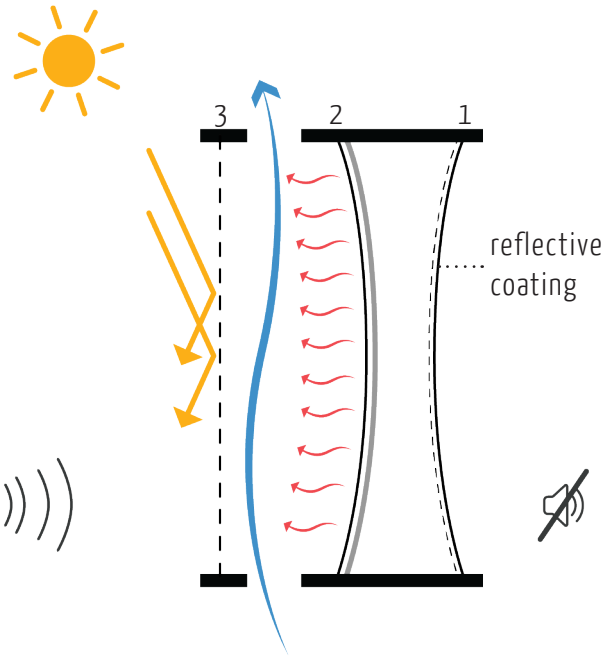
inflated cushions + vacuum system = a multilayer façade element for thermal and acoustical insulation



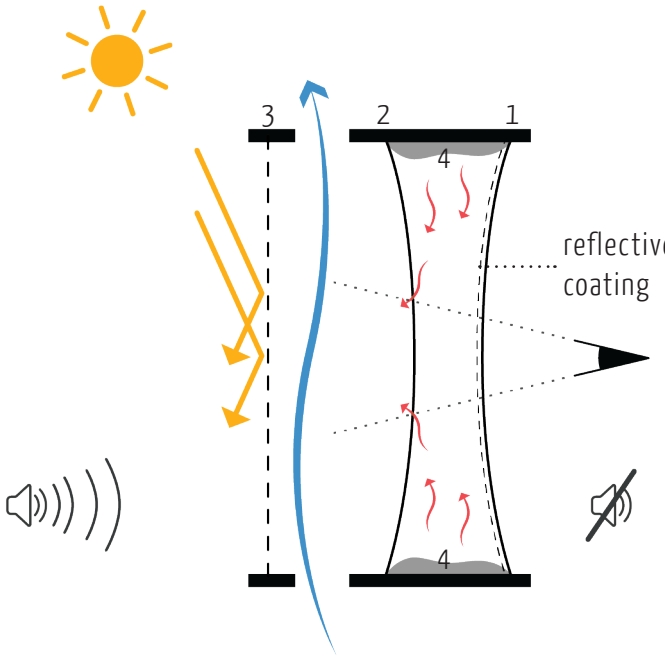
2.




**4:** PCM inside the vacuum




**2:** mulitlayer fabric with integrated PCM (translucent)



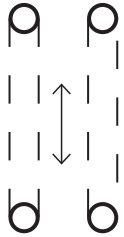

**4:** PCM integrated on the upper and bottom part of the façade element

**1-2:** vacuum with a reflective coating on the inner layer so radiation can be reflected back to the outside

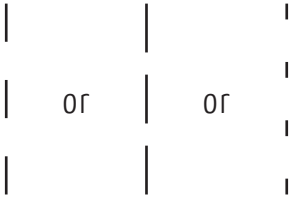
**2-3:** ventilated cavity for cooling purposes

**3:** outer layer --> shading // in case of rain it can be loosed up to avoid drums:

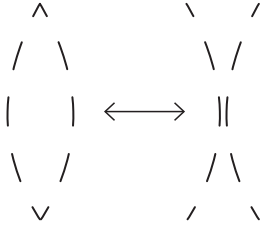
a) 2-layered printed pattern moving parallel to each other // possible use of bi-metals



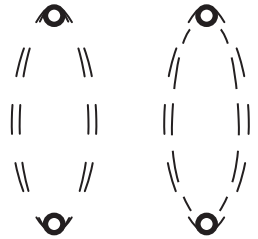
b) 2 fabrics with different expansion coefficient with the use of bi-metals or acting like bi-metals



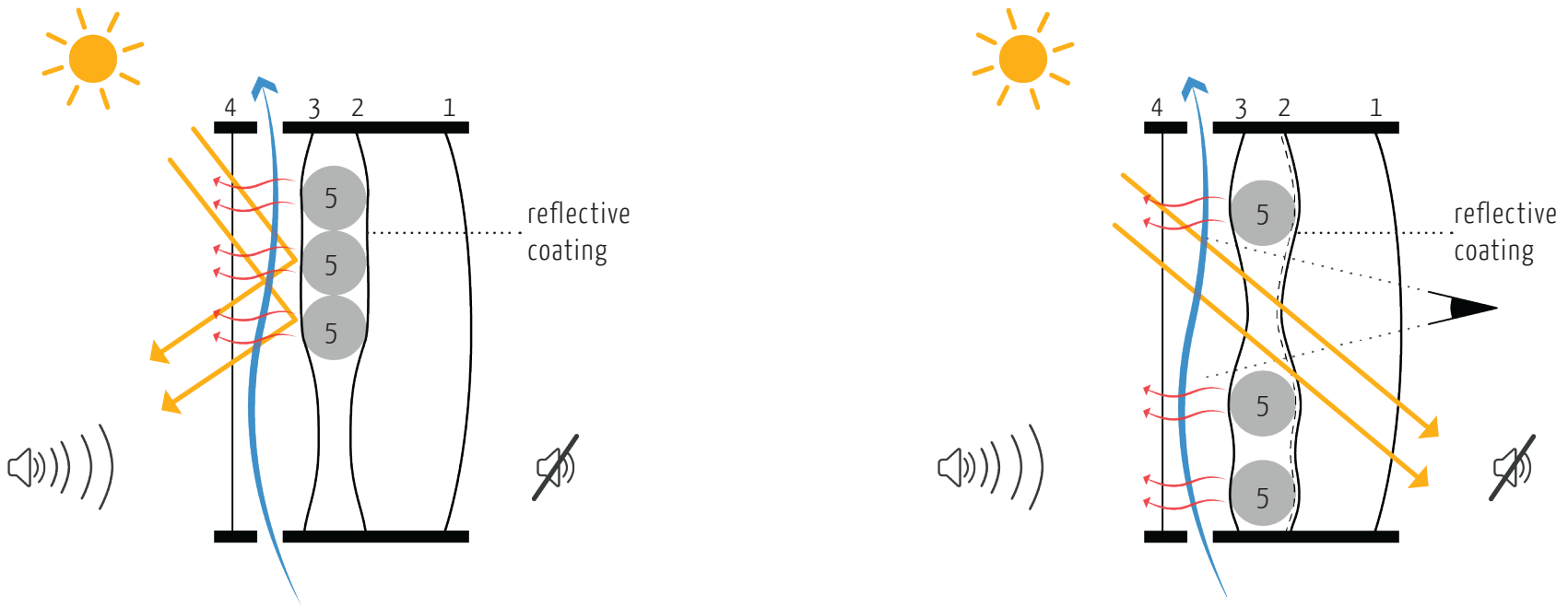

c) inflated and deflated cushion with printed pattern



d) 4-layered cushion with printed pattern on all layers // inner layer rotating



3.



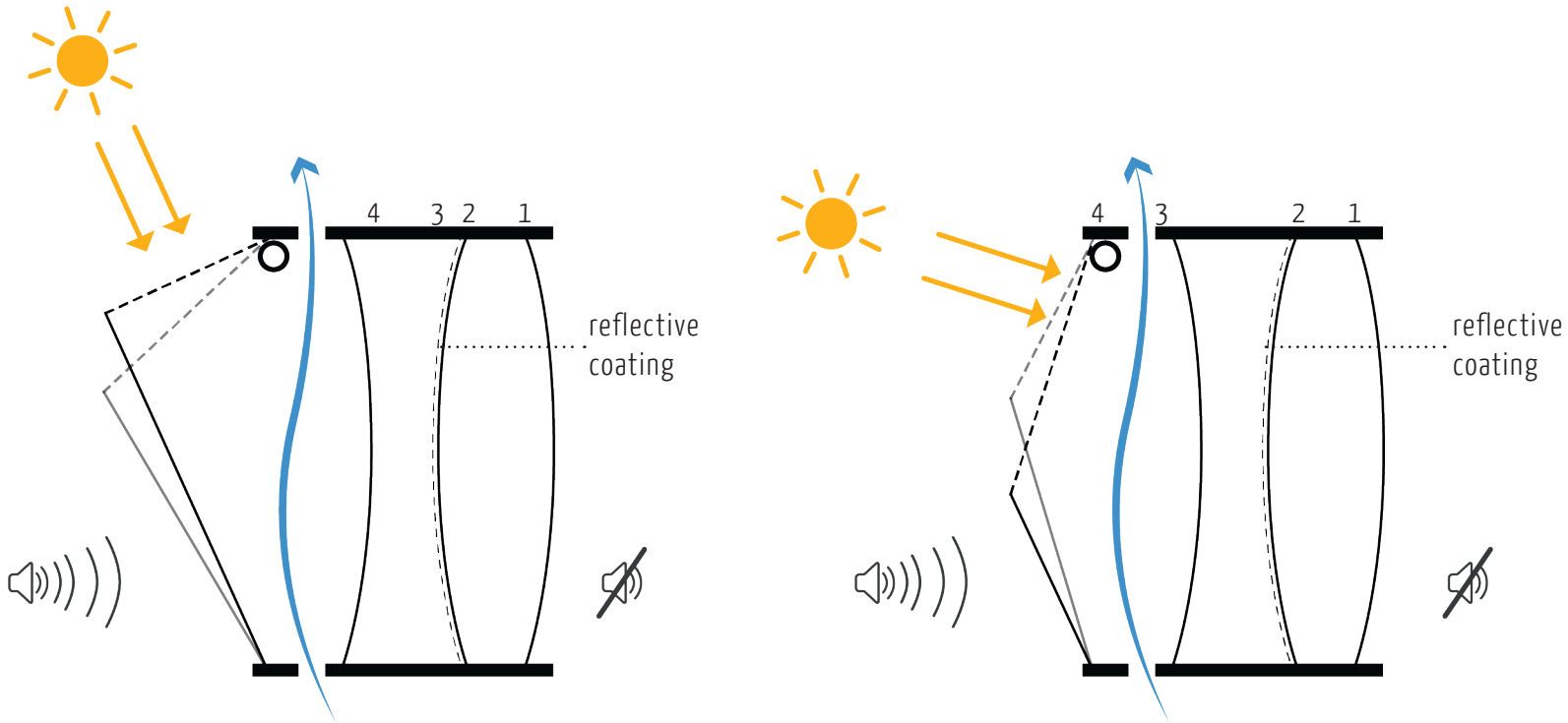

**1-2:** inflated cushion filled with either aerogel (translucent) or argon gas (transparent)

**2-3:** vacuum with a reflective coating on the inner layer // cylinders with PCM that reduce the cooling loads and they can be moved vertically to provide sunshading

**3-4:** ventilated cavity for cooling purposes

**4:** outer layer --> protective layer that can be loosened up in case of rain to avoid drums (+low-e coating is also possible)

# 4.



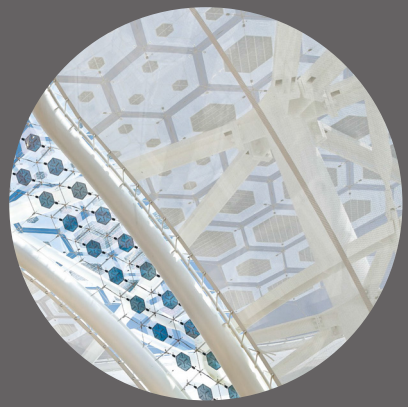

**1-2**: inflated cushion filled with either aerogel (translucent) or argon gas (transparent)

**2-3**: vacuum with a reflective coating on the inner layer so radiation can be reflected back to the outside

**3-4**: ventilated cavity for cooling purposes

**4**: sunshading layer --> integration of PV films on the outer layer // it can be adjusted according to sun's angle in order to be more efficient + sunshading

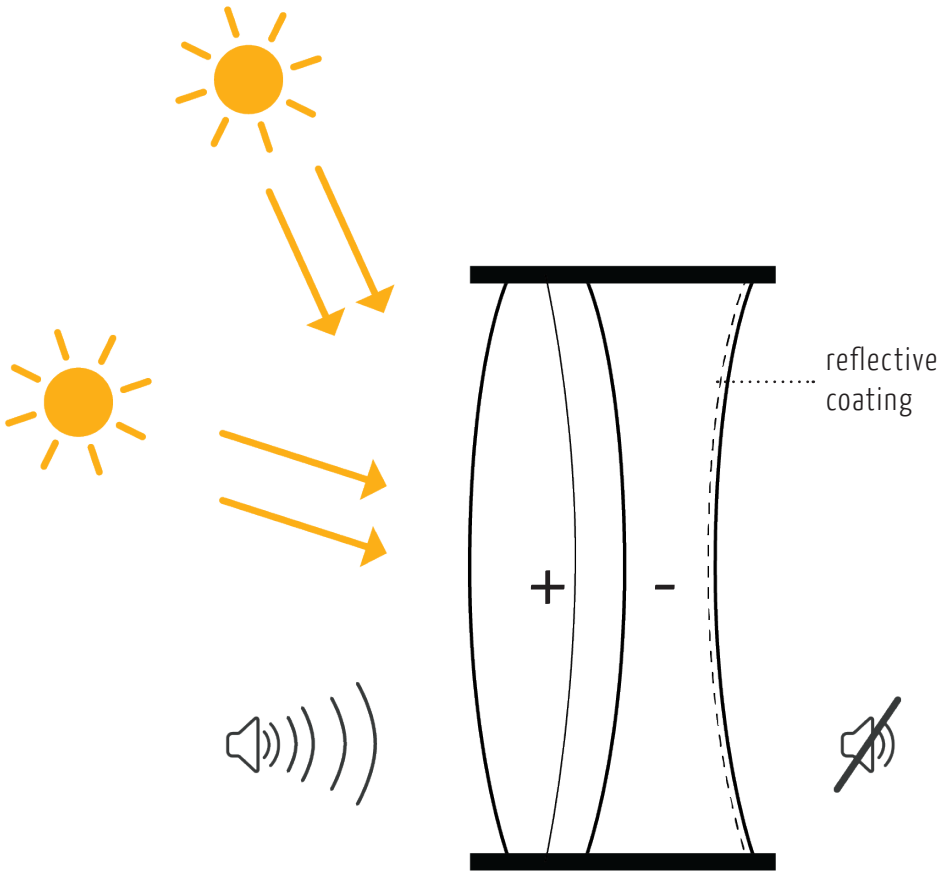
## Flexible Organic Photovoltaic modules



- made out of sustainable, carbon-based, "organic" materials
- roll-to-roll manufacturing process
- different shapes, colours and degrees of transparency
- compatibility with membrane architecture
- angular independent
- power efficiency under diffuse light conditions

# chosen concept

inflated cushions + vacuum system




why?

thermal and acoustical purposes

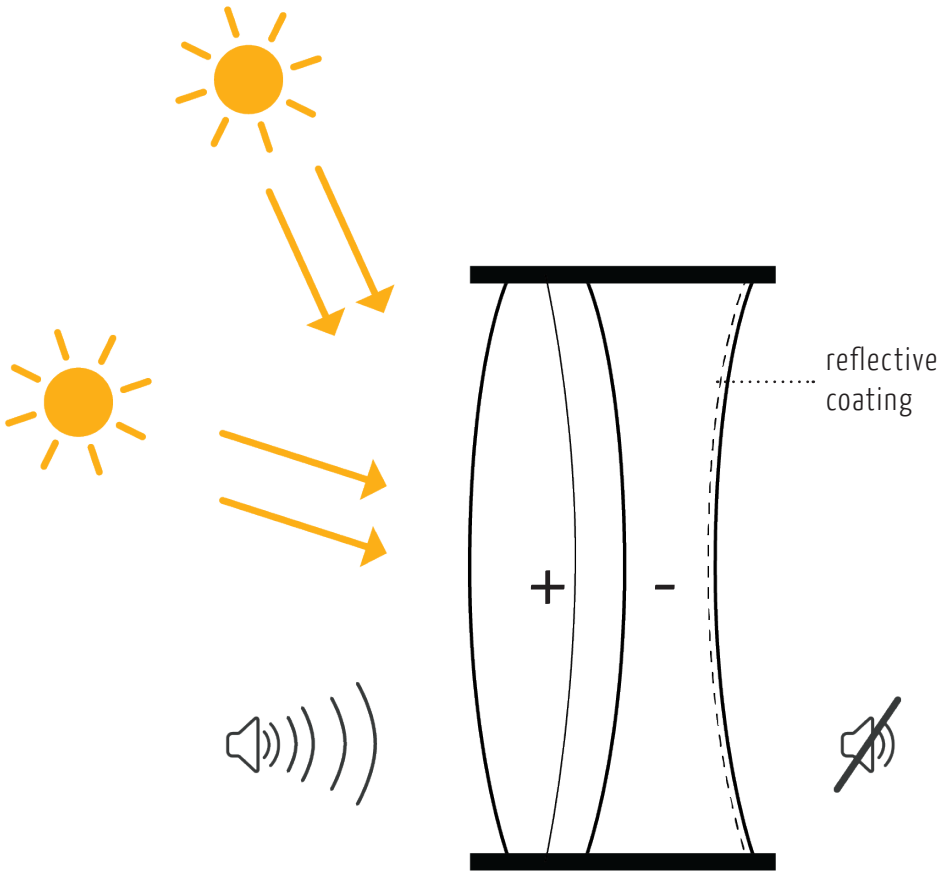
exploration of the vacuum system potentials (acoustic insulation)

investigation of how inflated cushions and vacuum system can be combined

# chosen concept

define

inflated cushions + vacuum system




how many layers of fabric

cavity filling

vacuum: how low can
the pressure become?

shading system

3

# climate + building physics

# paris, france

## climate

- **warm temperate** climate (oceanic)
- annual average temperature --> **11°C** // min. **3°C** January, max. **22°C** in July and August
- annual **sky coverage** --> 62% // August: 47% and January: 73%
- sun' s angle --> $18^0$ (winter) and $65^0$ (summer)

# paris, france

## climate

» **warm temperate** climate (oceanic)

» annual average temperature --> **11°C** // min. **3°C** January, max. **22°C** in July and August

» annual **sky coverage** --> 62% // August: 47% and January: 73%

» sun' s angle --> $18^0$ (winter) and $65^0$ (summer)

## building regulations (RT 2012+EN15251_2007)

### thermal:

» U-value (max): **1.2 - 1.5** $W/m^2K$

» Solar transmittance factor > **0.35**

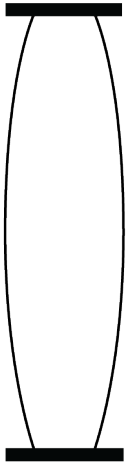
### acoustics:

» values in offices for equivalent levels (average): **33 - 45** dB

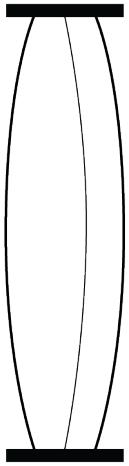
» values in offices for instantaneous levels (peaks): **35-50** dB

# thermal hand calculations

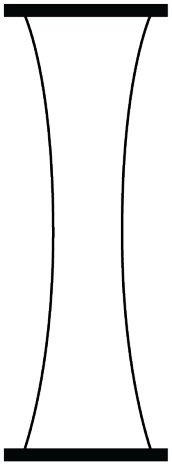
inflated cushion
(2 layers)



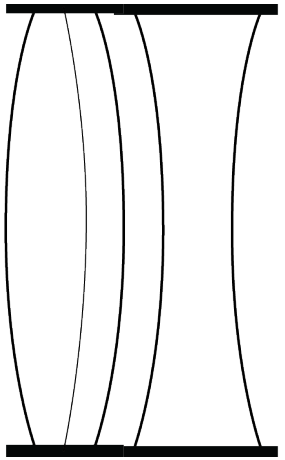
inflated cushion
(3 layers)



vacuum
system

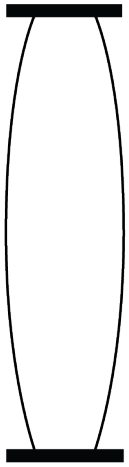


combination



# thermal hand calculations

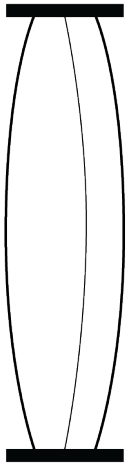
## inflated cushion_2 layers



| double layer system | AIR | ARGON | AEROGEL | AIR with coatings | ARGON with coatings | AEROGEL with coatings |
|---|---|---|---|---|---|---|
| $\lambda_{gas\_cav}$ (W/mK) | 0.0248 | 0.016 | 0.012 | 0.0248 | 0.016 | 0.01349 |
| $\lambda_{fabric}$ (W/mK) | 0.238 | 0.238 | 0.238 | 0.238 | 0.238 | 0.238 |
| $d_{cav}$ (m) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| $d_{fabric}$ (m) | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 |
| Te ( C ) | 11 | 11 | 11 | 11 | 11 | 11 |
| Ti ( C ) | 24.5 | 24.5 | 24.5 | 24.5 | 24.5 | 24.5 |
| $a_{cond}$ (gas) (W/m$^2$K) | 0.248 | 0.16 | 0.12 | 0.248 | 0.16 | 0.1349 |
| $a_{conv}$ (air) (W/m$^2$K) | 1 | 1 | 1 | 1 | 1 | 1 |
| ε1 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| ε2 | 0.9 | 0.9 | 0.9 | 0.2 | 0.2 | 0.2 |
| $a_{rad}$ 2 (W/m$^2$K) | 4.56 | 4.56 | 4.56 | 1.09 | 1.09 | 1.09 |
| $a_{cav}$ (W/m$^2$K) | 6.16 | 6.07 | 6.03 | 2.42 | 2.33 | 2.31 |
| $r_{cushion}$ (m$^2$K/W) | 0.165 | 0.167 | 0.168 | 0.415 | 0.431 | 0.436 |
| **R (m$^2$K/W)** | **0.335** | **0.337** | **0.338** | **0.585** | **0.601** | **0.606** |
| **U (W/m$^2$K)** | **2.986** | **2.965** | **2.955** | **1.708** | **1.664** | **1.651** |

# thermal hand calculations

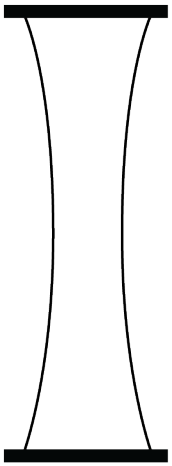
## inflated cushion_3 layers



| triple layer system | 1st cavity | 2nd cavity |
|---|---|---|
| $\lambda_{gas\_cav}$ (W/mK) | 0.016 | 0.016 |
| $\lambda_{fabric}$ (W/mK) | 0.238 | |
| $d_{cav}$ (m) | 0.05 | 0.05 |
| $d_{fabric}$ (m) | 0.0003 | 0.0001 |
| Te ( C ) | 11 | 11 |
| Ti ( C ) | 24.5 | 24.5 |
| a $_{cond}$ (gas) (W/m$^2$K) | 0.32 | 0.32 |
| a $_{conv}$ (gas) (W/m$^2$K) | 1 | 1 |
| ε1 | 0.9 | 0.2 |
| ε2 | 0.2 | 0.9 |
| a $_{rad}$ 2 (W/m$^2$K) | 1.09 | 1.09 |
| a $_{cav}$ (W/m$^2$K) | 2.41 | 2.41 |
| $r_{cushion}$ (m$^2$K/W) | 0.83 | |
| **R (m$^2$K/W)** | **1.00** | |
| **U (W/m$^2$K)** | **1.00** | |

# thermal hand calculations

## vacuum system



$$K_e/K_0 = 1/(1+C/PP)$$

where

**Ke:** the new thermal conductivity of air in lower pressure

**Ko:** the thermal conductivity of air at 1 bar ($10^5$ Pascal)

**C:** constant equal to $7.6*10^{-5}$ [mK/N]

**PP:** pressure parameter P*d/T [N/mK]

**P:** pressure [Pa]

**d:** plate distance [m]

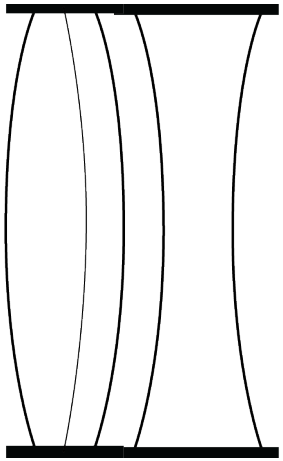
**T:** absolute temperature [K]

| 100 Pa ($10^{-3}$ bar) | | 10 Pa ($10^{-4}$ bar) | | 1 Pa ($10^{-5}$ bar) | |
|---|---|---|---|---|---|
| $\lambda_{gas}$ | 0.0247 | $\lambda_{gas}$ | 0.0238 | $\lambda_{gas}$ | 0.0172 |
| $\lambda_{fabric}$ (W/mK) | 0.238 | $\lambda_{fabric}$ (W/mK) | 0.238 | $\lambda_{fabric}$ (W/mK) | 0.238 |
| $d_{air}$ (m) | 0.05 | $d_{air}$ (m) | 0.05 | $d_{air}$ (m) | 0.05 |
| $d_{fabric}$ (m) | 0.0003 | $d_{fabric}$ (m) | 0.0003 | $d_{fabric}$ (m) | 0.0003 |
| Te ( C ) | 11 | Te ( C ) | 11 | Te ( C ) | 11 |
| Ti ( C ) | 24.5 | Ti ( C ) | 24.5 | Ti ( C ) | 24.5 |
| Te (K) | 284 | Te (K) | 284 | Te (K) | 284 |
| Ti (K) | 297.5 | Ti (K) | 297.5 | Ti (K) | 297.5 |
| $a_{cond}$ (air) (W/m²K) | 0.49 | $a_{cond}$ (air) (W/m²K) | 0.48 | $a_{cond}$ (air) (W/m²K) | 0.34 |
| $a_{conv}$ (air) (W/m²K) | 1 | $a_{conv}$ (air) (W/m²K) | 1 | $a_{conv}$ (air) (W/m²K) | 1 |
| ε1 | 0.9 | ε1 | 0.9 | ε1 | 0.9 |
| ε2 | 0.9 | ε2 | 0.9 | ε2 | 0.9 |
| $a_{rad}$ 2 (W/m²K) | 4.56 | $a_{rad}$ 2 (W/m²K) | 4.56 | $a_{rad}$ 2 (W/m²K) | 4.56 |
| $a_{cav}$ (W/m²K) | 6.40 | $a_{cav}$ (W/m²K) | 6.38 | $a_{cav}$ (W/m²K) | 6.25 |
| $r_{cushion}$ (m²K/W) | 0.15870 | $r_{cushion}$ (m²K/W) | 0.15916 | $r_{cushion}$ (m²K/W) | 0.16244 |
| R (m²K/W) | **0.3287** | R (m²K/W) | **0.3292** | R (m²K/W) | **0.3324** |
| U (W/m²K) | **3.0423** | U (W/m²K) | **3.0380** | U (W/m²K) | **3.0080** |

| $\lambda_{AIR}$ (W/mK) | 0.0248 |
|---|---|

# thermal hand calculations

## combination

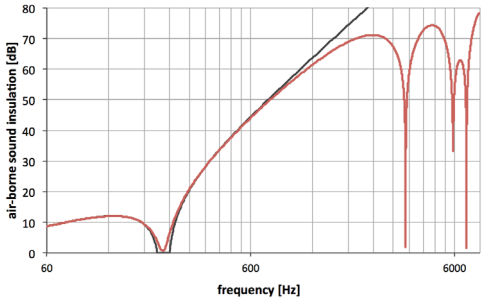


| | 1st cavity | 2nd cavity | 3rd cavity | 4th cavity |
|---|---|---|---|---|
| $\lambda_{gas\_cav}$ (W/mK) | 0.016 | 0.016 | 0.0248 | 0.0247 |
| $\lambda_{fabric}$ (W/mK) | 0.238 | 0.238 | 0.238 | 0.238 |
| $d_{cav}$ (m) | 0.05 | 0.05 | 0.06 | 0.05 |
| $d_{fabric}$ (m) | 0.0003 | 0.0001 | 0.0003 | 0.0003 |
| $T_1$ ( C ) | 11 | 14.375 | 17.75 | 21.125 |
| $T_2$ ( C ) | 14.375 | 17.75 | 21.125 | 24.5 |
| r cond (gas) ($m^2K/W$) | 3.13 | 3.13 | 2.42 | 2.02 |
| a cond (gas) ($W/m^2K$) | 0.32 | 0.32 | 0.41 | 0.50 |
| a cond (fabric) ($W/m^2K$) | 793.33 | 2380.00 | 793.33 | 793.33 |
| a conv (gas) ($W/m^2K$) | 1 | 1 | 1 | 1 |
| ε1 | 0.9 | 0.9 | 0.9 | 0.9 |
| ε2 | 0.9 | 0.2 | 0.9 | 0.9 |
| a rad 2 ($W/m^2K$) | 4.33 | 1.07 | 4.64 | 4.80 |
| a cav ($W/m^2K$) | 5.65 | 2.39 | 6.05 | 6.30 |
| $r_{cushion}$ ($m^2K/W$) | 0.92 | | | |
| R ($m^2K/W$) | **1.09** | | | |
| U ($W/m^2K$) | **0.91** | | | |

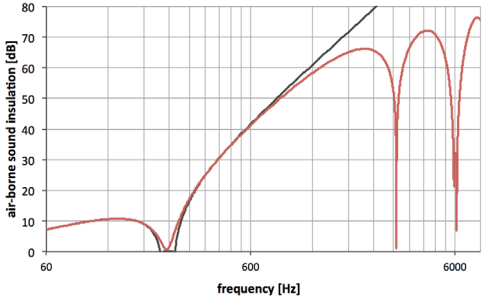
# acoustics hand calculations

## inflated system

### double glazing

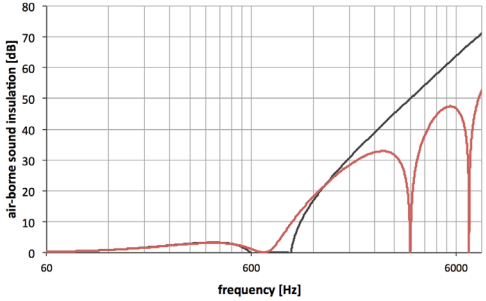



air

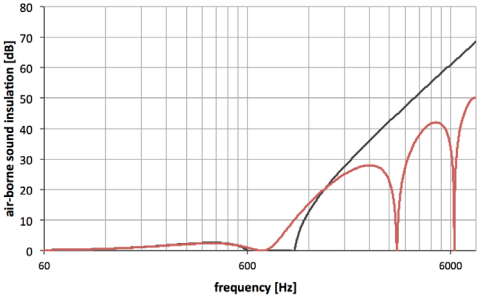



argon

### ETFE 2 layers

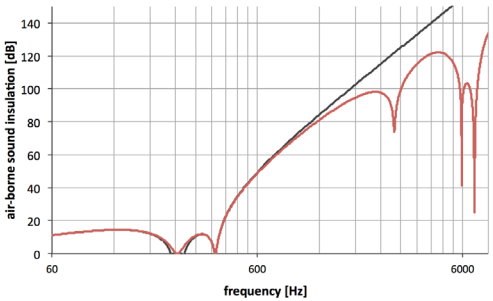


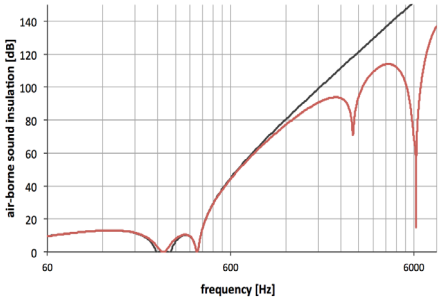

air



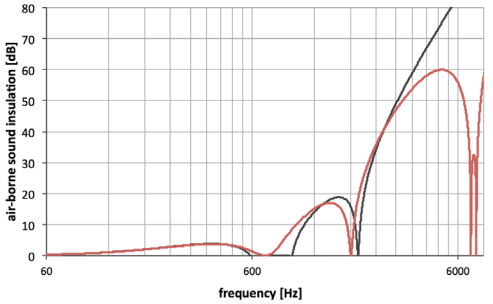

argon

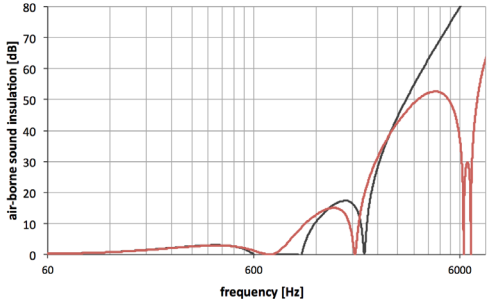
### triple glazing




### ETFE 3 layers



# acoustics hand calculations

## new air density in lower pressures

Ideal Gas Law (or Boyle's Law):

$$P = \rho * R * T \quad (1)$$

where

P: pressure

$\rho$: density [kg/m$^3$]

R: gas constant equal to 287 [J/kg/K]

T: absolute temperature [K]

and for the new pressure level and new density:

$$P' = \rho' * R * T \quad (2)$$

where

P': new pressure

$\rho'$: new density [kg/m$^3$]

R: gas constant equal to 287 [J/kg/K]

T: absolute temperature [K]

For the same gas and keeping the temperature constant, equations 1 and 2 can be written as:

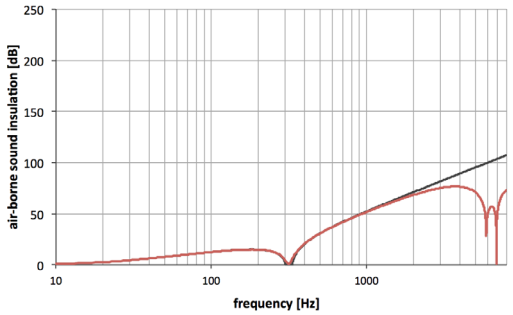
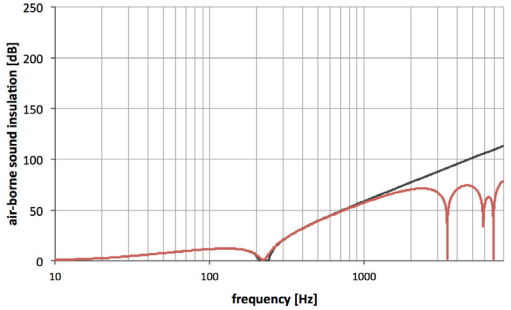
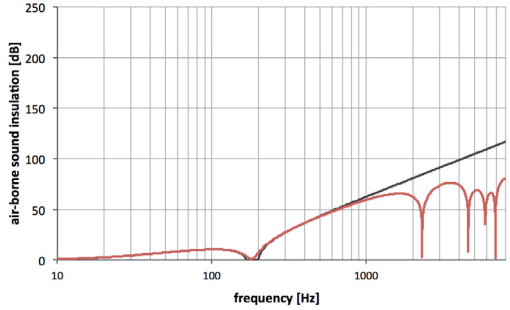
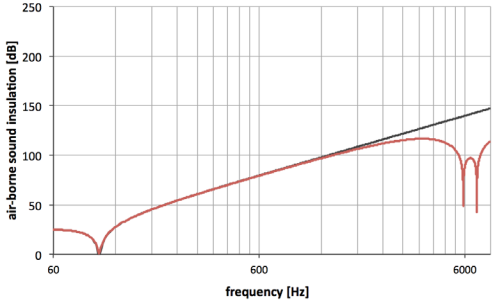
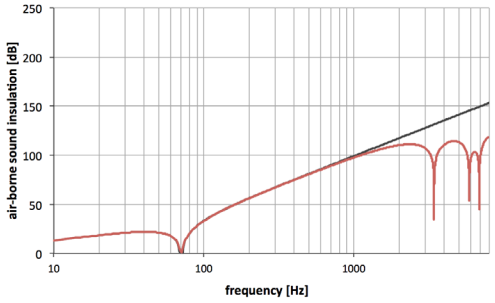
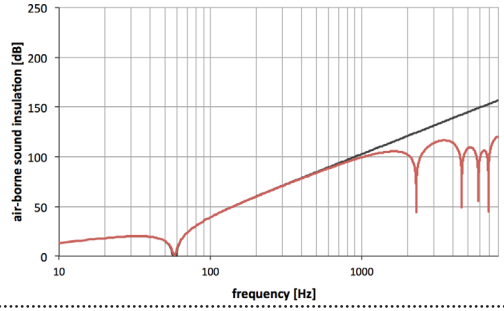
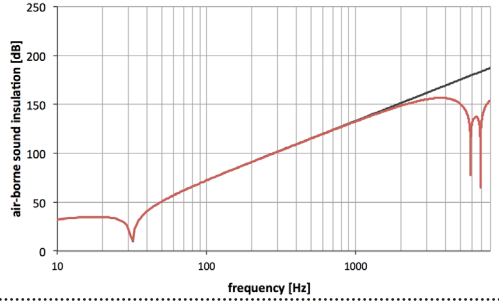
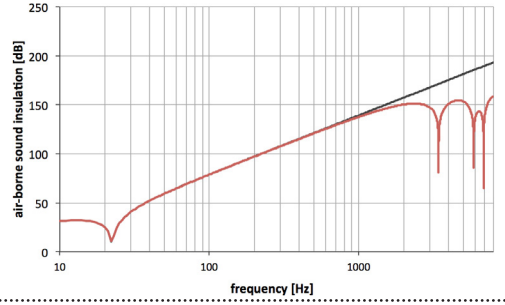
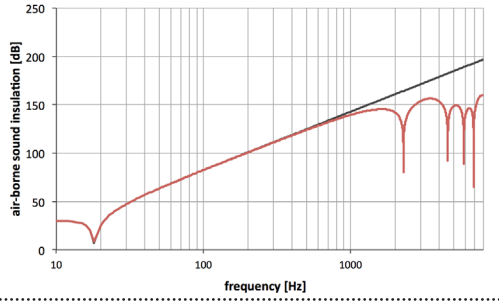
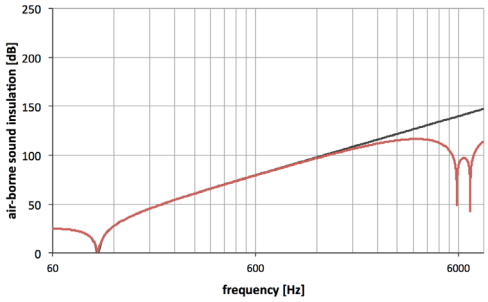
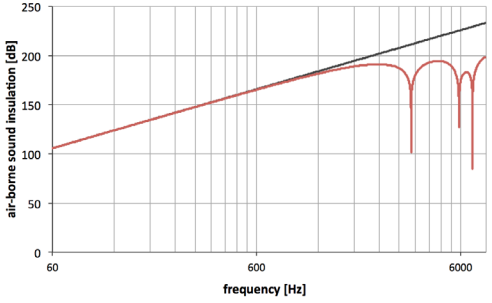
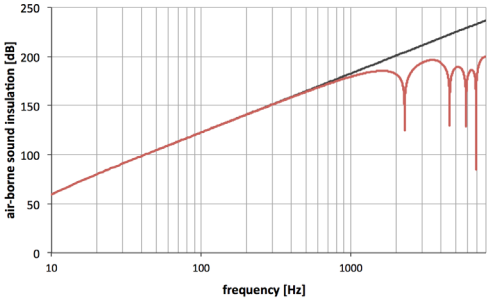
$$R * T = P / \rho$$

$$R * T = P' / \rho'$$

$$\longrightarrow \quad P / \rho = P' / \rho' \quad \longrightarrow \quad \rho' = P' * \rho / P$$

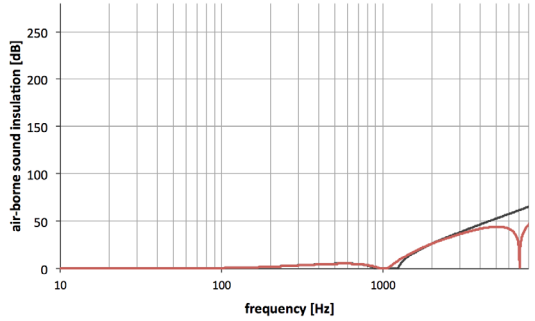
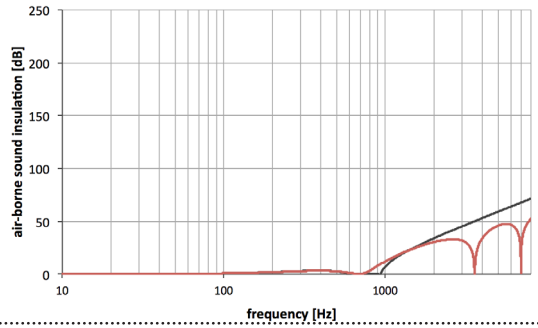
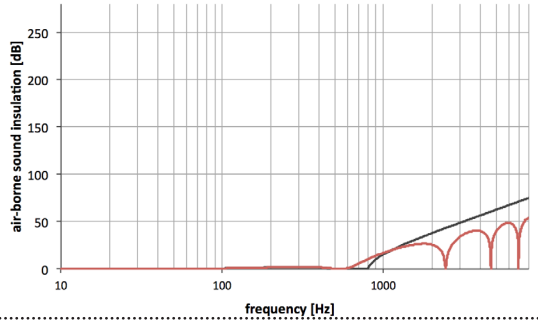
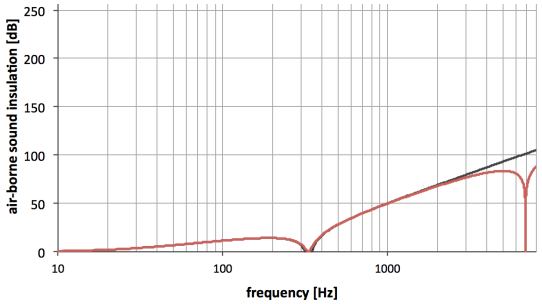
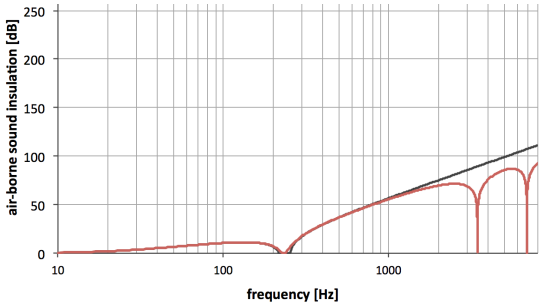
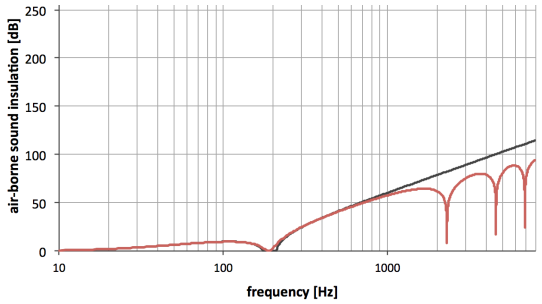
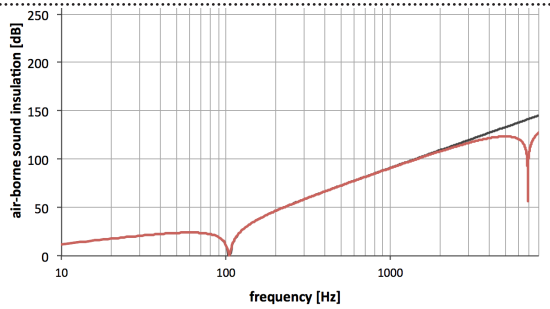
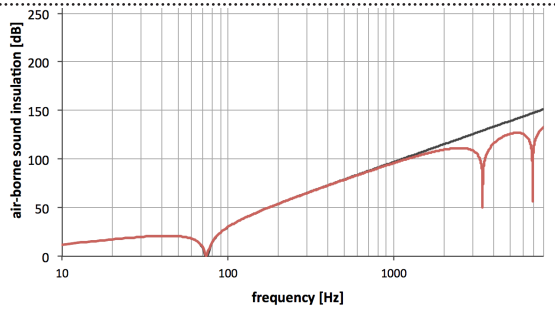
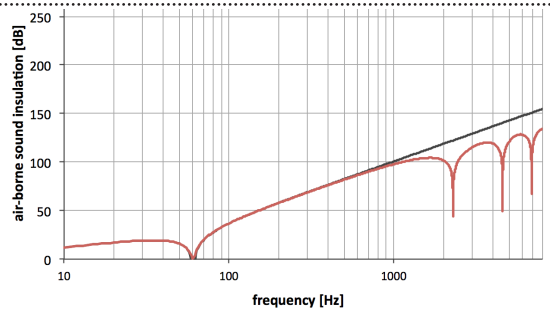
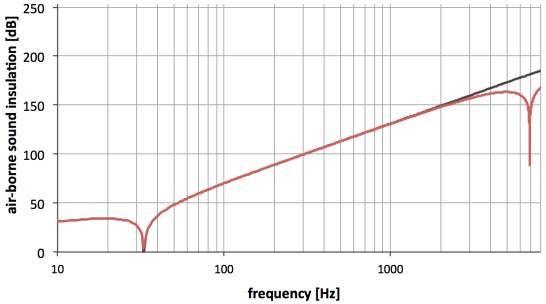
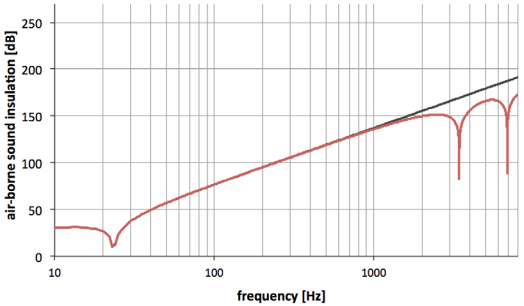
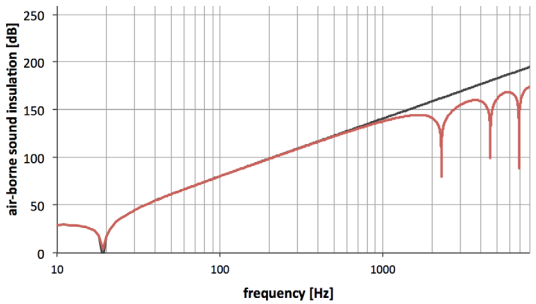
# acoustics hand calculations

## vacuum system_glazing

| | 5cm | 10cm | 15cm |
|---|---|---|---|
| $10^5$ Pa (atmospheric pressure) |  |  |  |
| $10^4$ Pa |  |  |  |
| $10^3$ Pa |  |  |  |
| $10^2$ Pa |  |  |  |

# acoustics hand calculations

## vacuum system_ETFE

| | 5cm | 10cm | 15cm |
|---|---|---|---|
| $10^5$ Pa (atmospheric pressure) |  |  |  |
| $10^4$ Pa |  |  |  |
| $10^3$ Pa |  |  |  |
| $10^2$ Pa |  |  |  |

# conclusions

## thermal

» reflective coatings --> significant role in the reduction of radiation and total U-value

» aerogel --> best results (U=1.651 $W/m^2K$ with coating)

» argon --> U=1.664 $W/m^2K$ with coating

» vacuum --> from 100 Pa ($10^{-3}$ bar) and below (at 1 Pa: U=3.00 $W/m^2K$)

» combination --> U=0.91 $W/m^2K$

# conclusions

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» aerogel --> best results (U=1.651 W/m²K with coating)

» argon --> U=1.664 W/m²K with coating

» vacuum --> from 100 Pa ($10^{-3}$ bar) and below (at 1 Pa: U=3.01 W/m²K)

» combination --> U=0.91 W/m²K

## acoustics

» inflated cushion --> behaves like a glazing unit but since the mass of the membrane is less than glass the $f_{ms}$ shifts to higher frequences

» argon --> negative effect on the airborne sound insulation as it lacks attenuation of the mass-spring resonance (a lighter gas might have a positive impact)

» reduction of air pressure --> increases the airborne sound insulation and decreases stiffness of cavity / $f_{ms}$ shifts to lower frequences

$$S_t' = \gamma * P_{gas} / d_{cav}$$

$$f_{ms} = 1/\cos\theta * \sqrt{[S_t' * (1/m_1+1/m_2)]}$$

**$S_t$:** stiffness of the cavity

**dcav:** cavity width [m]

**γ:** heat capacity ratio

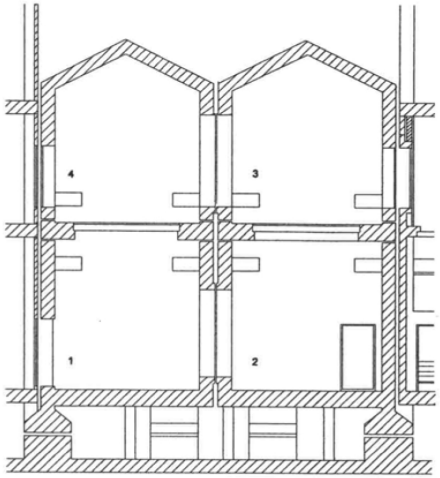
**θ:** angle of incidence

**Pgas:** gas pressure [Pa]

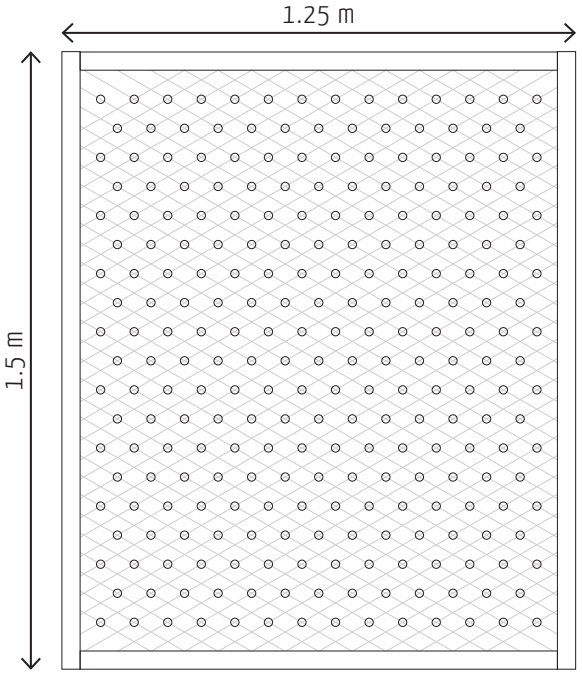
**m1, m2:** masses of membranes (kg/m²)

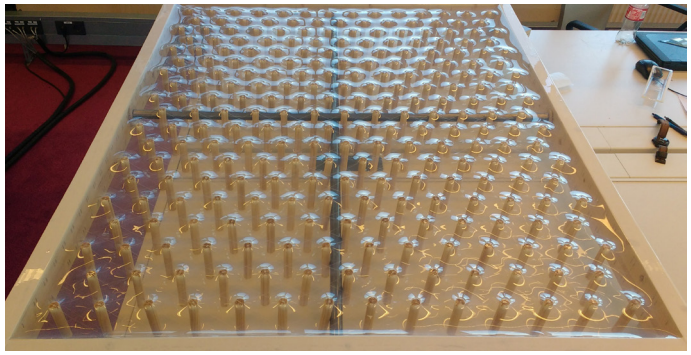
# acoustics test

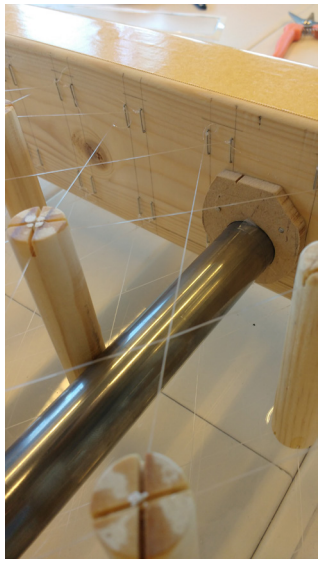
## first experiment

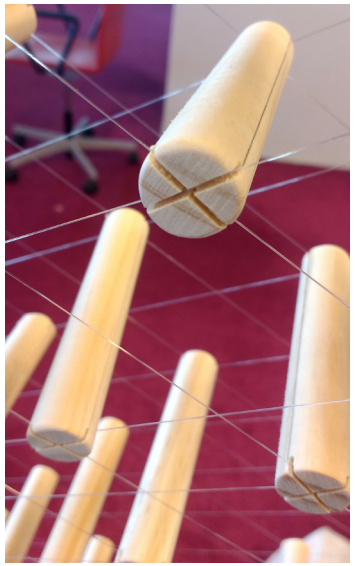


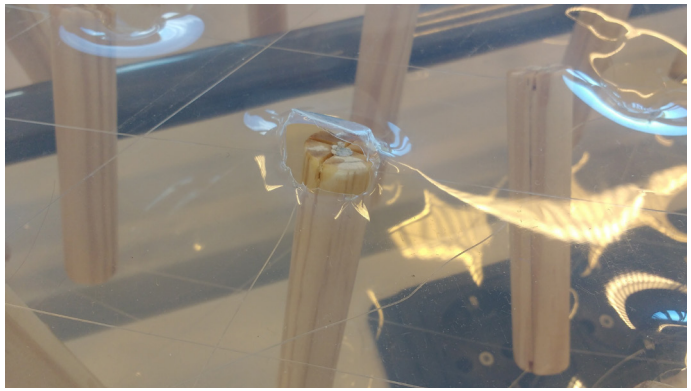

vertical section of the transmission chamber at TPD / TNO/ TU Delft



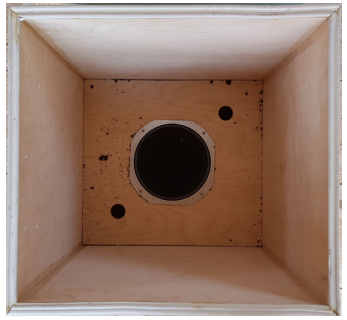


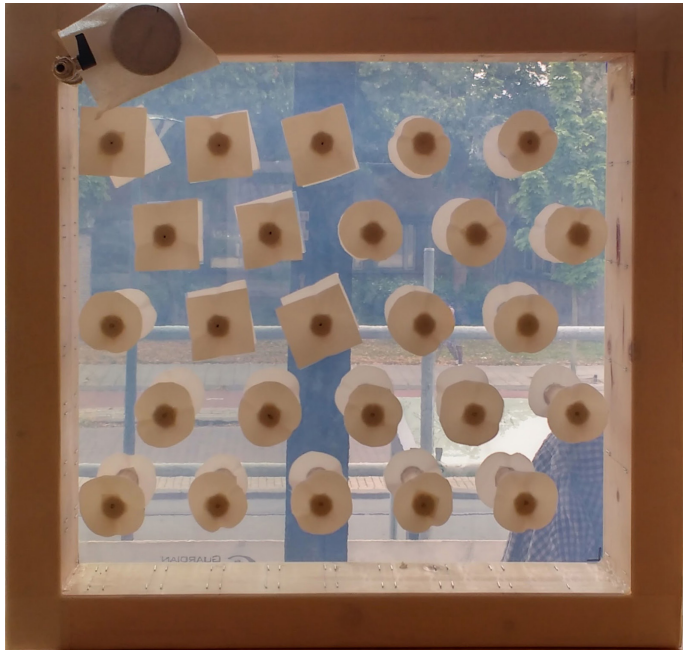


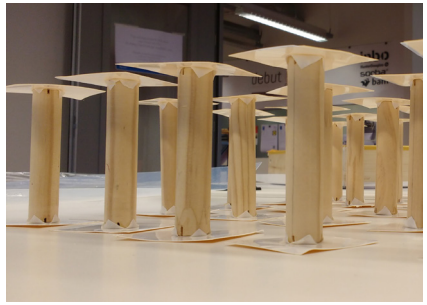


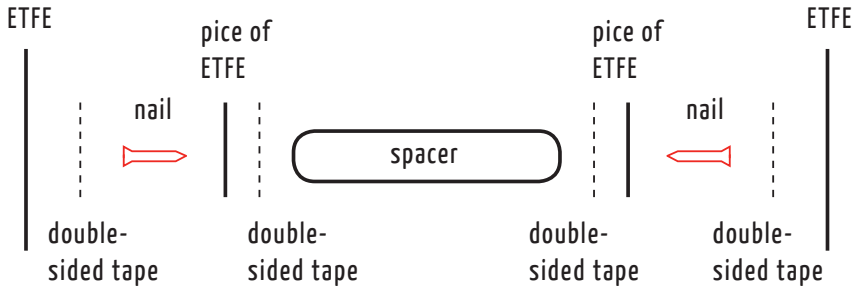
# acoustics test

## second experiment





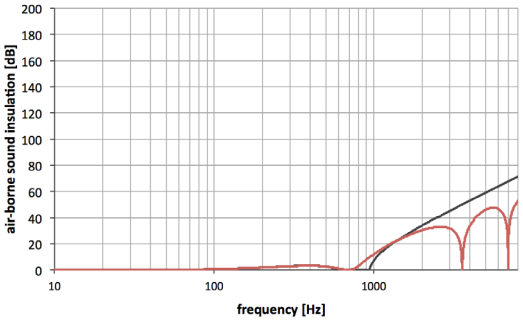





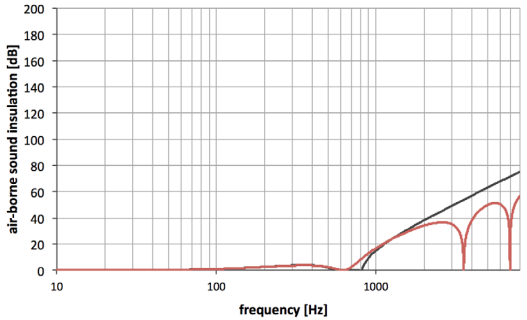

# acoustics test

## conclusions

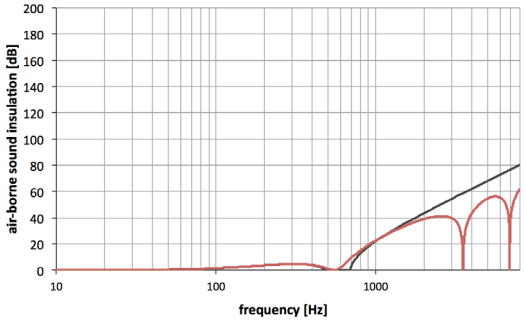
| pressure of air | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *pascal* | $8*10^4$ | $6*10^4$ | $5.5*10^4$ | $2*10^4$ | 10000 | $8*10^3$ | 1000 | 100 |
| *bar* | 0.8 | 0.6 | 0.55 | 0.2 | 0.1 | 0.08 | 0.01 | 0.001 |
| **density of air ($kg/m^3$)** | 0.968 | 0.726 | 0.6655 | 0.242 | 0.121 | 0.0968 | 0.0121 | 0.00121 |



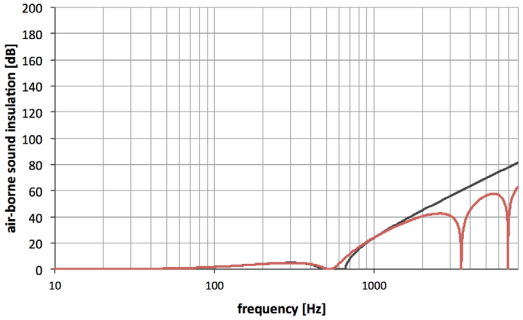

1 bar ($10^5$ Pa)



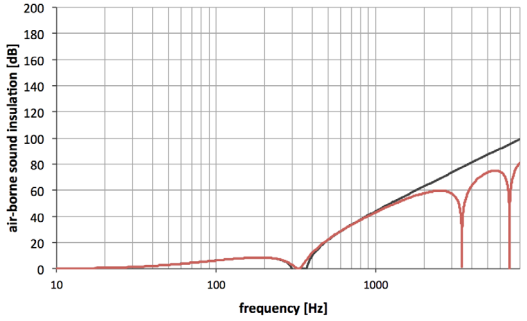

0.8 bar ($8*10^4$ Pa)



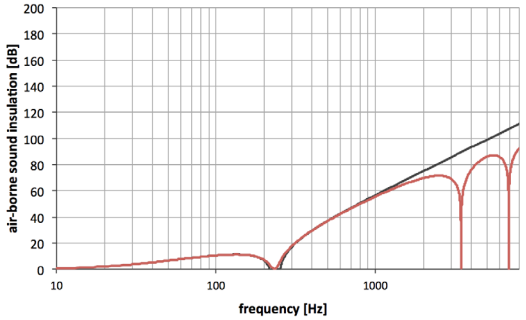

0.6 bar ($6*10^4$ Pa)



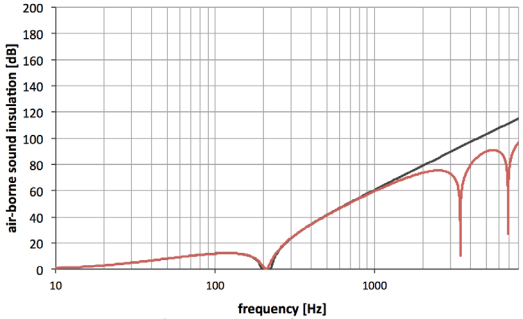

0.55 bar ($5.5*10^4$ Pa)



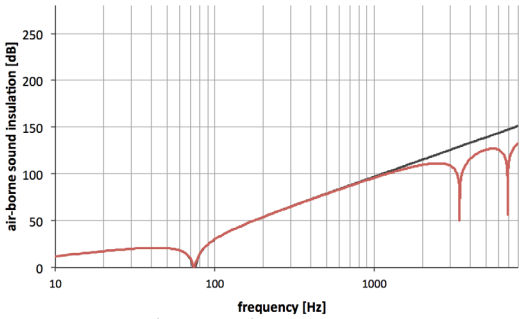

0.2 bar ($2*10^4$ Pa)



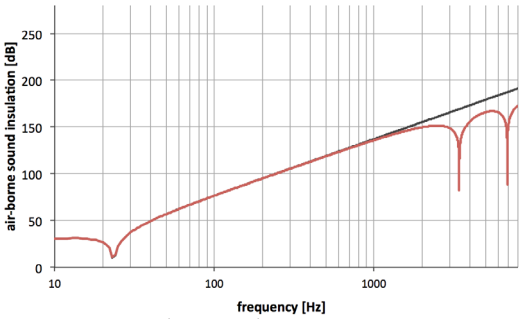

0.1 bar ($10^4$ Pa)




0.08 bar ($8*10^3$ Pa)




0.01 bar ($10^3$ Pa)

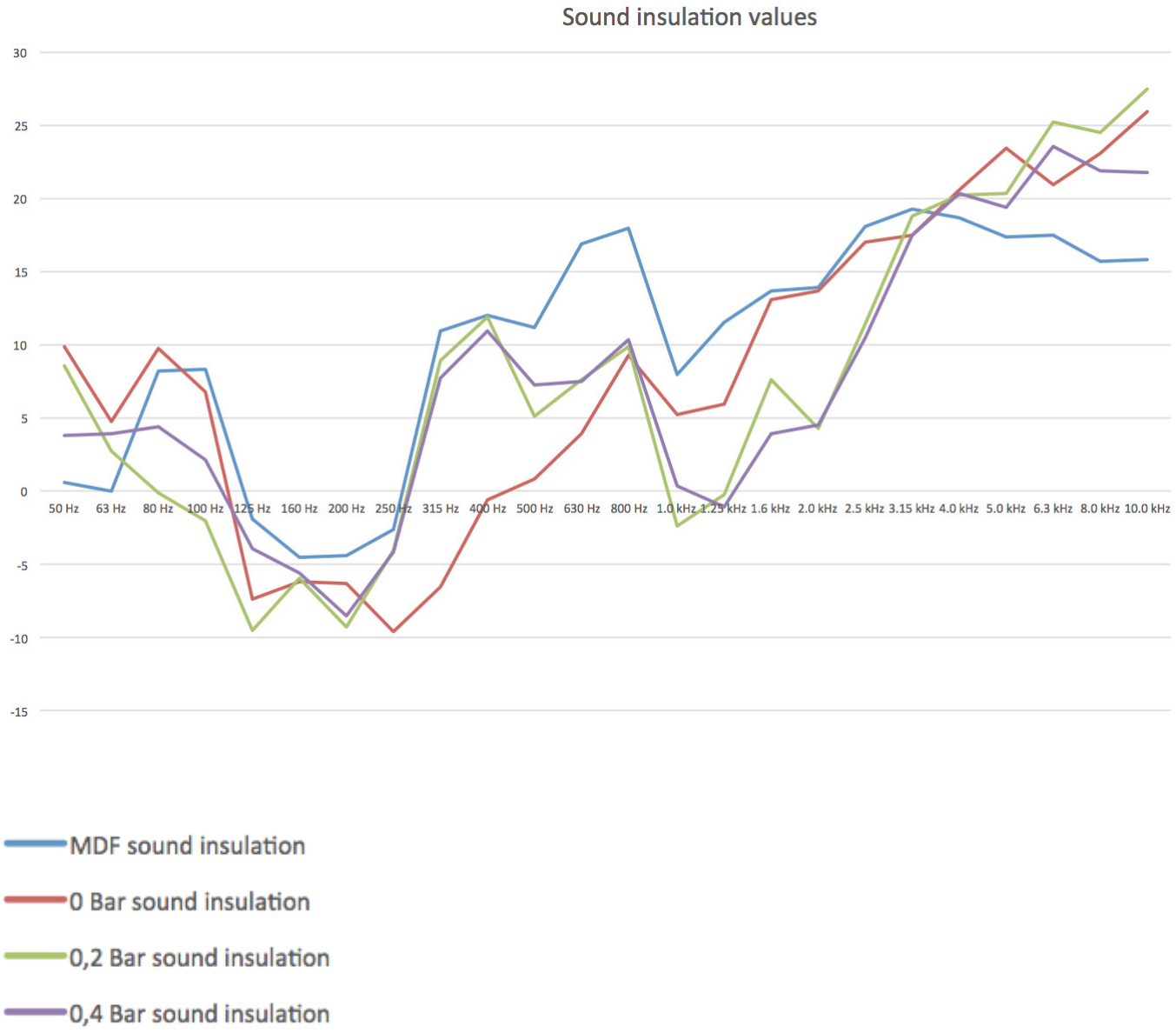



0.001 bar ($10^2$ Pa)

# acoustics test

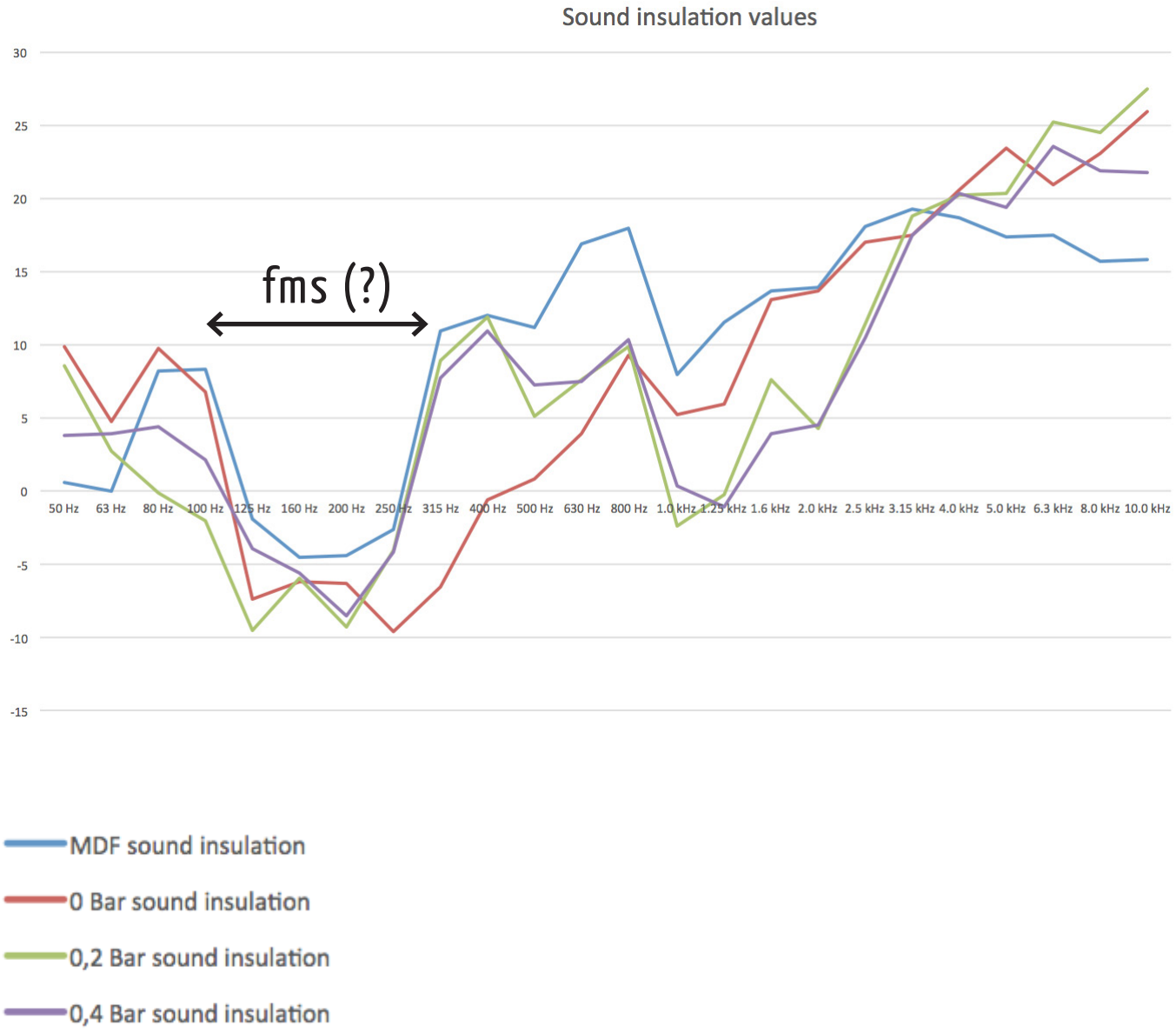
## conclusions

1. negative sound insulation values



# acoustics test

## conclusions

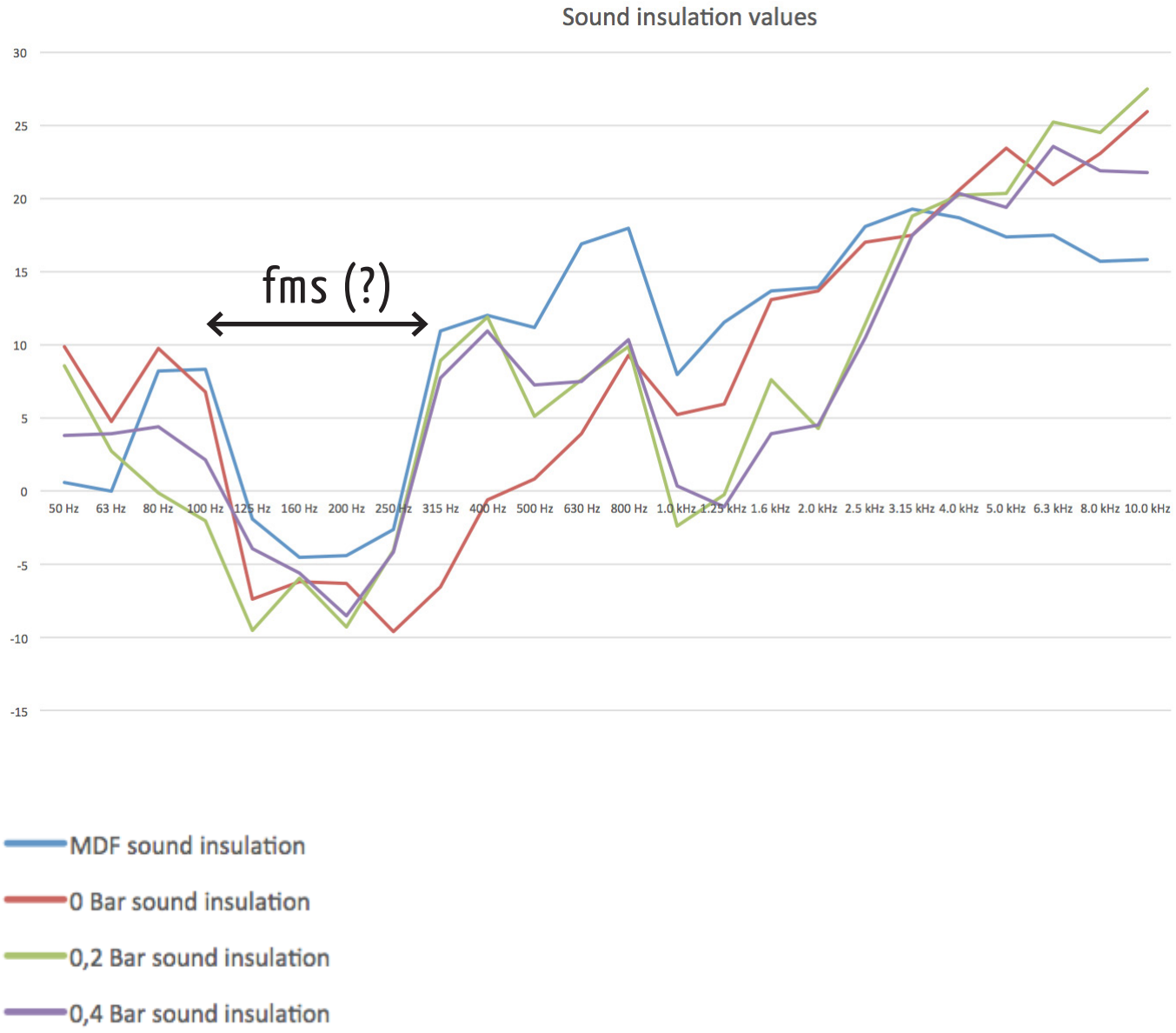



**1.** negative sound insulation values

**2.** mass-spring resonance does not happen in one specific frequency but in a wider range

# acoustics test

## conclusions




**1.** negative sound insulation values

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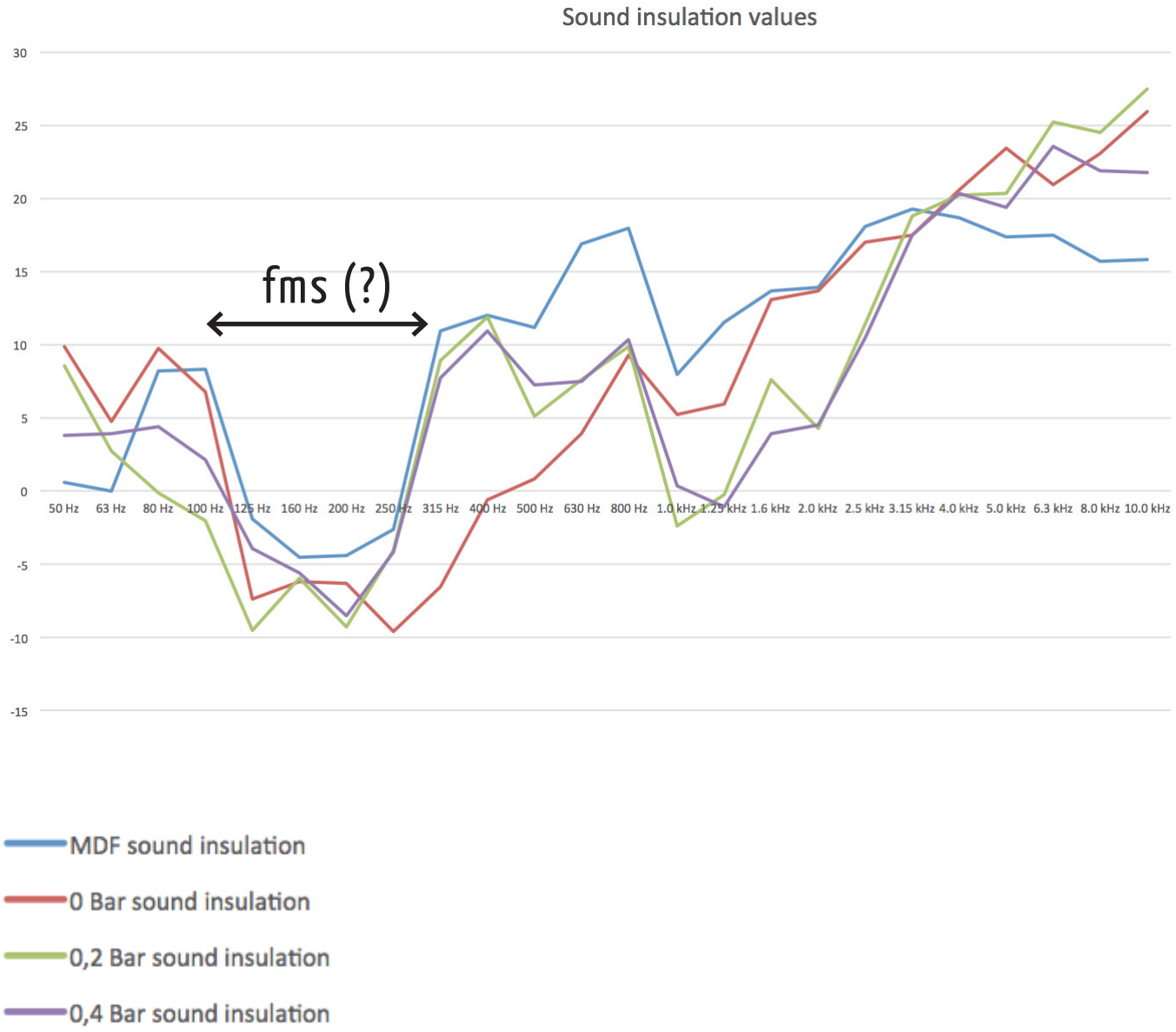
**3.** wooden box --> unreliable // small dimensions: small room or big cavity ??

# acoustics test

## conclusions




**1.** negative sound insulation values

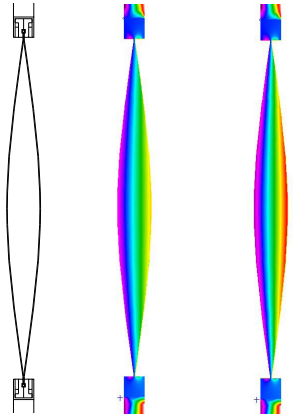
**2.** mass-spring resonance does not happen in one specific frequency but in a wider range

**3.** wooden box --> unreliable // small dimensions: small room or big cavity ??

**4.** ETFE --> flexible material // stretch due to deflation: impact on acoustic performance ??

# THERM simulations

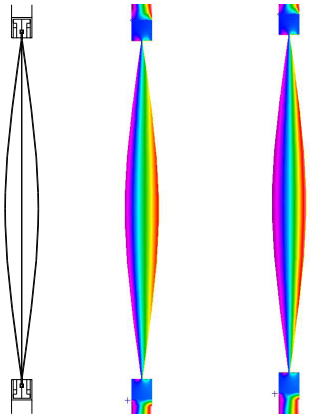
2 layers



air filling-no coating

air filling-coating

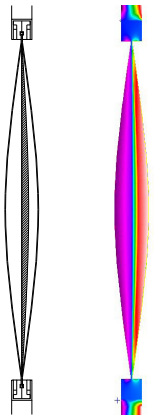
3 layers



no coatings

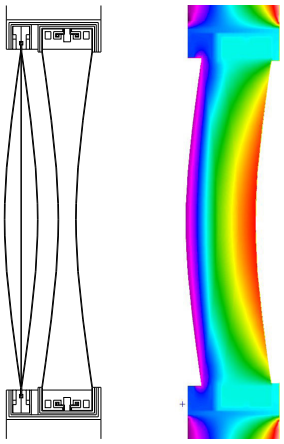
argon / air - coating on the inside

2 layers with aerogel



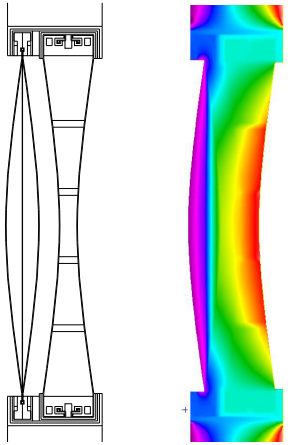
no coating

5 cm vacuum



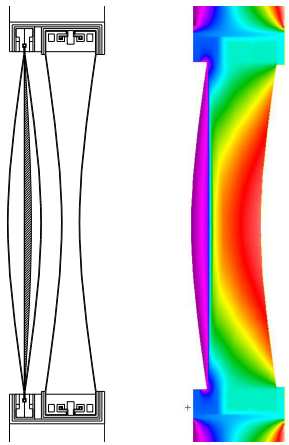
argon - coating on the middle layer of the inflated

5 cm vacuum with spacers



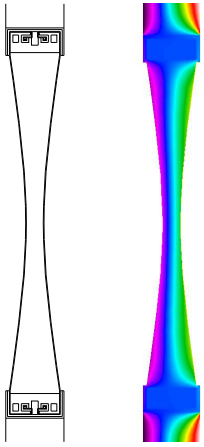
argon - coating on the middle layer of the inflated

5 cm vacuum with aerogel



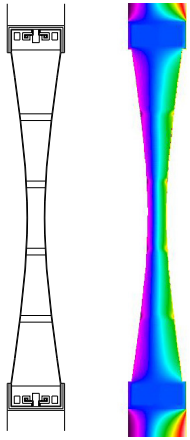
no coatings

5 cm



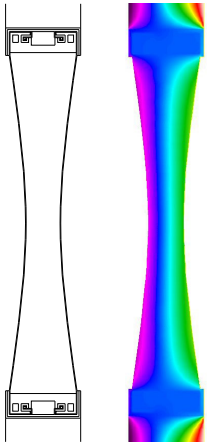
no coatings

5 cm with spacers



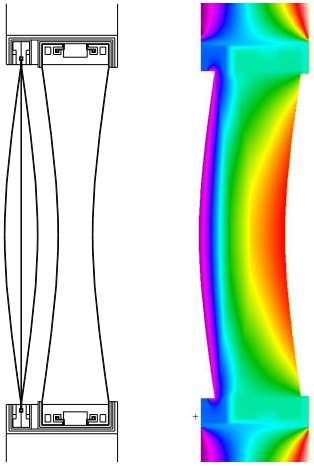
no coatings

10 cm



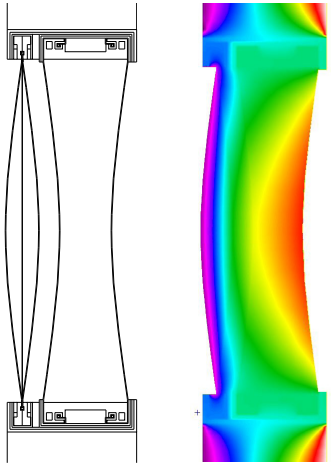
no coatings

10 cm vacuum

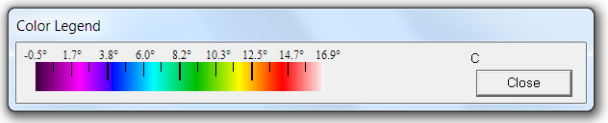


argon - coating on the middle layer of the inflated

15 cm vacuum



argon - coating on the middle layer of the inflated



# THERM simulations

## conclusions

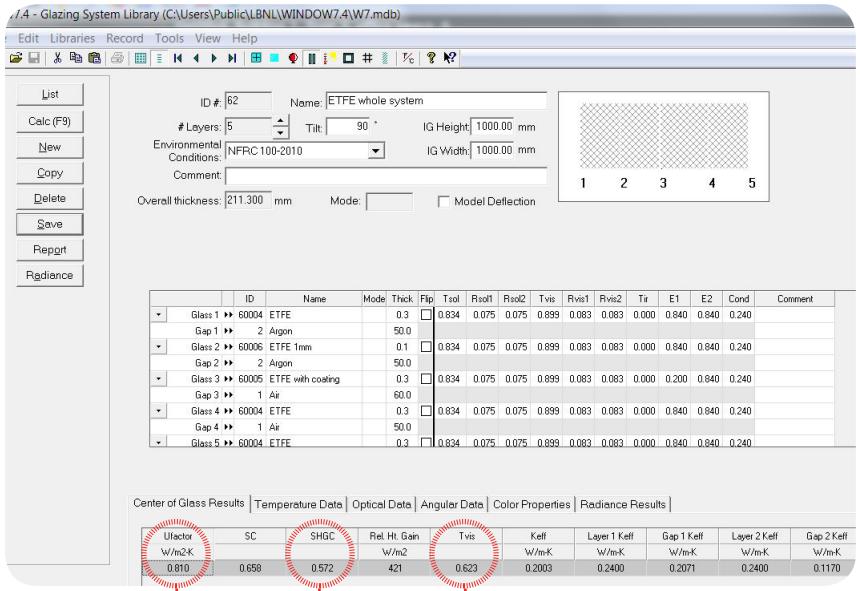
| | U-value |
|---|---|
| **3layers inflated** | |
| *aerogel + coating* | 1.17 |
| *argon + coating* | 1.8 |
| **vacumm** | |
| *100mm + coating* | 2.17 |
| **combinations** | |
| *3layers inflated_argon no coating-argon coating +50mm vacuum with SPACERS air no coatings* | 1.335 |
| *3layers inflated_air no coating-aerogel-air coating +50mm vacuum air no coatings* | 0.98 |

## comparison hand / THERM

| | U-value (hand) | U-value (THERM) |
|---|---|---|
| **2layers inflated** | | |
| ***air*** | | |
| air no coating | 2.986 | 3.22 |
| air coating on the inside | 1.708 | 2.38 |
| ***argon*** | | |
| argon no coating | 2.965 | 2.18 |
| argon coating on the inside | 1.664 | 2.17 |
| **3layers inflated** | | |
| ***argon*** | | |
| no coating /coating | 1 | 1.8 |
| **vacumm** | | |
| ***50 mm*** | | |
| air no coating | 3.04 | 3.18 |
| **combinations** | | |
| 3layers inflated_argon no coating-argon coating +50mm vacuum air no coatings | 0.91 | 1.385 |

# Design Builder simulations

## WINDOW software




U=0.81 W/m²K

SHGC=0.572

Tvis=0.623

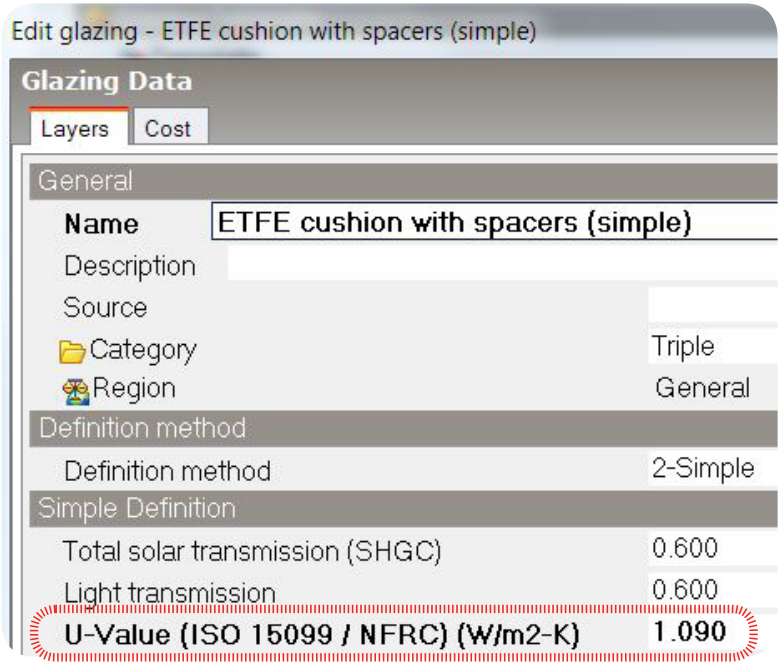
+

## THERM

*3layers inflated_argon no coating-argon coating*

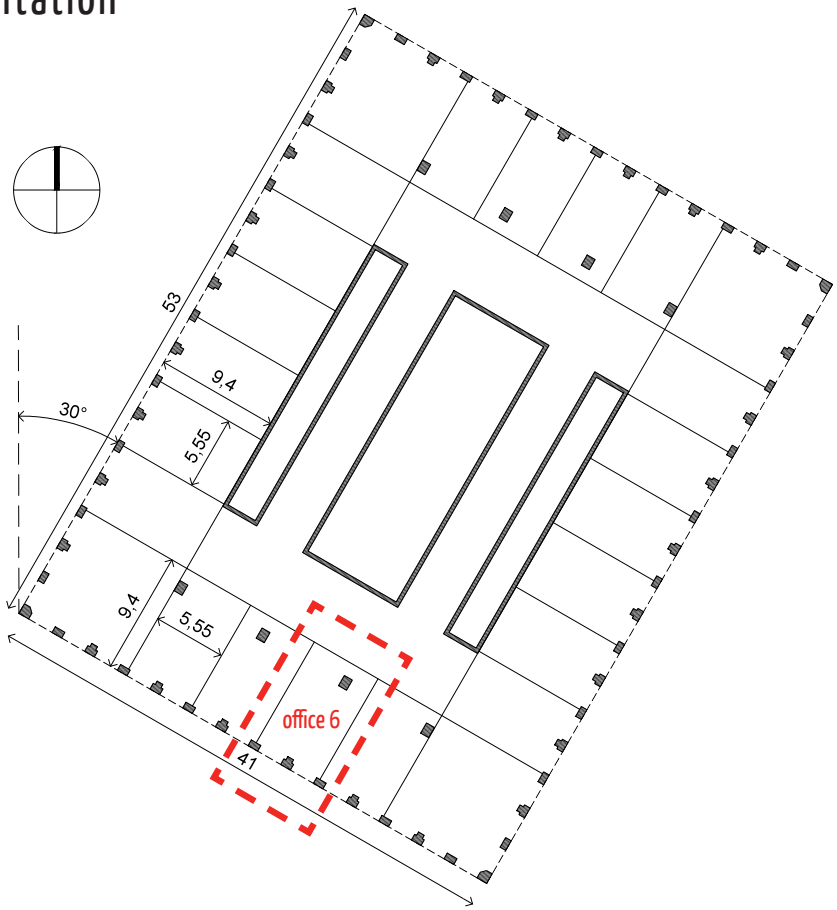
*+50mm vacuum with SPACERS air no coatings*

1.335

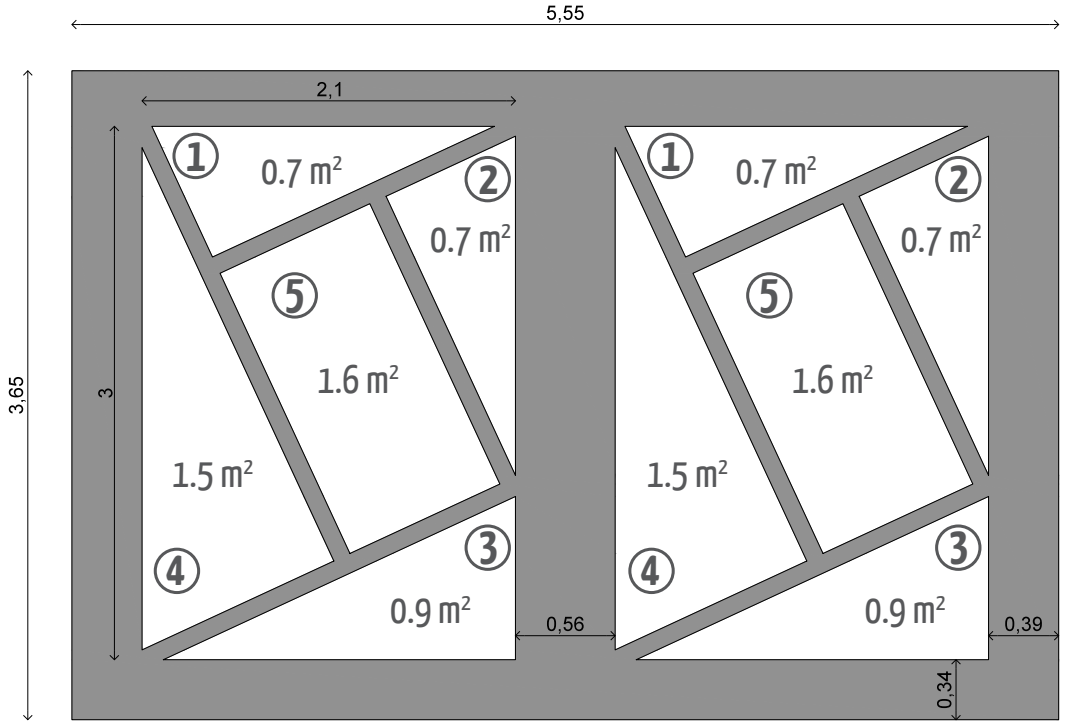


# Design Builder simulations

## orientation

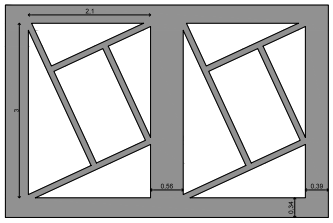



## openings

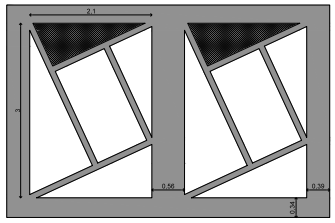



## shading

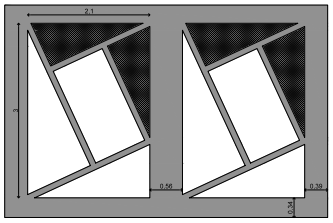
0%



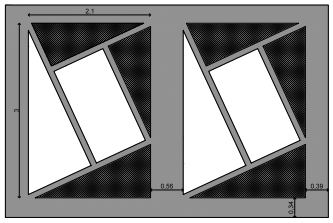
20%



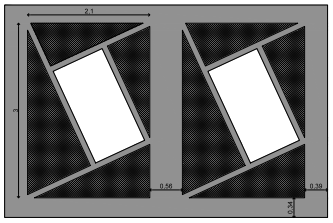
40%



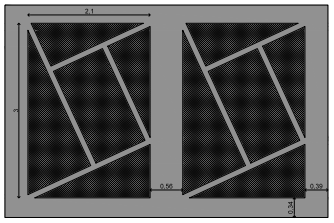
60%



80%



100%



# Design Builder simulations

## heating & cooling on

| | Annual energy per total building area (kWh/m$^2$) | | | Summer energy per total building area (kWh/m$^2$) | | | Winter energy per total building area (kWh/m$^2$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total (kWh/m$^2$) | District heating (kWh) | District cooling (kWh) | Total (kWh/m$^2$) | District heating (kWh) | District cooling (kWh) | Total (kWh/m$^2$) | District heating (kWh) | District cooling (kWh) |
| **heating / cooling ON** | | | | | | | | | |
| **No shading** | 122.45 | 284.66 | 3156.63 | 83.57 | 0 | 2768.34 | 39.36 | 289.83 | 396.62 |
| **Shading** | | | | | | | | | |
| *20%* | 117.04 | 302.34 | 2884.45 | 79.24 | 0 | 2564.62 | 38.23 | 315.47 | 327.06 |
| *40%* | 112.36 | 320.4 | 2646.09 | 75.36 | 0 | 2381.94 | 37.41 | 333.47 | 270.58 |
| *60%* | 105.97 | 350.86 | 2314.91 | 69.8 | 0 | 2120.1 | 36.52 | 363.45 | 198.51 |
| *80%* | 96.65 | 426.64 | 1800.23 | 60.7 | 1.16 | 1690.65 | 36.09 | 432.7 | 109.19 |
| *100%* | 88.75 | 544.06 | 1310.77 | 51.71 | 10.14 | 1258.12 | 37.09 | 539.06 | 49.89 |

# Design Builder simulations

## heating & cooling off

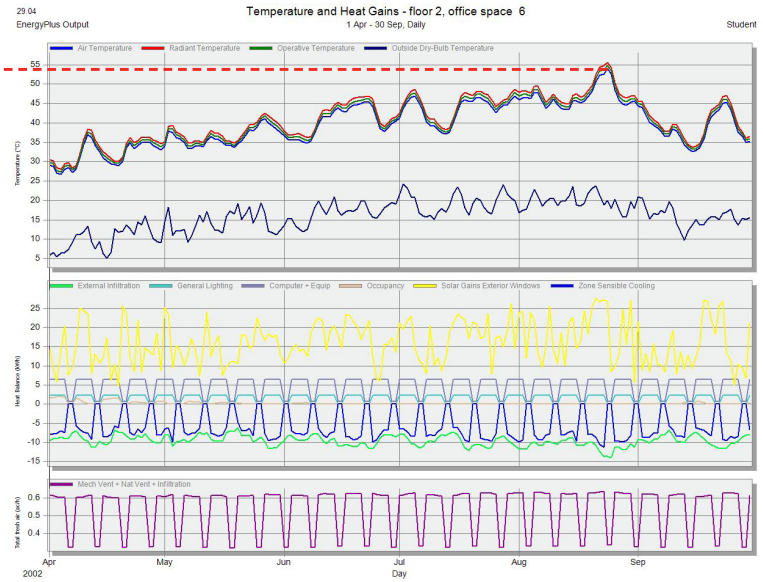
| | Annual energy per total building area (kWh/m²) | | | Max summer temperature (°C) |
|---|---|---|---|---|
| | Total (kWh/m²) | District heating (kWh) | District cooling (kWh) | |
| **heating / cooling OFF** | | | | |
| **Natural ventilation OFF** | | | | |
| **No shading** | 55.08 | 269.59 | 0 | 53.96 (24 Aug) |
| **Shading** | | | | |
| *20%* | | | | 51.84 (24 Aug) |
| *40%* | | | | 49.95 (24 Aug) |
| *60%* | | | | 47.21 (24 Aug) |
| *80%* | | | | 43.29 (25 Aug) |
| *100%* | | | | 39.31 (25 Aug) |
| **Natural ventilation ON** | | | | |
| **No shading** | 51.25 | 93.83 | 0 | 44.44 (22 Aug) |
| **Shading** | | | | |
| *20%* | | | | 42.93 (21 Aug) |
| *40%* | | | | 41.71 (21 Aug) |
| *60%* | | | | 39.41 (25 Aug) |
| *80%* | | | | 37.47 (25 Aug) |
| *100%* | | | | 34.87 (25 Aug) |

# Design Builder simulations

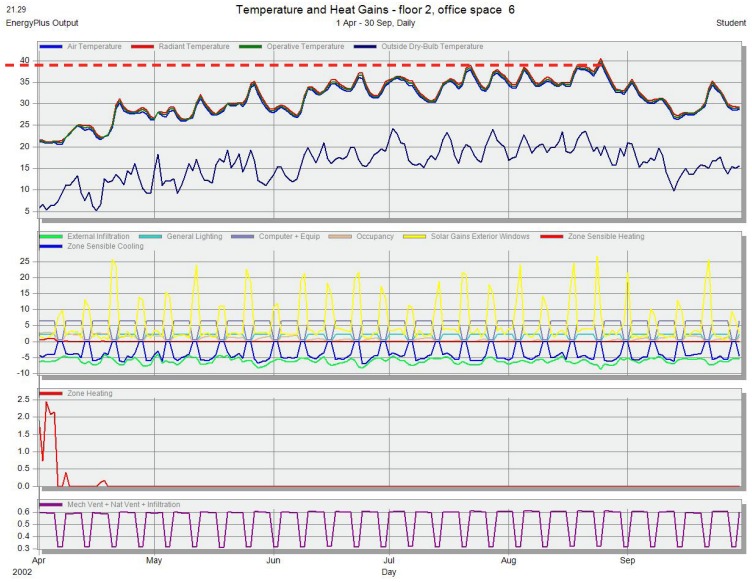
## cooling **off** // graphs

### natural ventilation **off**

54ºC

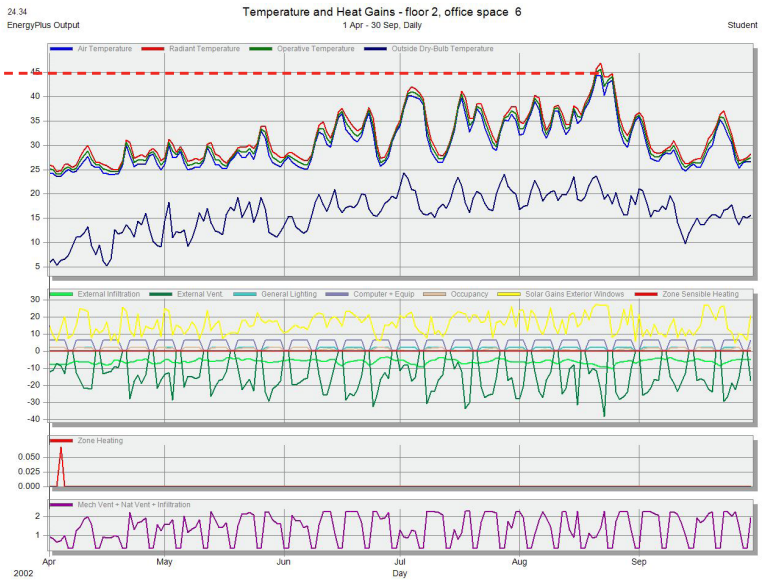



39ºC

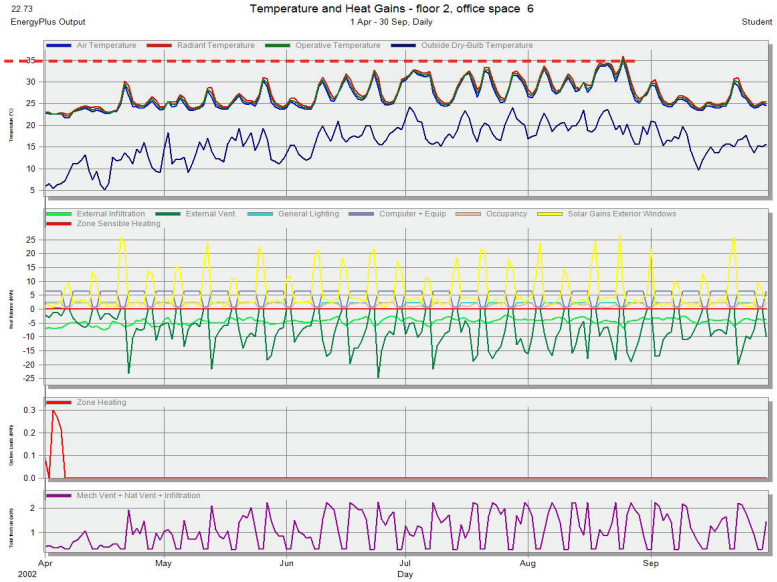



### natural ventilation **on**

45ºC




35ºC



# conclusions

## heating+cooling on

### no shading

» total energy consumption --> **122.45** kWh/m²

### shading

» energy for heating increases

» energy for cooling decreases

» total energy consumption --> **88.75** kWh/m² (3/4)

## heating on +cooling off

### ventilation off

#### no shading

» total energy consumption --> **55.08** kWh/m²

» max. indoor temperature --> **54°C** (24/8)

#### shading

» indoor temperature decreases

» min. value --> **39°C** (25/8)

### ventilation on

#### no shading

» total energy consumption --> **51.25** kWh/m²

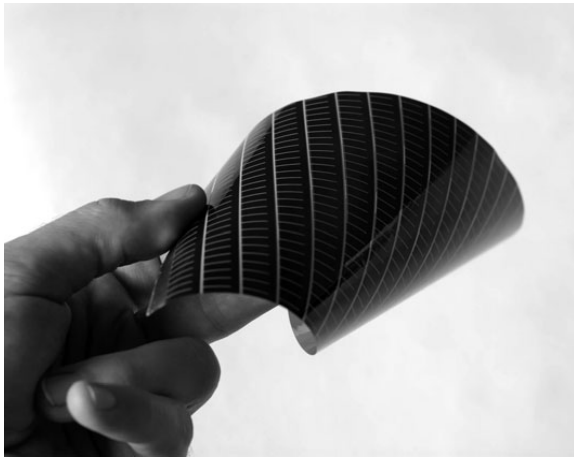
» max. indoor temperature --> **45°C** (22/8)

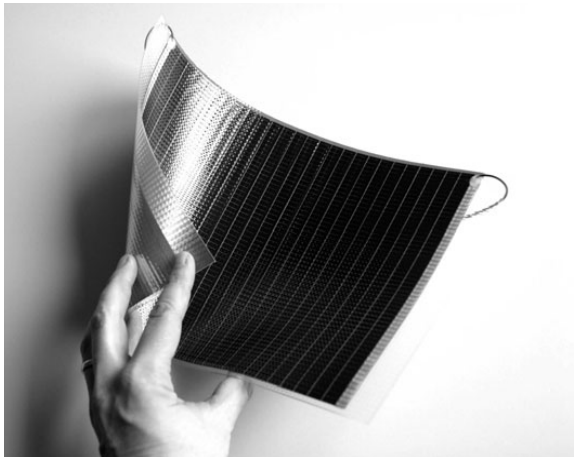
#### shading

» indoor temperature decreases

» min. value --> **35°C** (25/8)

# energy gains from PV films





PV flexibles --> thin-film solar cells:

**12-20% efficiency**

Global Horizontal Irradiance (GHI) for Paris:

**1617 kWh/m²/year**

| | *reduction factor* | *solar radiation values on the surface* | *energy gains from each façade surface* | *energy gains for the whole façade* |
|---|---|---|---|---|
| *South-West façade:* | 0.68 | 1100 kWh/m²/year | 176 kWh/m²/year | 99759 kWh/year |
| *South-East façade:* | 0.66 | 1067 kWh/m²/year | 170.7 kWh/m²/year | 498489 kWh/year |
| *North-West façade:* | 0.36 | 582 kWh/m²/year | 93.1 kWh/m²/year | 271882 kWh/year |
| *North-East façade:* | 0.36 | 582 kWh/m²/year | 93.1 kWh/m²/year | 211464 kWh/year |

1/10 of total energy consumption from design builder

Total: 1.38 GWh/year

# conclusions

**ways of reducing the total energy consumption:**

- » sun shading
- » natural ventilation
- » integration of PV films (compensation)
- » efficient HVAC system

# 4

# case study + design

# tour areva

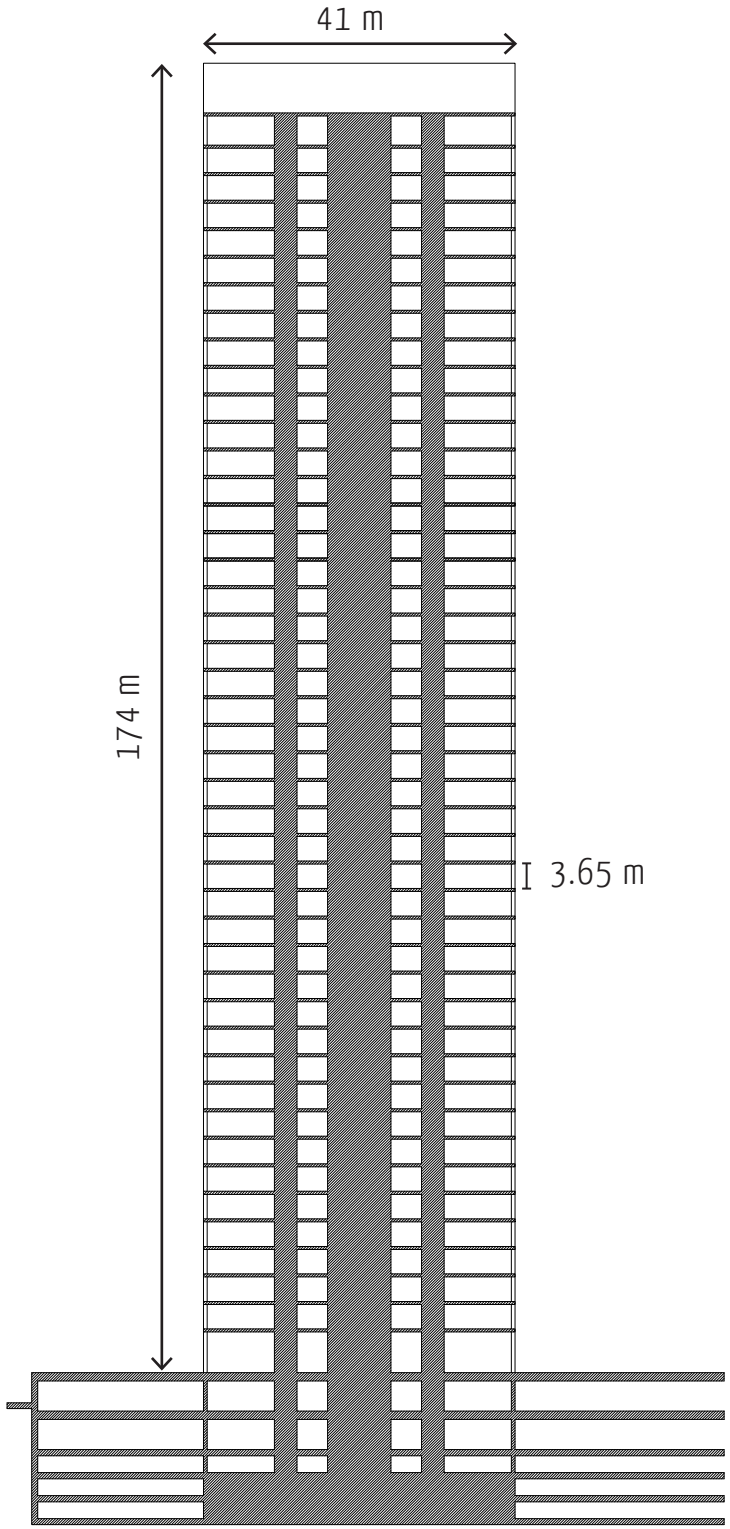
## La Défense, Paris

| | |
|---|---|
| **architects:** | Roger Saubot, François Jullien and Skidmore, Owings & Merrill LLP |
| **built:** | 1974 |
| **height:** | 174m from the ground floor |
| **number of floors:** | 45 + 5 underground |
| **ground floor surface:** | 53 x 41 m |
| **structural material:** | concrete |
| **façade material:** | granite cladding |
| **façade system:** | curtain wall |
| **function:** | offices / open-plan floor |

# tour areva

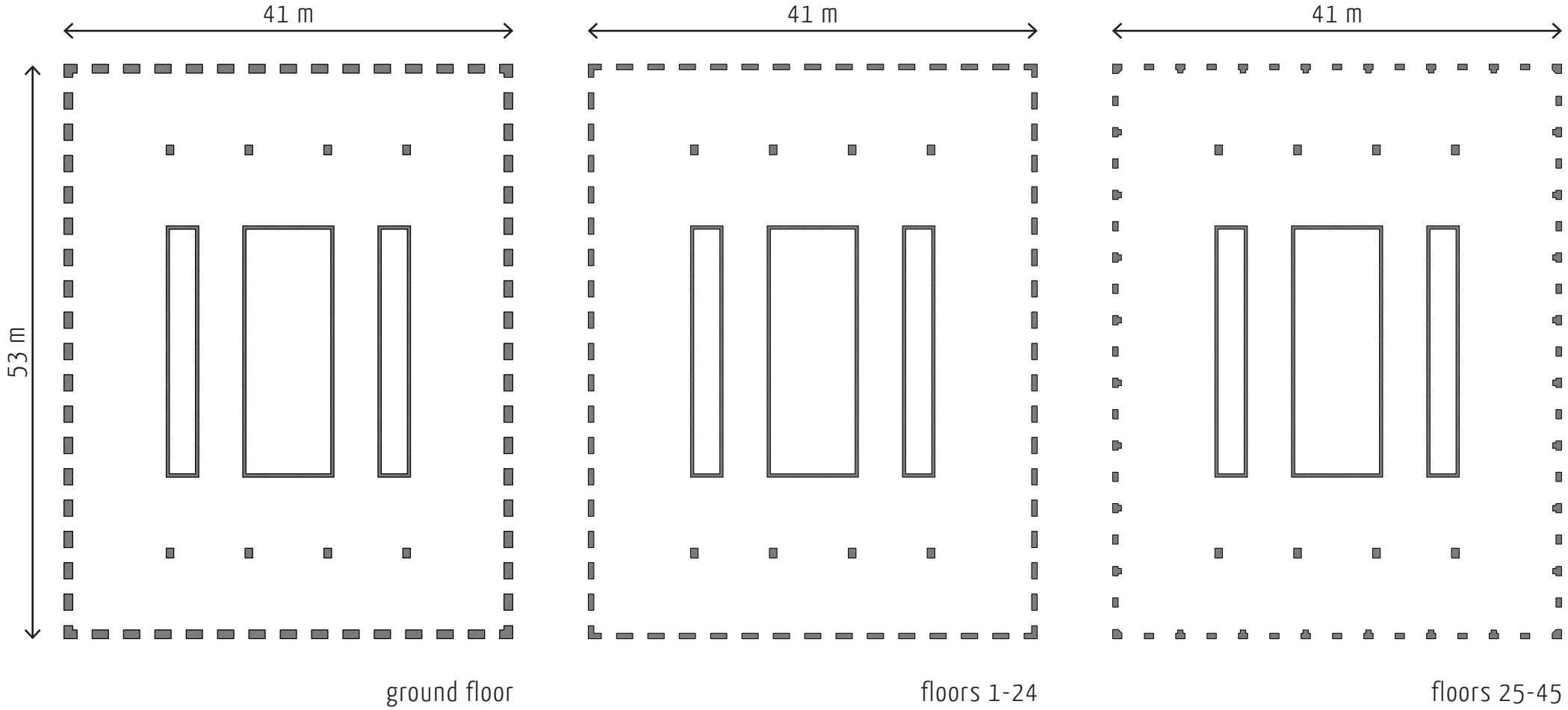
## La Défense, Paris


vertical section



# tour areva

## La Défense, Paris



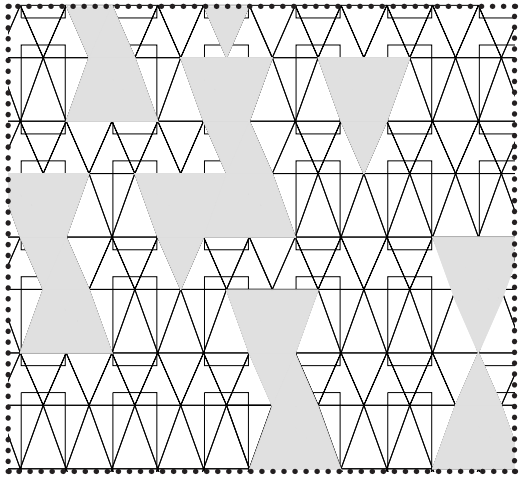

ground floor

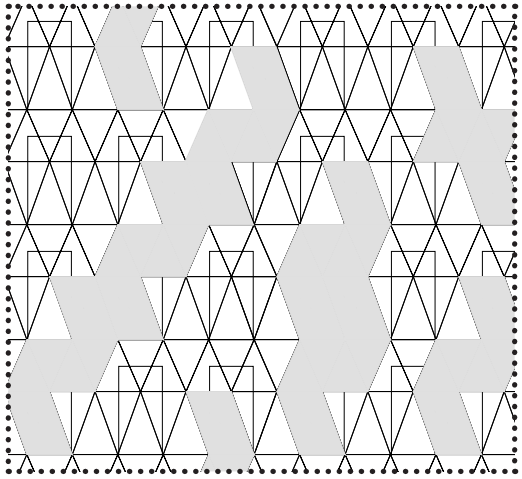
floors 1-24

floors 25-45

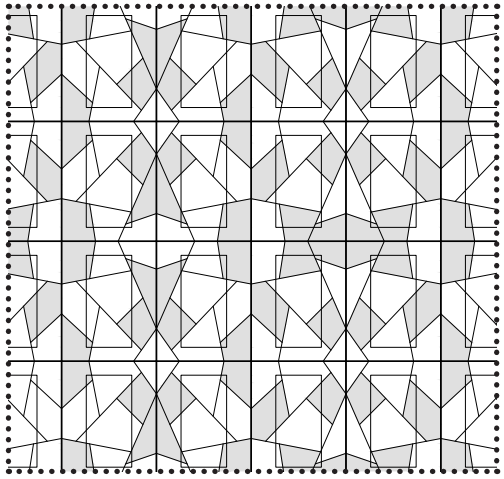
# shape / pattern

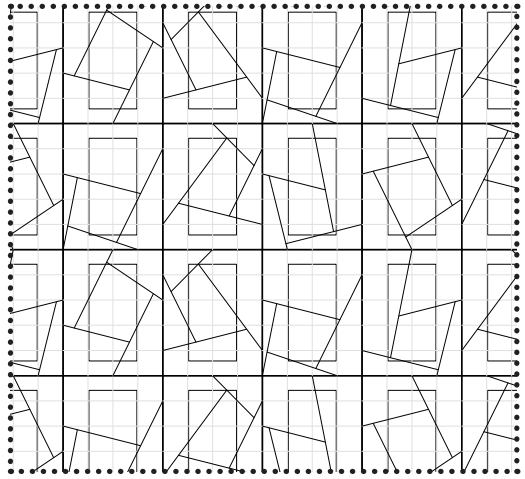
## diagrid



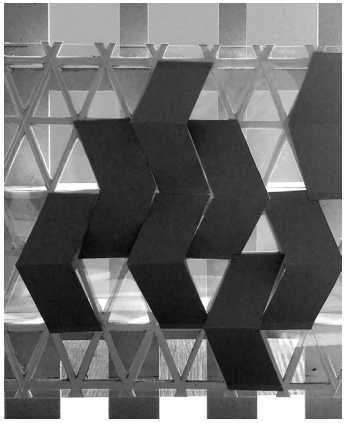


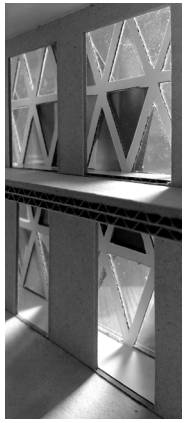
## rectangular grid

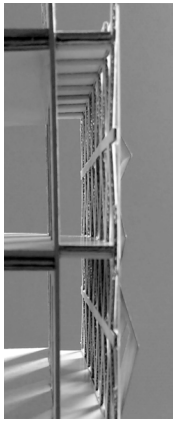


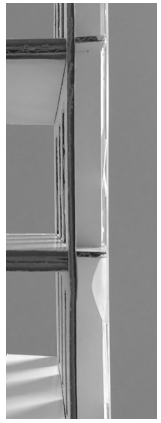


## physical models



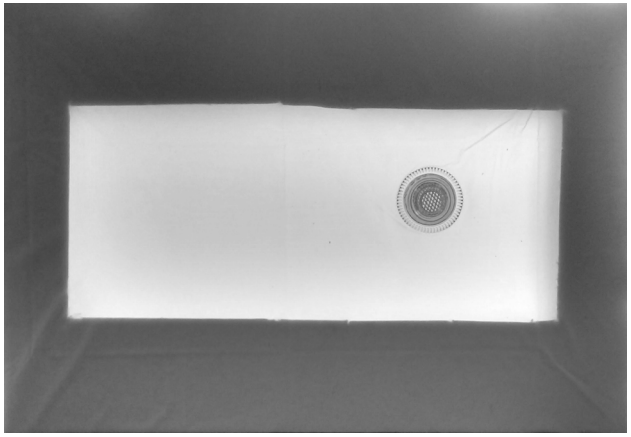




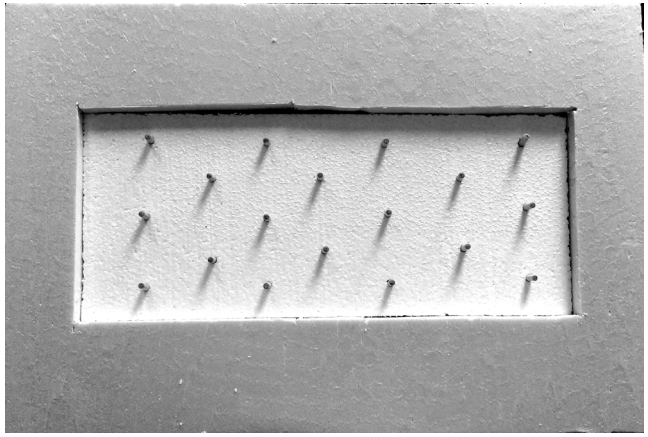


# vacuum experiments

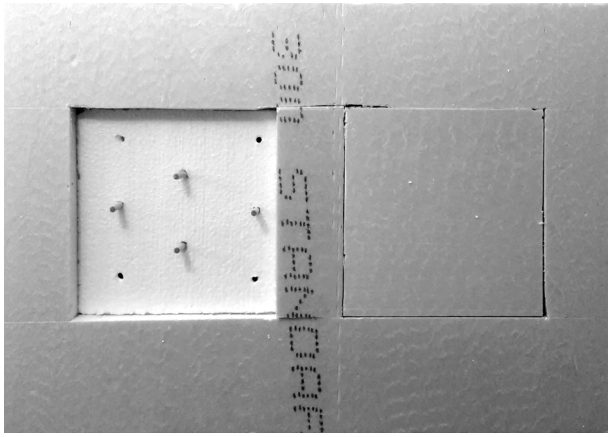
big opening



big opening with spacers

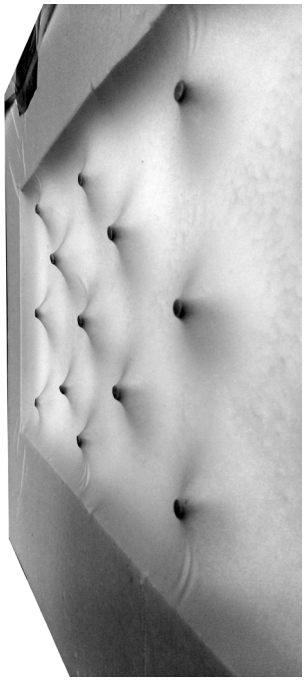


small opening with spacers



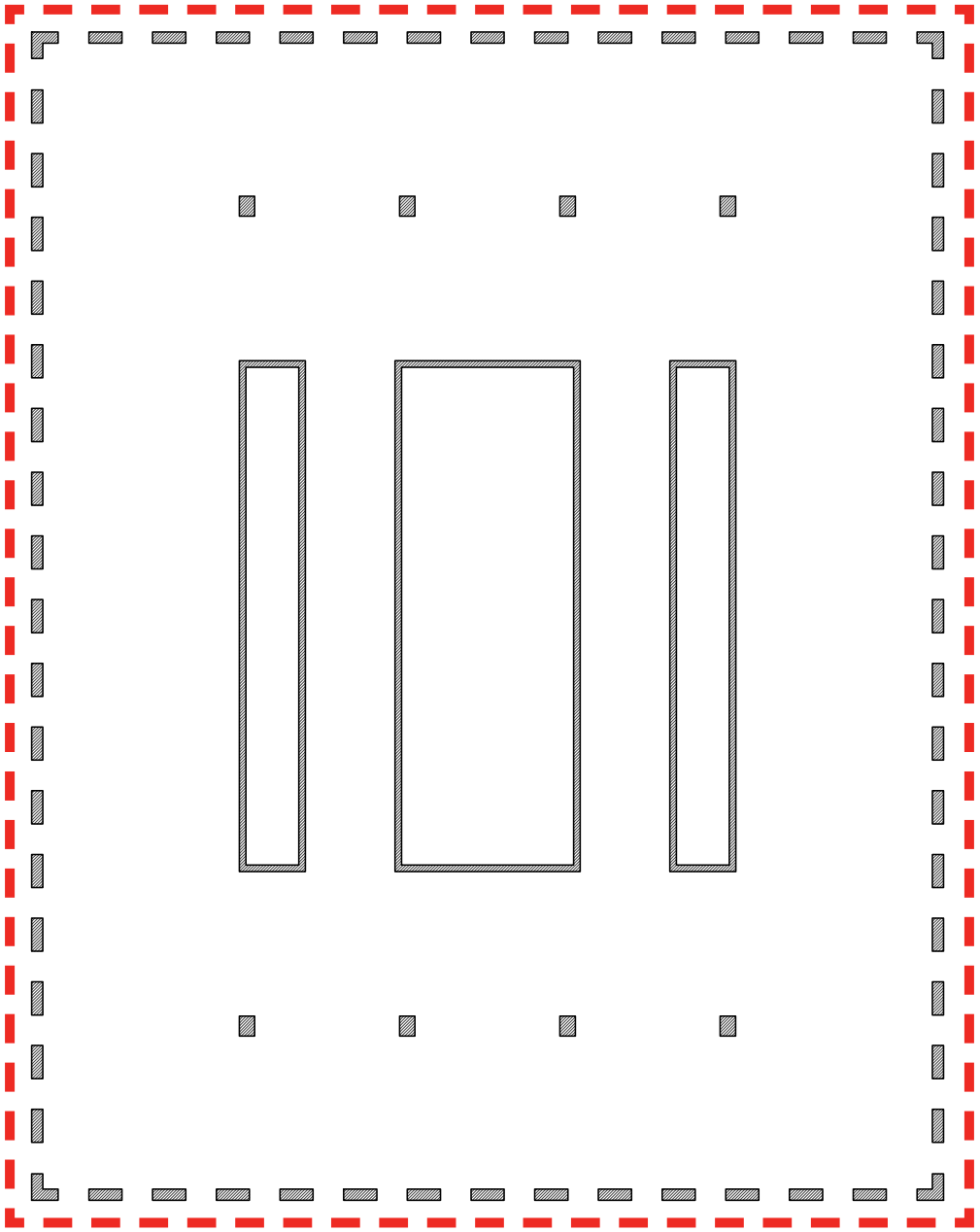
with spacers

with spacers and lower air pressure



with less spacers

# position of the new façade



# chosen design

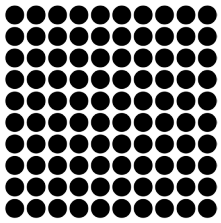
**orthogonal grid** following the existing façade

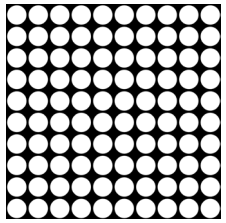
**rectangular frame** --> stiff “wide” element

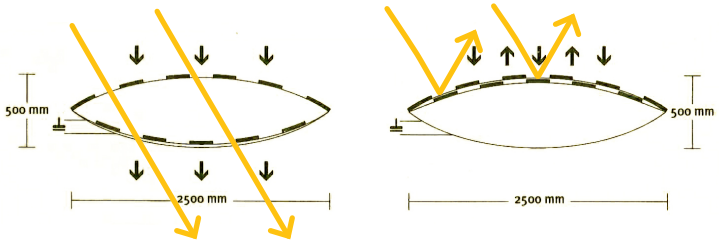
**cushions pattern** --> internal “thinner” connections

**transparent + translucent parts** --> shading

**Shading:**
printed pattern and movable middle layer for shading



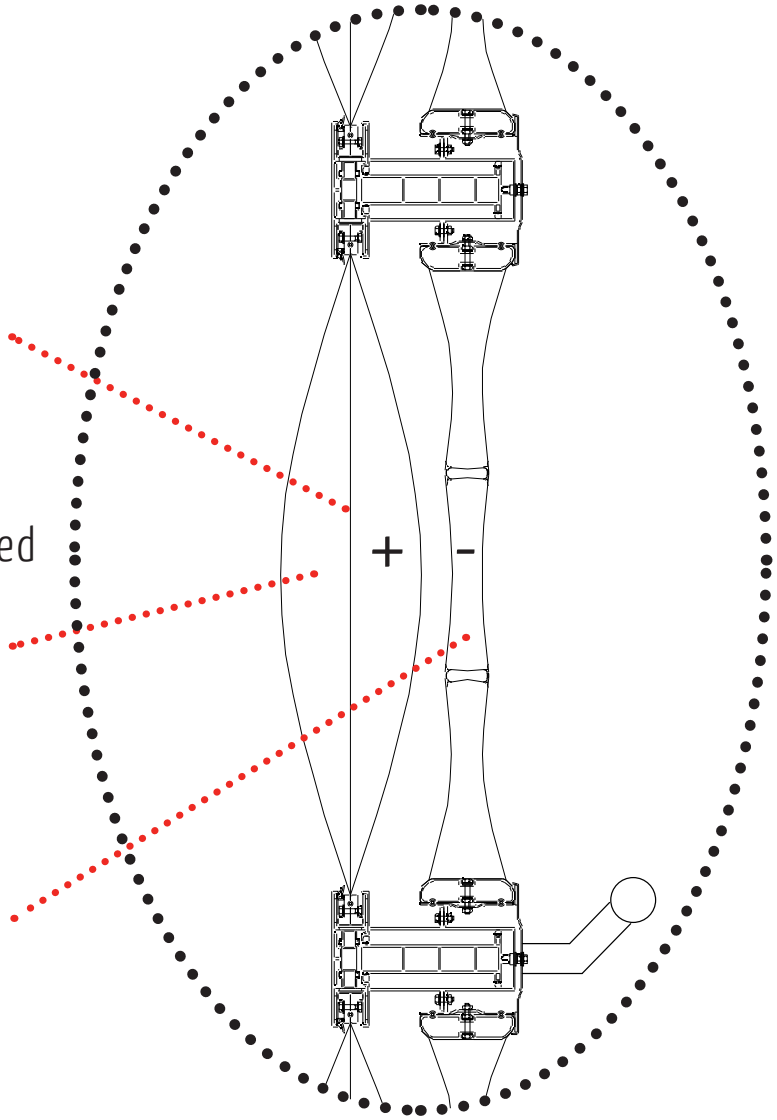




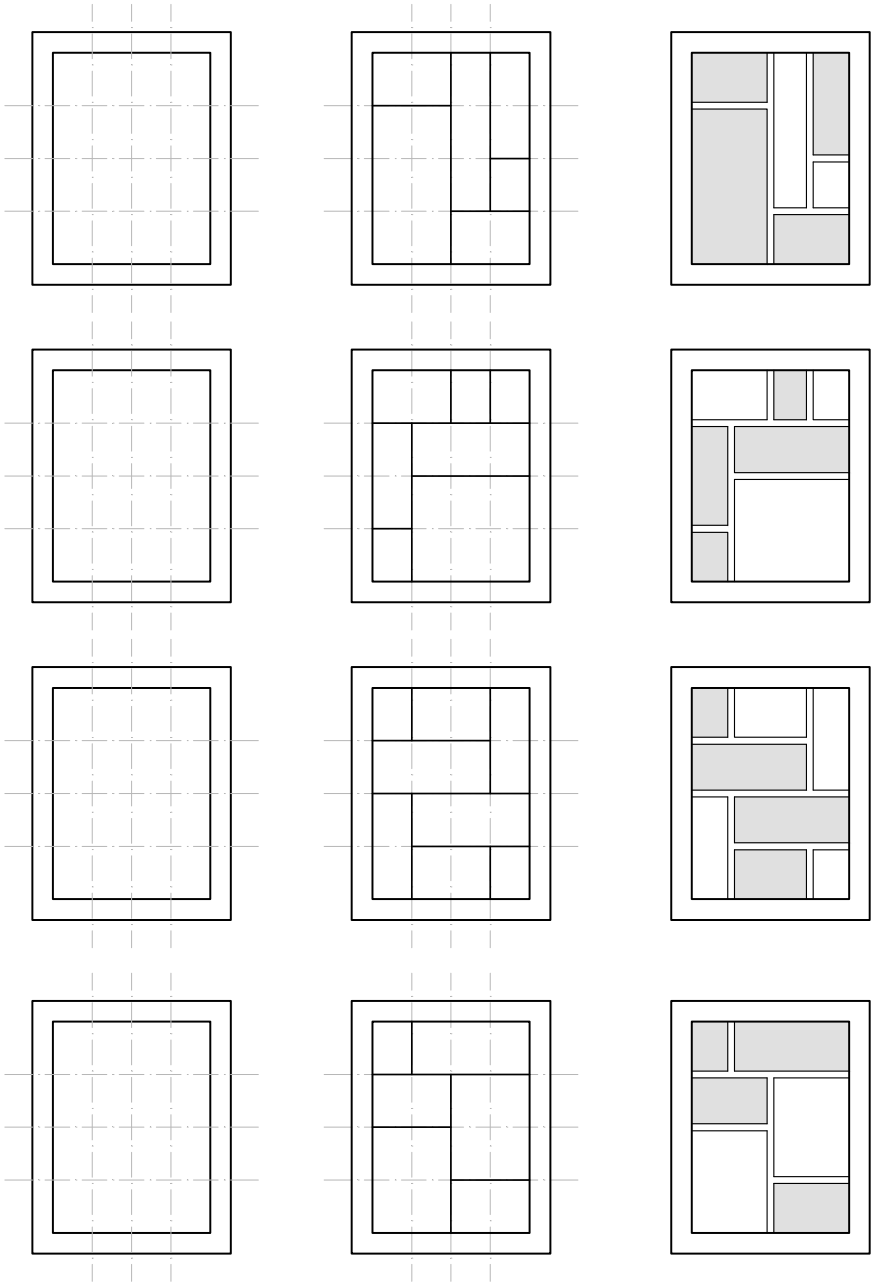

printed pattern and movable middle layer for shading

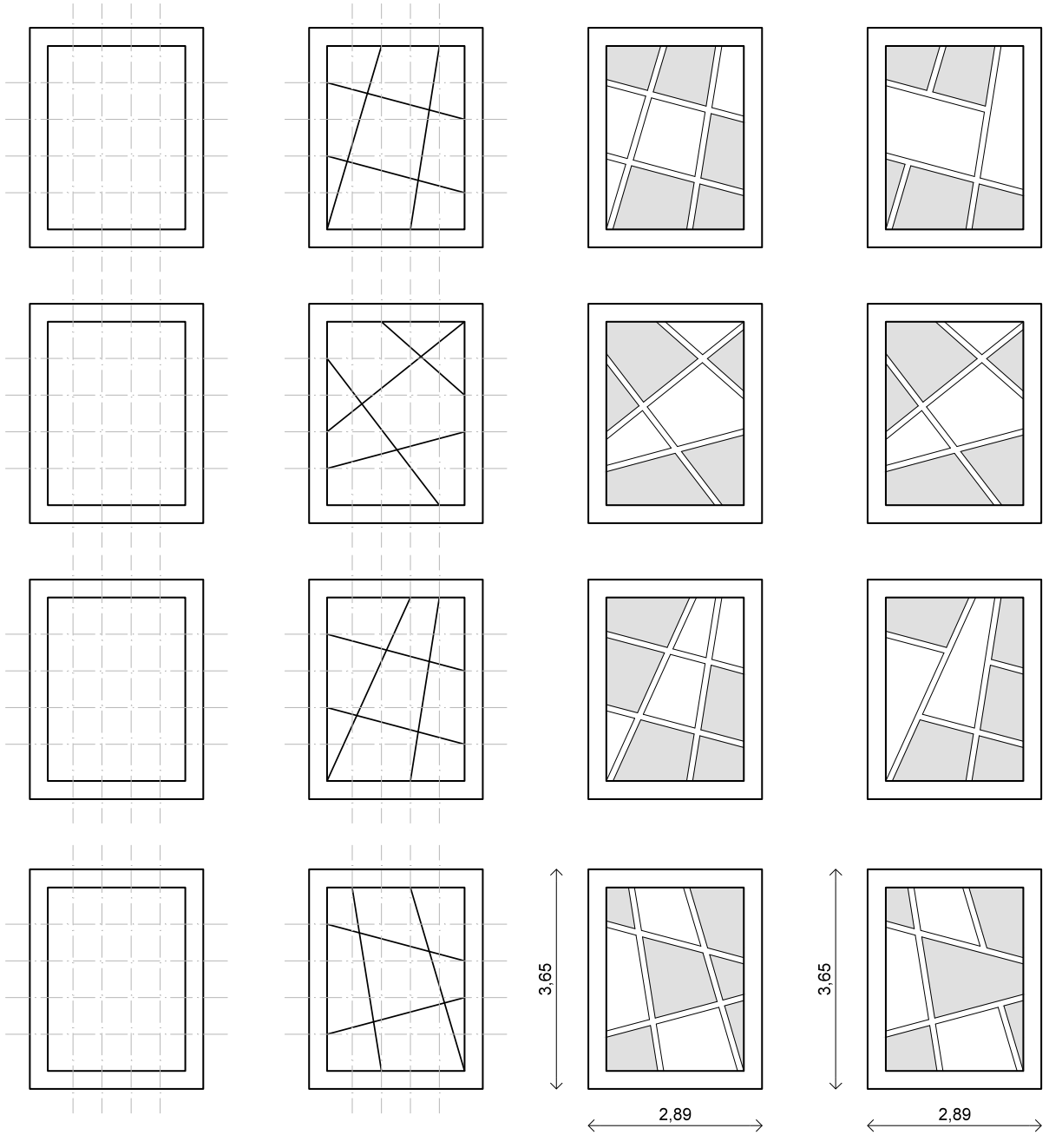
3-layered inflated cushion filled with argon or aerogel (partly)

2-layered vacuum cushion with reflective coating on the inner layer



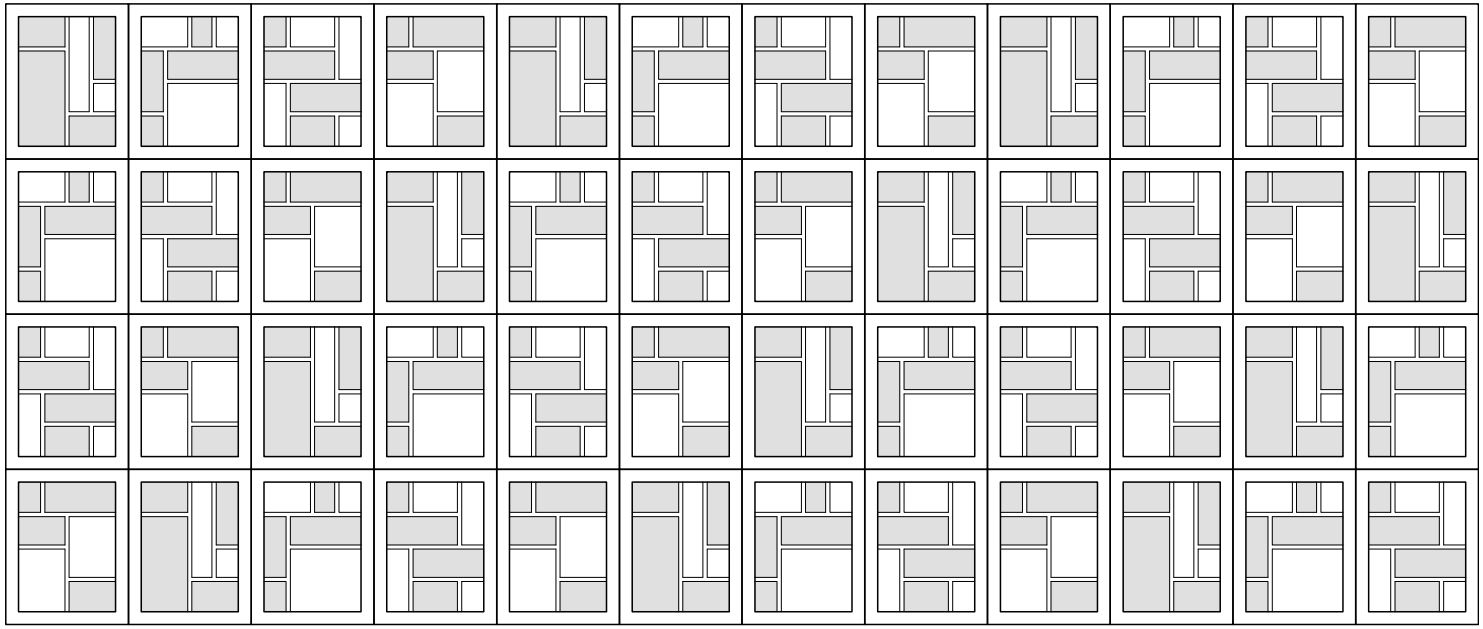
# pattern design



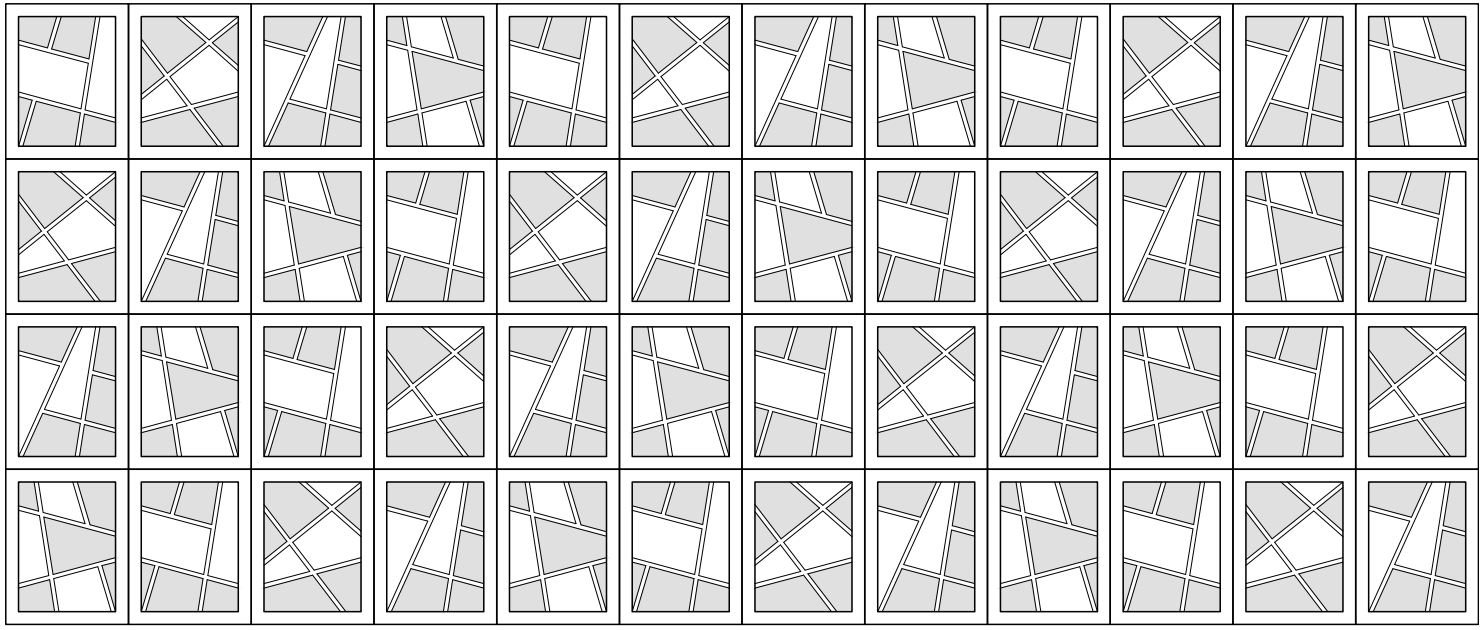


# part of the façade configuration

"regular "
cushions' pattern



irregular
cushions' pattern



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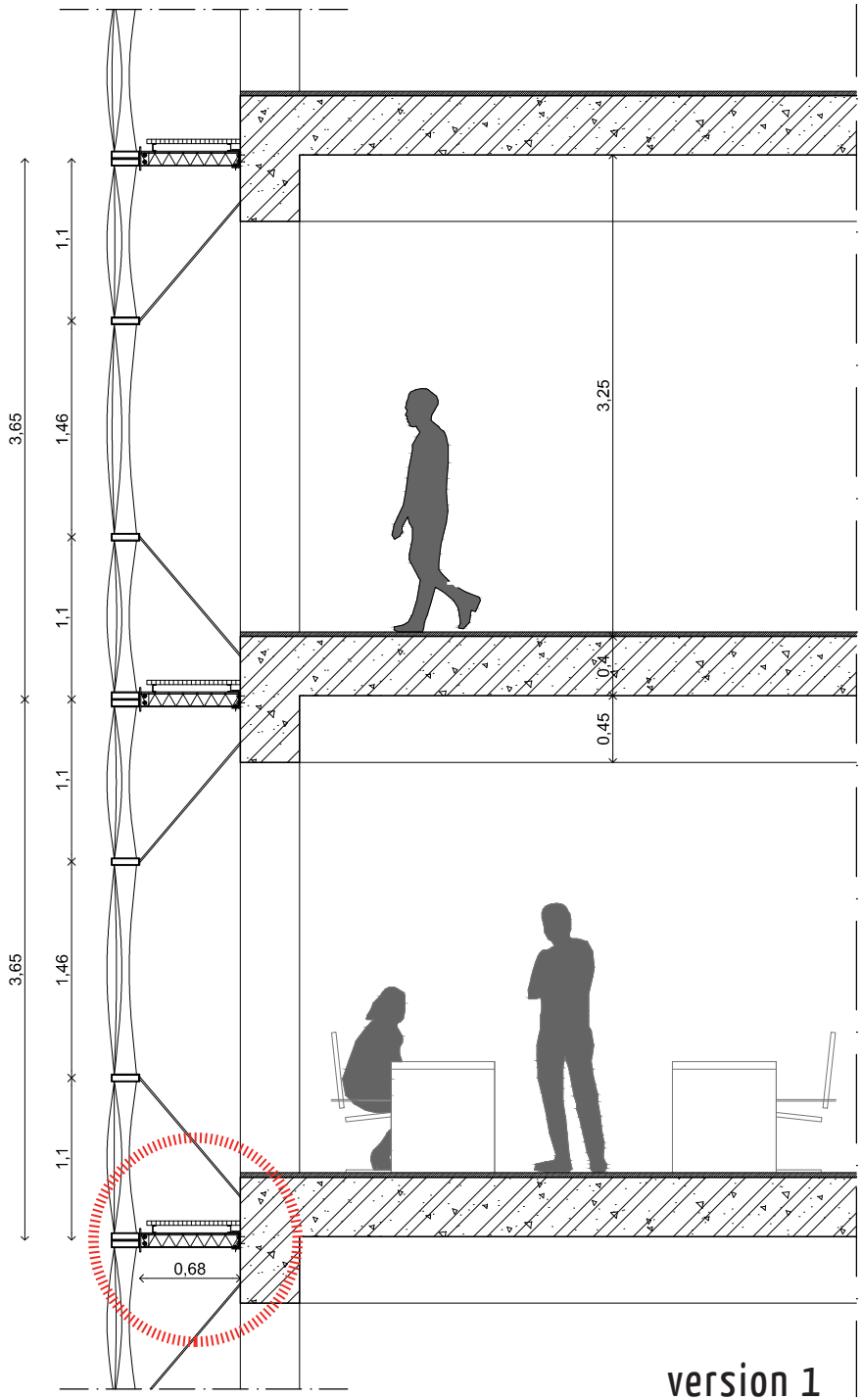
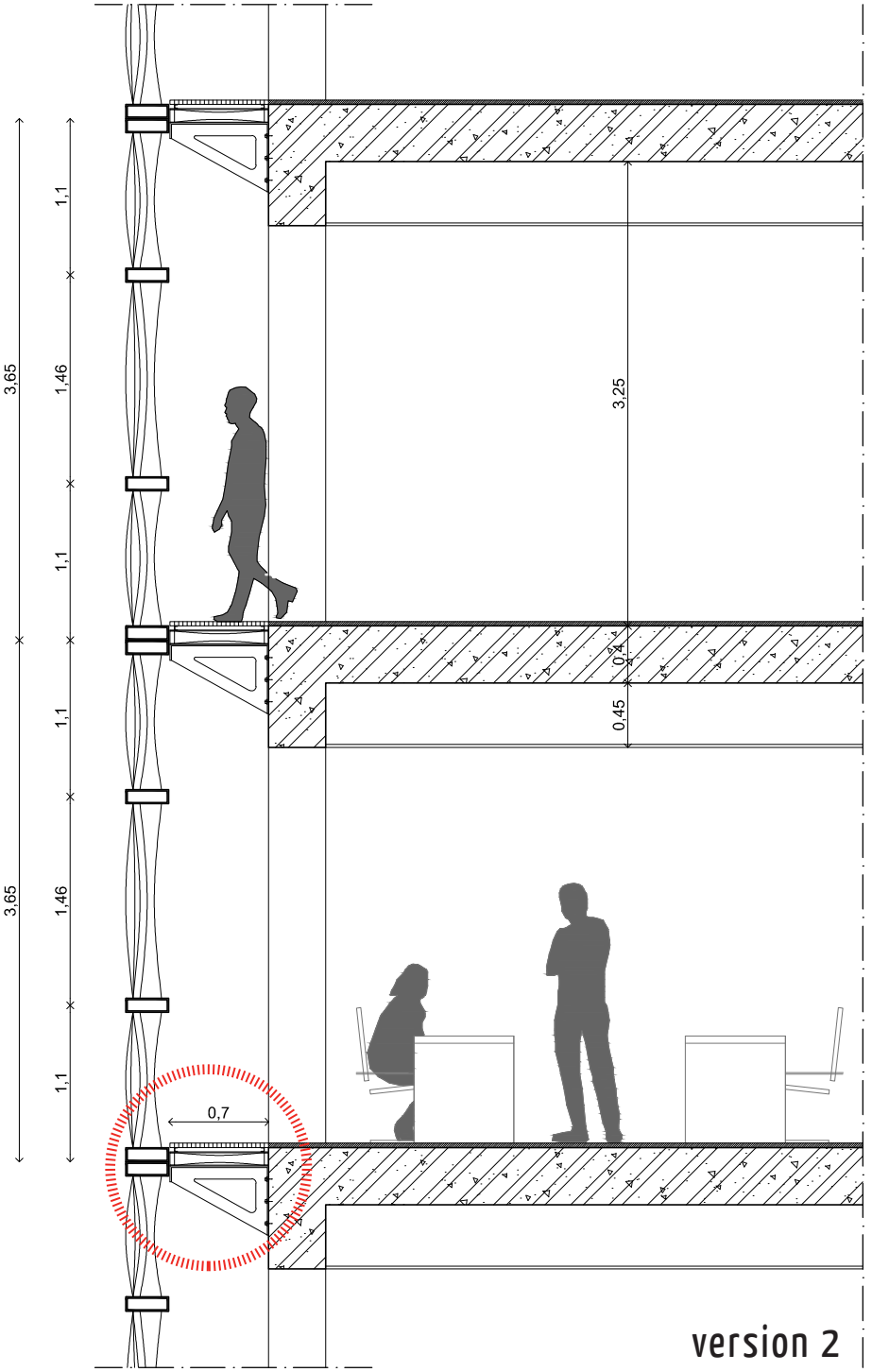



version 1




version 2

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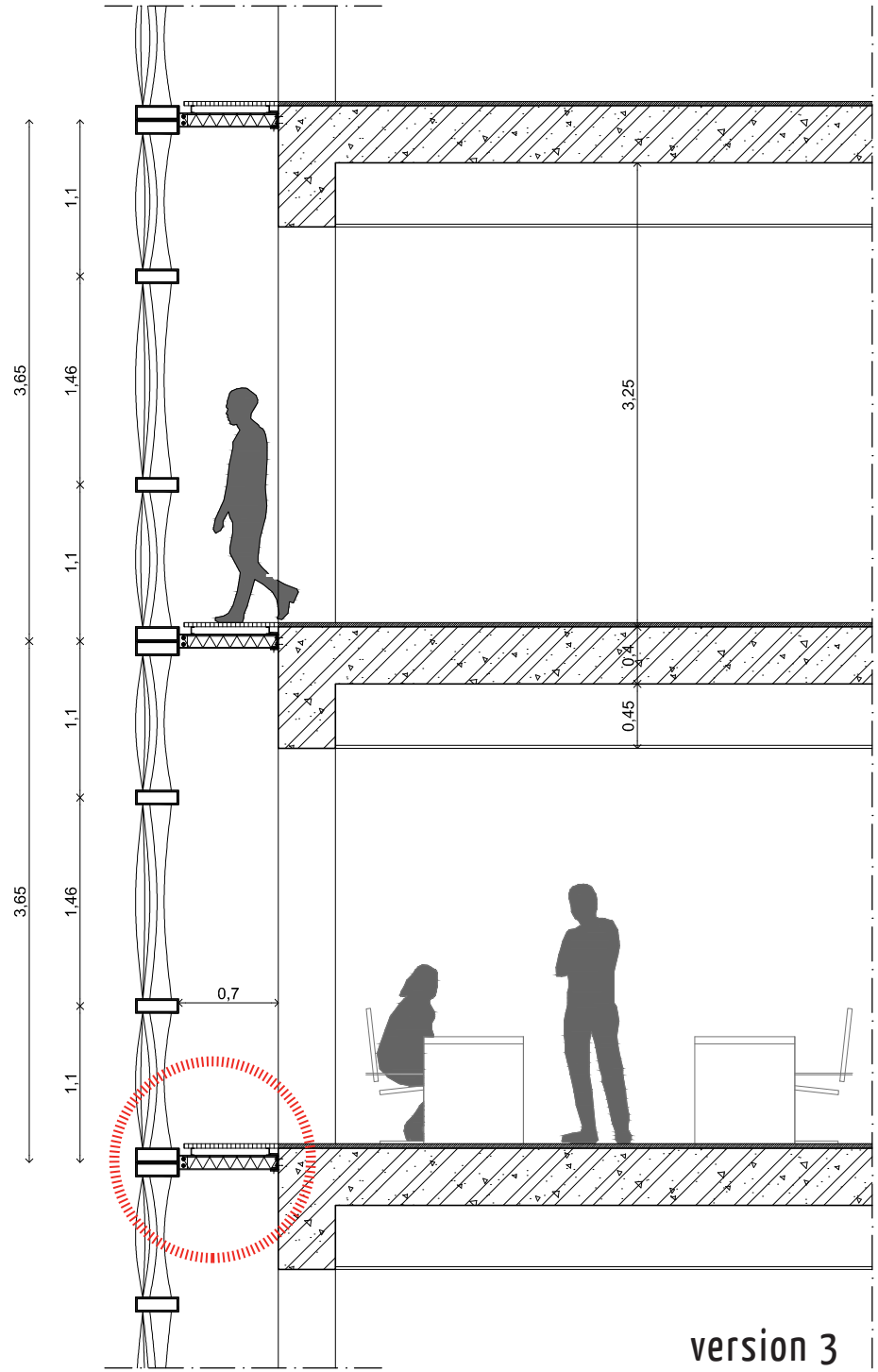
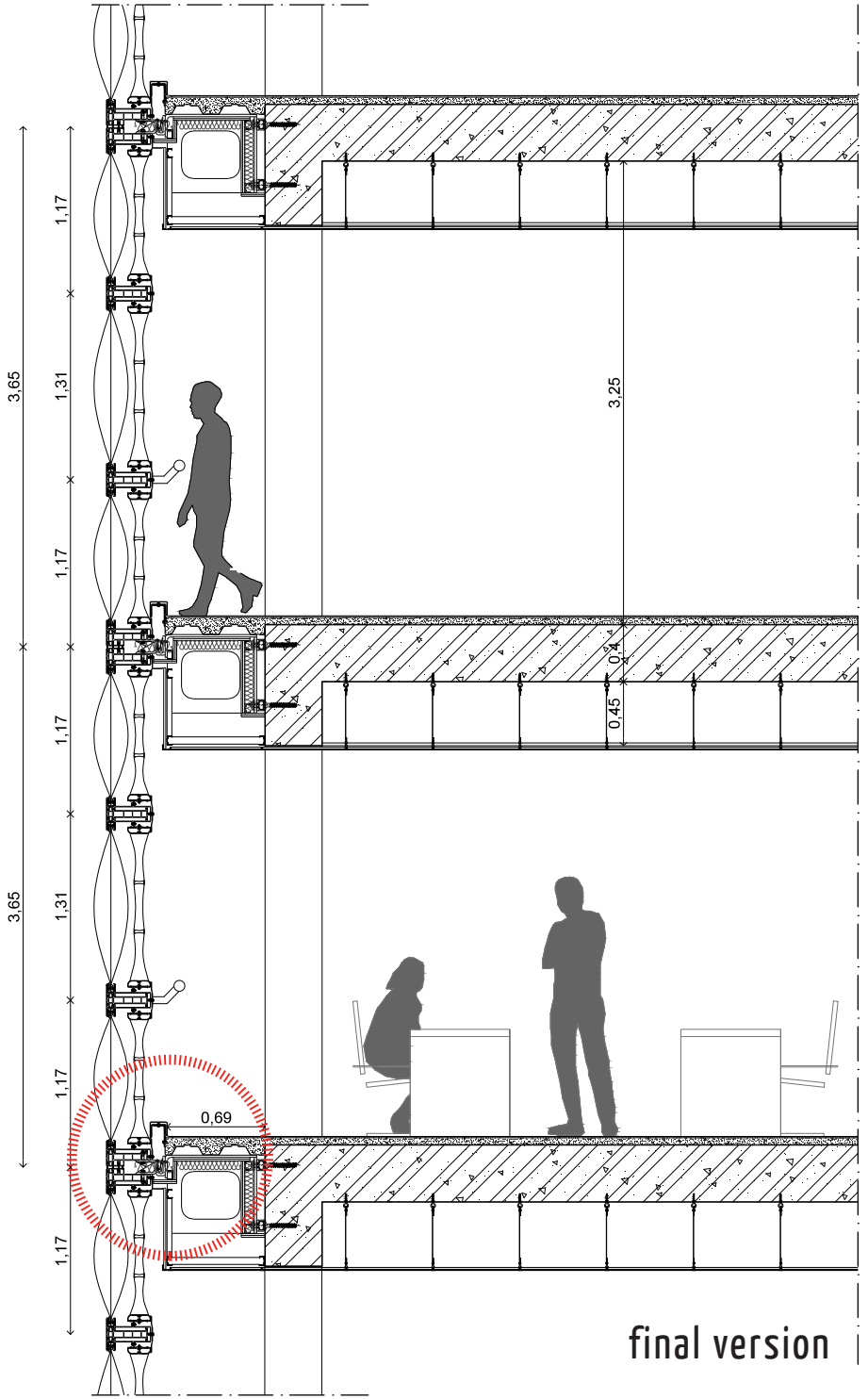


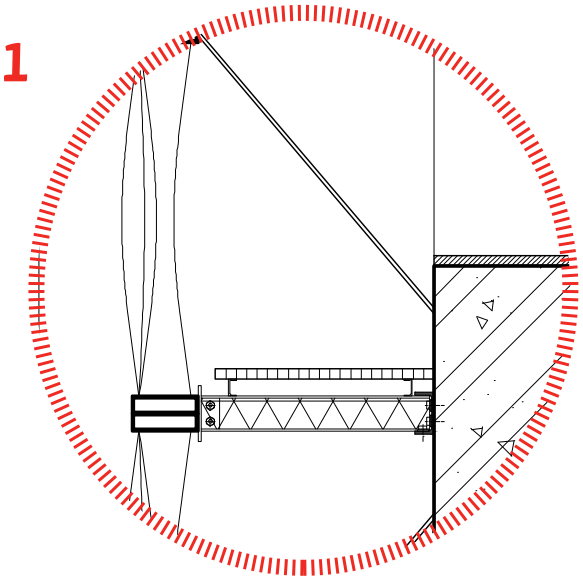

version 3




final version

# details

1



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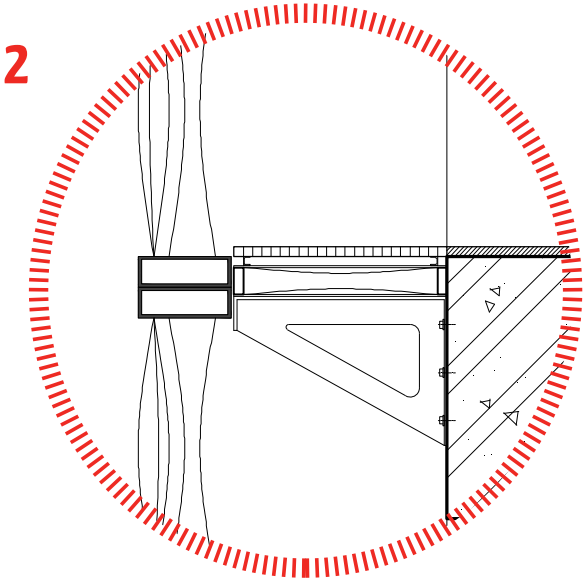

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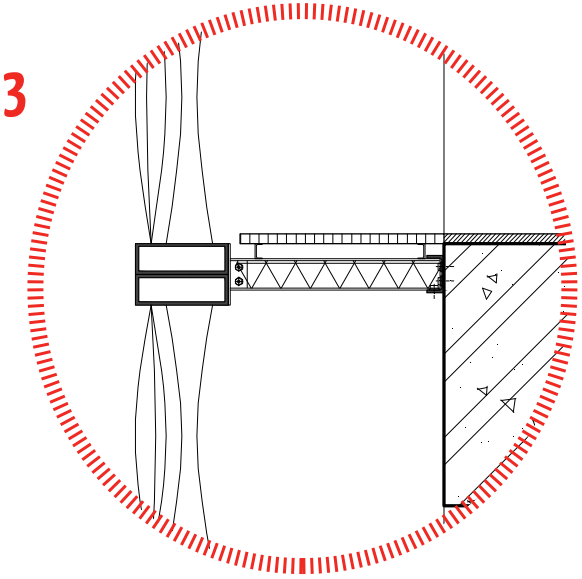

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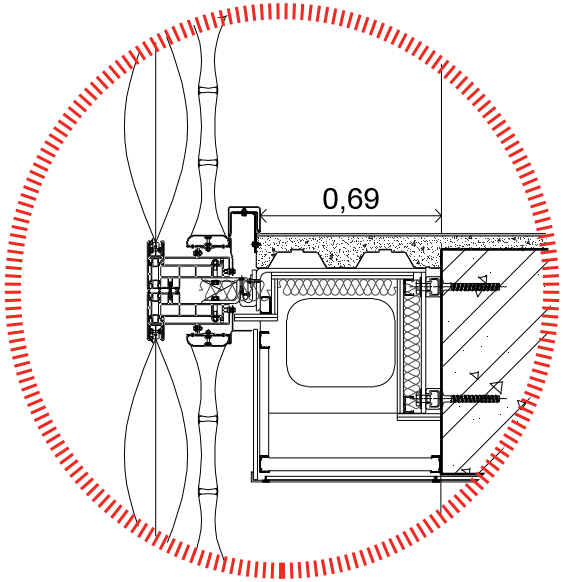

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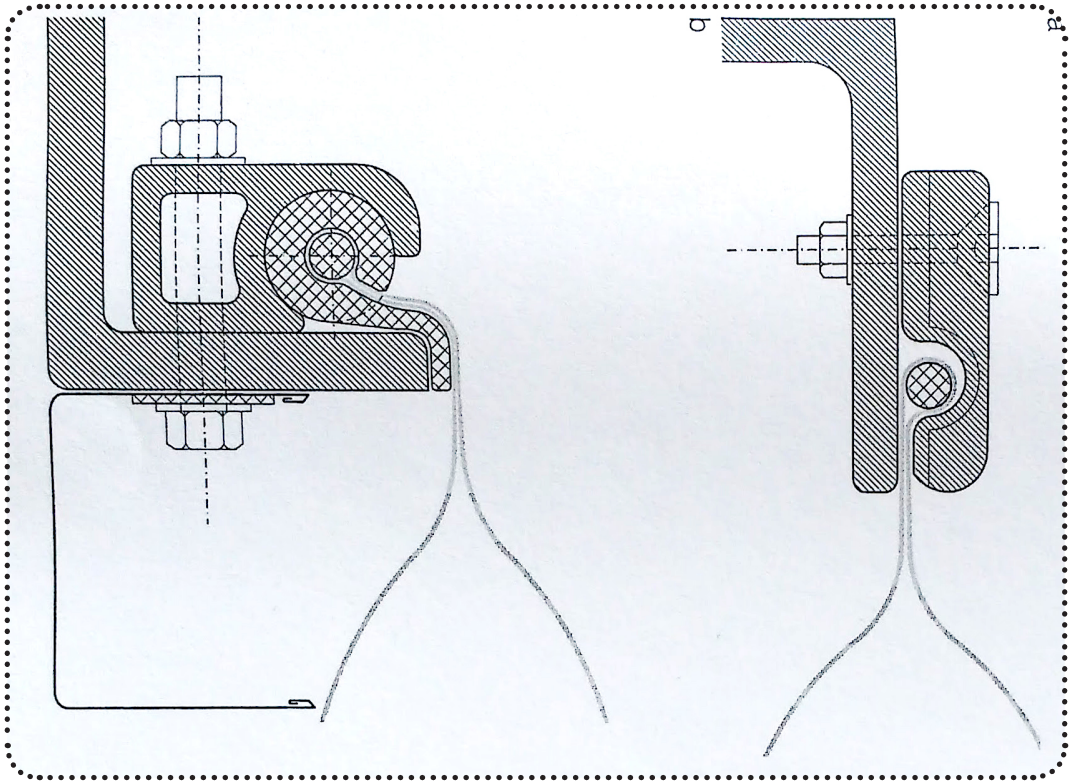
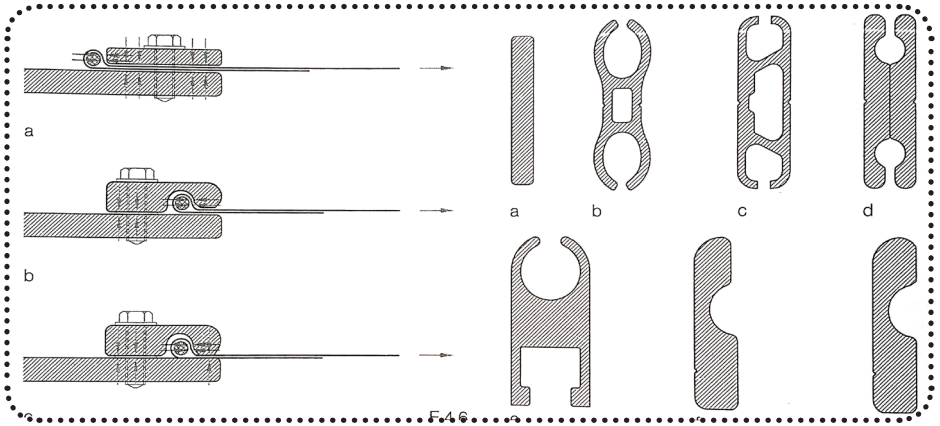
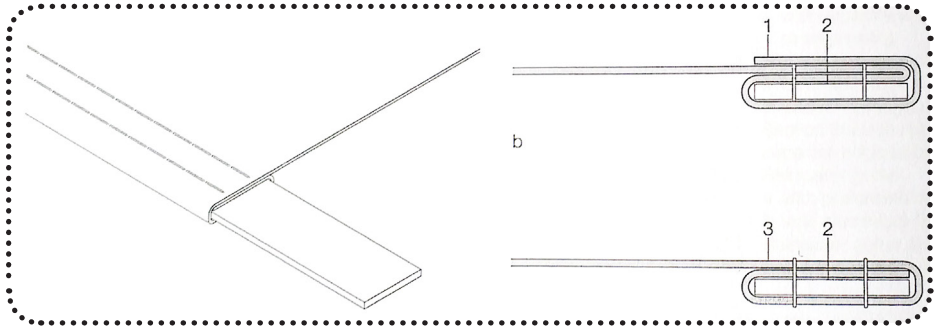
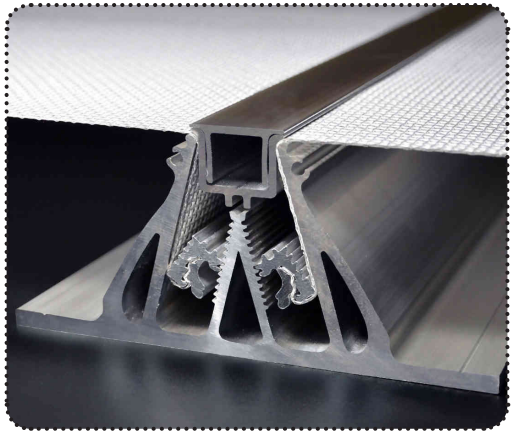
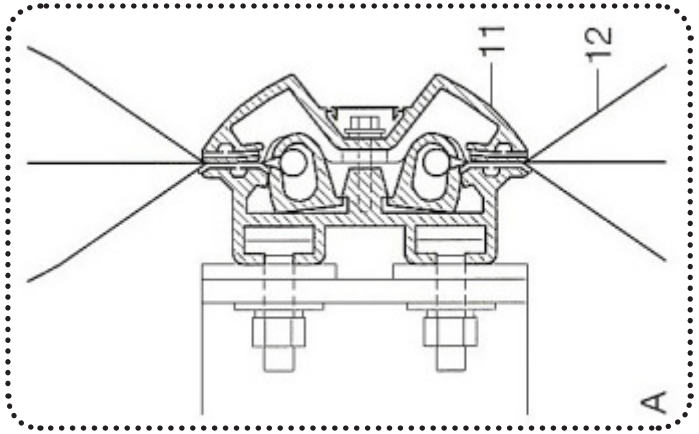
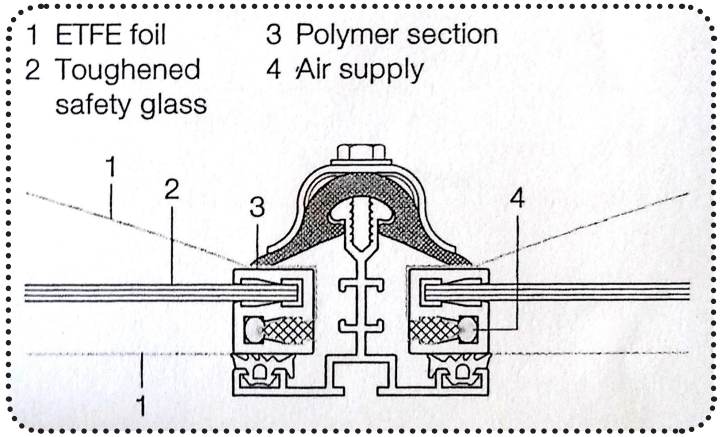




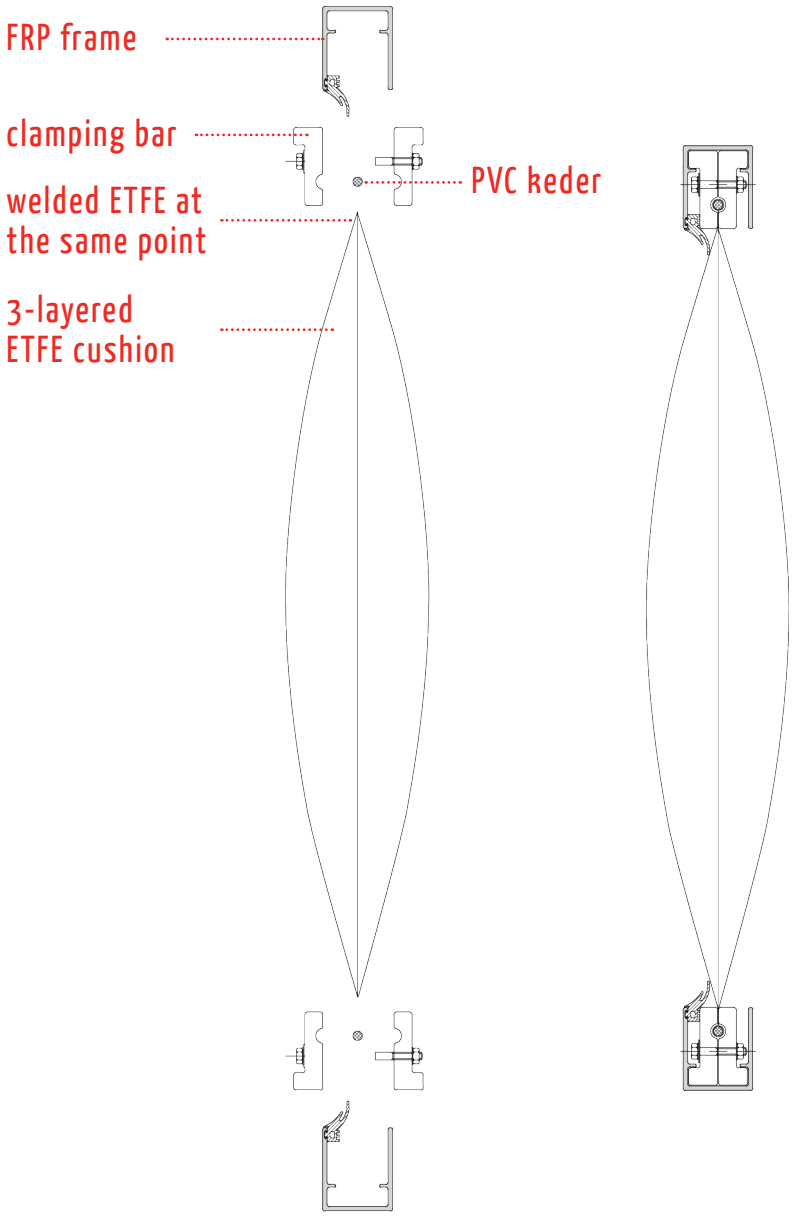





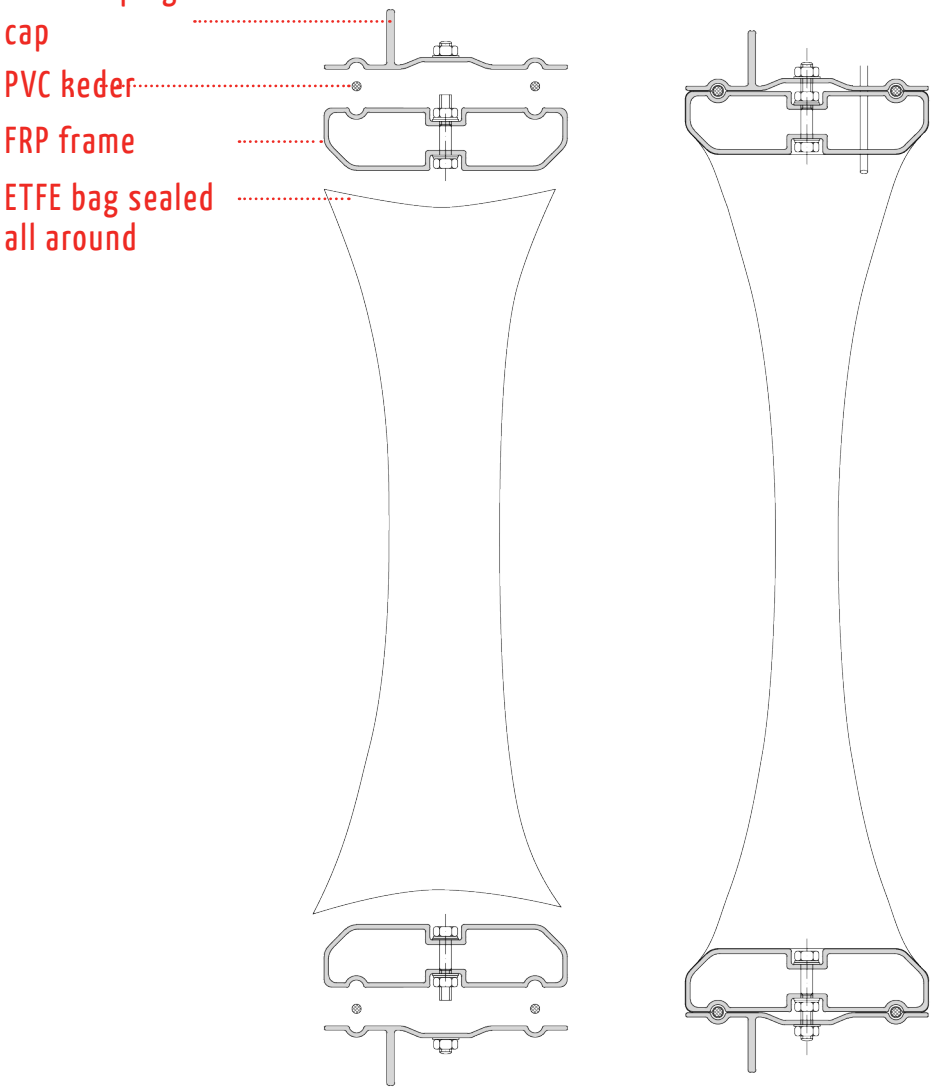



# cushions assembly concept

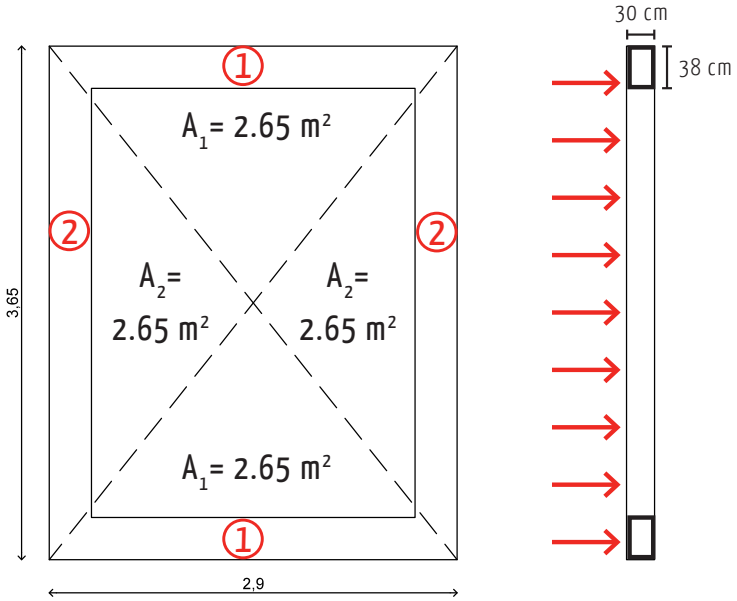
## inflated cushion assembly




## vacuum system assembly



# wind forces calculations




$A_{tot}$= 10.59 m², $v_{maxW}$ = 9 m/s, $C_d$= 2 (for buildings)

$P_{wind} = 0.613 \times v_{maxW} = 50$ N/m

$F_{wind} = A_{tot} \times P_{wind} \times C_d = 1059$ N

For one frame:

$F_{wind}/4 = 264.75$ N = 0.265 kN

For frame 1 the uniform load is:

$q_1 = F/l_1 = 0.265/3.65$

= 0.07 kN/m

For frame 2 the uniform load is:

$q_2 = F/l_2 = 0.265/2.9$

= 0.09 kN/m

| materials: | load (kN/m) | length (mm) | elastic modulus (N/mm²) | width (mm) | height(mm) | thickness (mm) | max stress (N/mm²) | max deflection (mm) |
|---|---|---|---|---|---|---|---|---|
| **steel** | | | | | | | | |
| *vertical beam* | 0.07 | 3650 | 210000 | 380 | 300 | 5 | 0.2 | 0 |
| | | | | | | 4 | 0.2 | 0 |
| | | | | | | 3 | 0.3 | 0 |
| | | | | | | 2 | 0.4 | 0 |
| *horizontal beam* | 0.09 | 2900 | 210000 | 380 | 300 | 5 | 0.1 | 0 |
| | | | | | | 4 | 0.2 | 0 |
| | | | | | | 3 | 0.2 | 0 |
| | | | | | | 2 | 0.3 | 0 |
| **aluminum** | | | | | | | | |
| *vertical beam* | 0.07 | 3650 | 71000 | 380 | 300 | 5 | 0.2 | 0 |
| | | | | | | 4 | 0.2 | 0 |
| | | | | | | 3 | 0.3 | 0 |
| | | | | | | 2 | 0.4 | 0.1 |
| *horizontal beam* | 0.09 | 2900 | 71000 | 380 | 300 | 5 | 0.1 | 0 |
| | | | | | | 4 | 0.2 | 0 |
| | | | | | | 3 | 0.2 | 0 |
| | | | | | | 2 | 0.3 | 0 |
| **FRP** | | | | | | | | |
| Glass FRP | | | | | | | | |
| *vertical beam* | 0.07 | 3650 | 40000 | 380 | 300 | 5 | 0.2 | 0 |
| | | | | | | 4 | 0.2 | 0 |
| | | | | | | 3 | 0.3 | 0.1 |
| | | | | | | 2 | 0.4 | 0.1 |
| *horizontal beam* | 0.09 | 2900 | 40000 | 380 | 300 | 2 | 0.3 | 0 |
| Aramid FRP | | | | | | | | |
| *vertical beam* | 0.07 | 3650 | 100000 | 380 | 300 | 2 | 0.4 | 0 |
| *horizontal beam* | 0.09 | 2900 | 100000 | 380 | 300 | 2 | 0.3 | 0 |

# vacuum forces calculations

For one side of the frame:

$$H = (w \times L^2)/(8 \times h)\ [kN]$$

For both sides of the frame:

$$H\ (x2)\ [kN]$$

For the whole length of the frame:

$$H_{tot} = H\ (x2) \times d\ [kN/m]$$

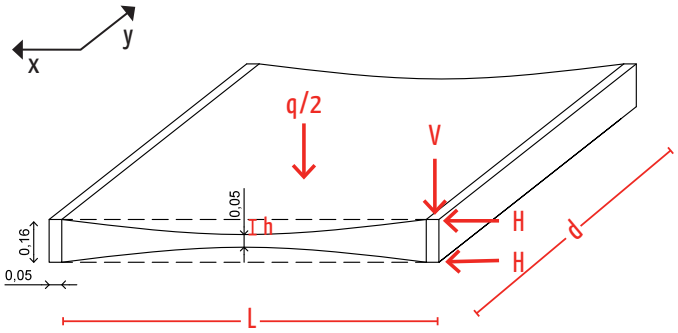
with

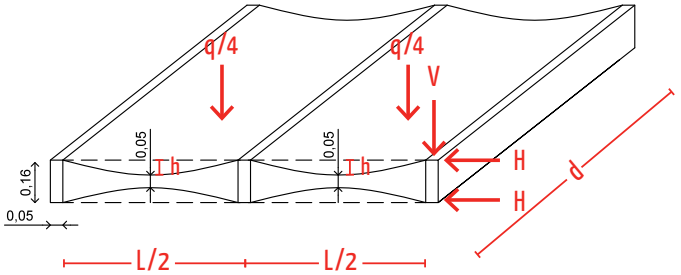
$P_{out}$ = 100 000 Pa , $P_{in}$ = 10 000 Pa

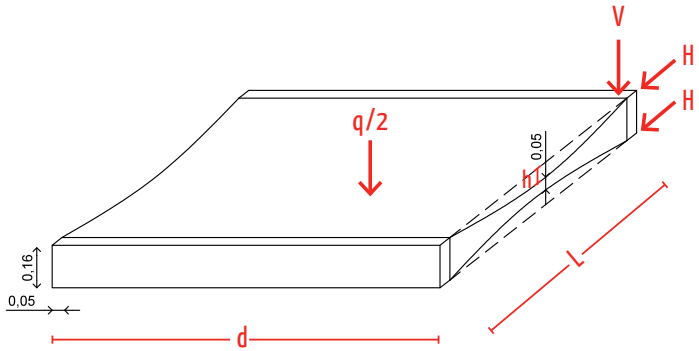
$\Delta P$ = 90 000 Pa = 90 000 N/m² = q

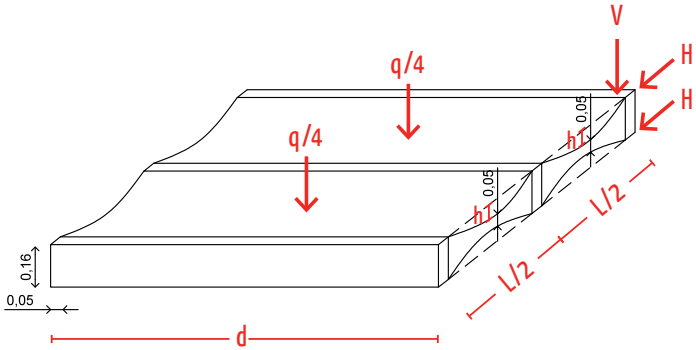
uniform load:

$$w = q \times d\ [N/m]$$



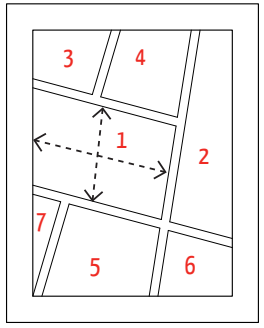



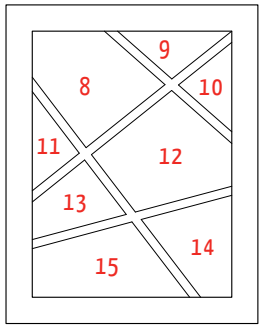



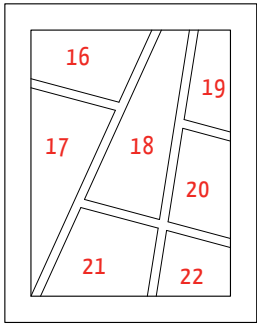



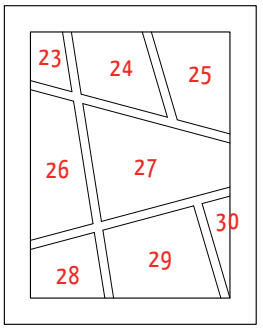

every cushion

- rectangular
- central axis taken into account



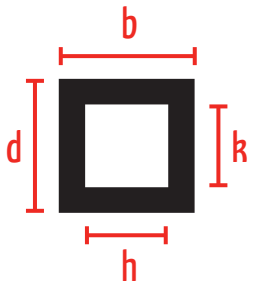



# vacuum forces calculations

Moment of Inertia:

$$I = (b*d^3) - (h*k^3)/12 \ [mm^4]$$




Max. deflection:

$$\Delta_{max} = (5/384) \times \{(H_{tot} * L^4)/(E*I)\} \ [mm]$$

where:

E = modulus of elasticity of the frame's material ($N/mm^2$)

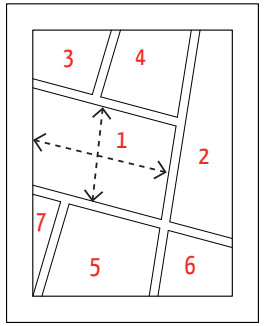
I = moment of inertia (mm4)

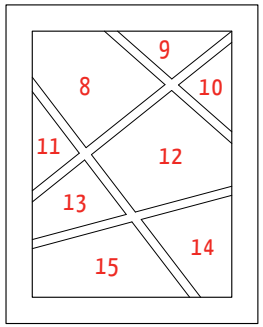
$H_{tot}$ = total force on the frame (N/mm)

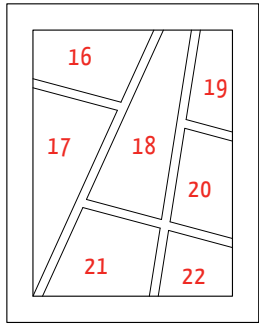
L = length of the frame (mm)

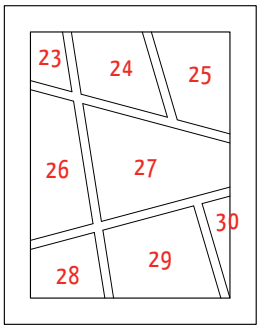
every cushion

- rectangular
- central axis taken into account



# conclusions | spacers

Moment of Inertia:

$I = (b*d^3) - (h*k^3)/12\ [mm^4]$




Max. deflection:

$\Delta_{max} = (5/384) \times \{(H_{tot} * L^4)/(E*I)\}\ [mm]$

where:

E = modulus of elasticity of the frame's material ($N/mm^2$)

I = moment of inertia (mm4)

$H_{tot}$ = total force on the frame (N/mm)

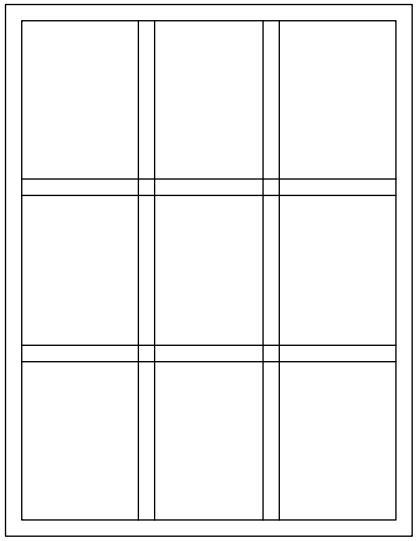
L = length of the frame (mm)

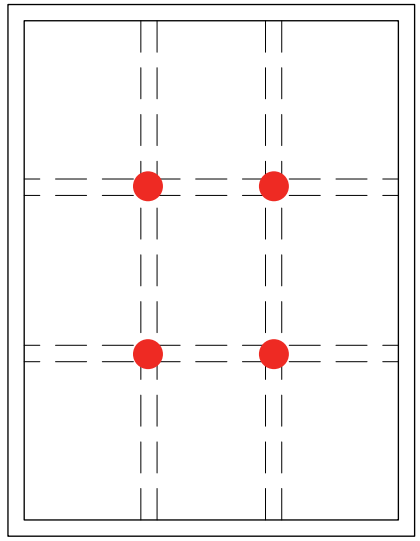
every cushion

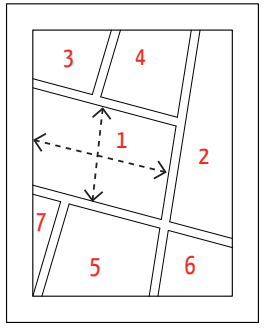
- rectangular
- central axis taken into account

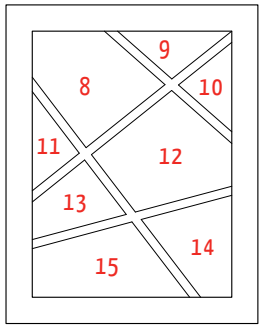
» at least 2 divisions per axis --> 1 spacer in between

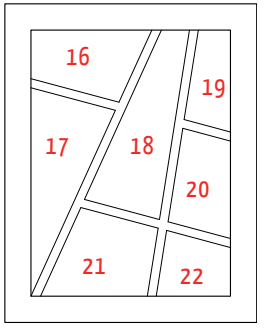
» spacers --> placed in the meeting points of the rectangular grid

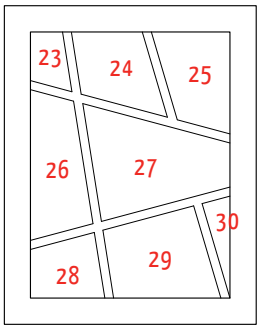




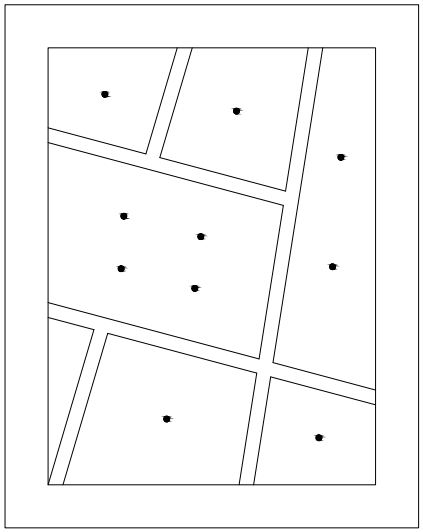


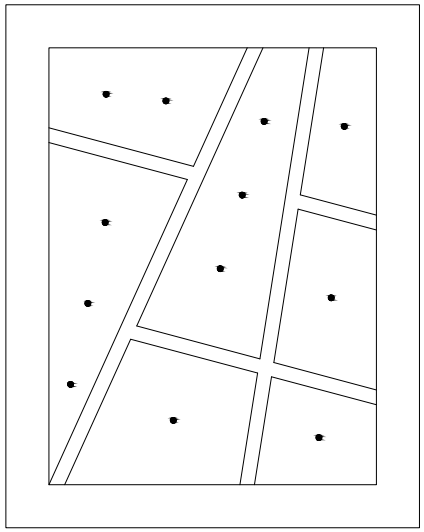



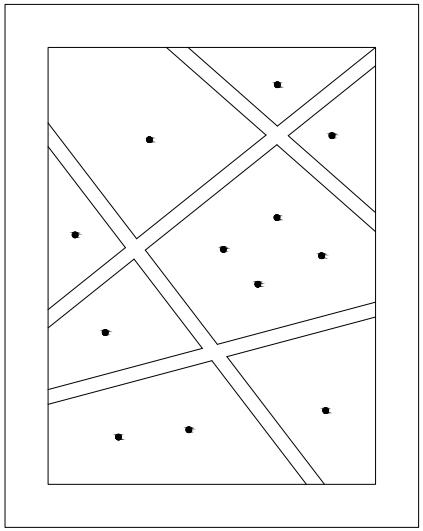



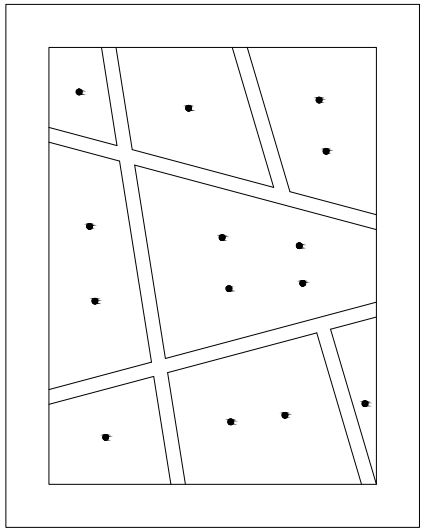



# conclusions | spacers

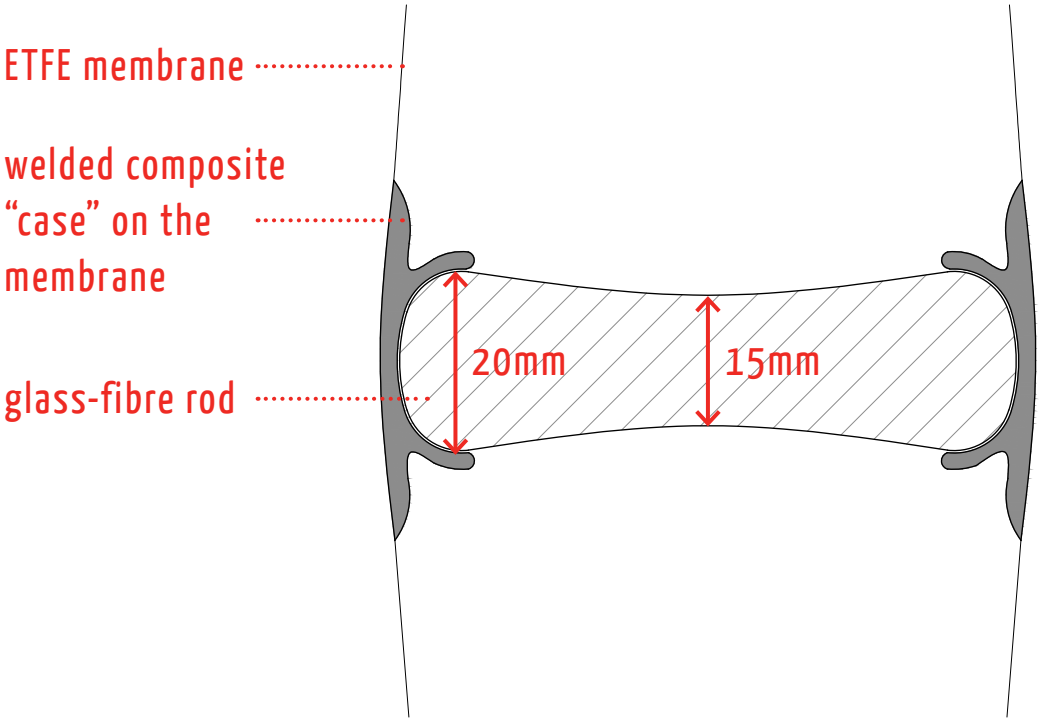






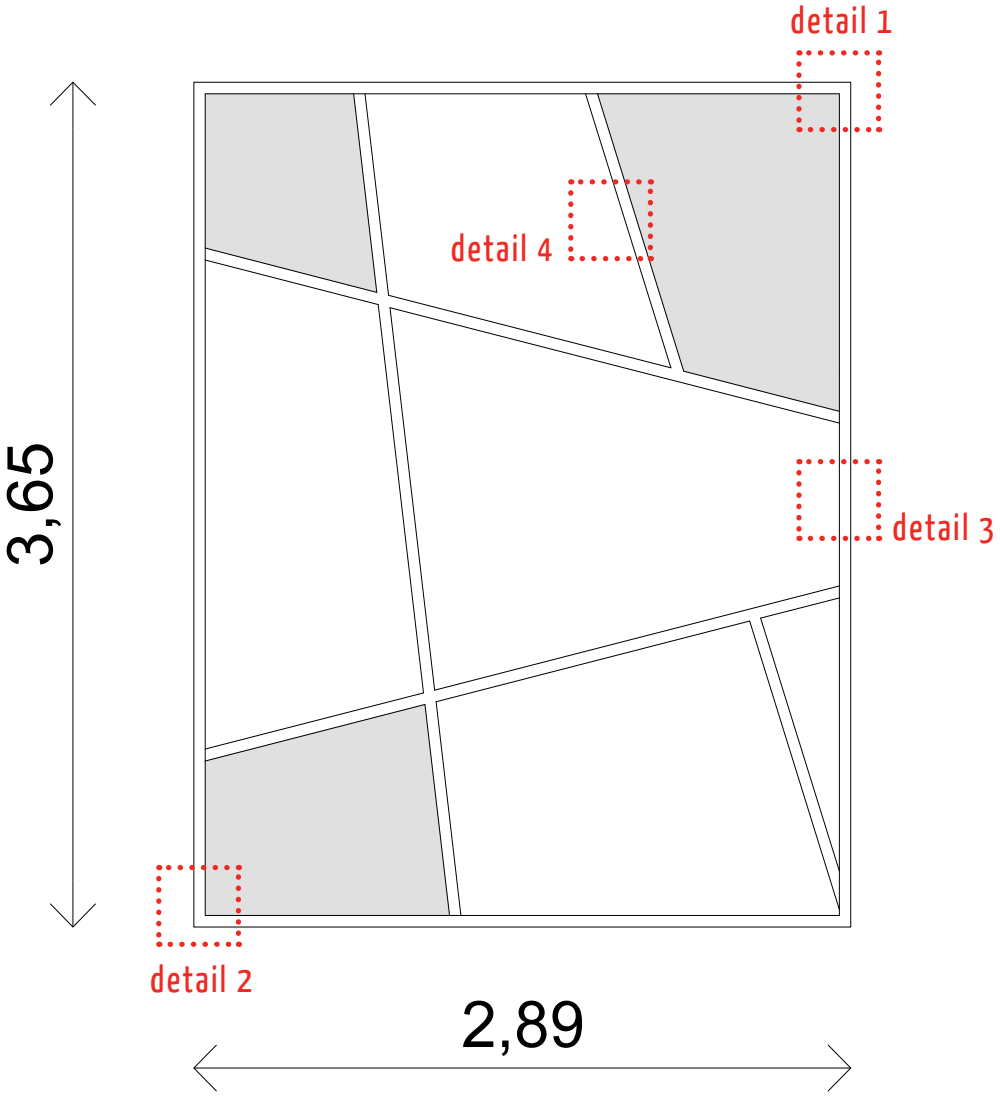


## glass-fibre rods:

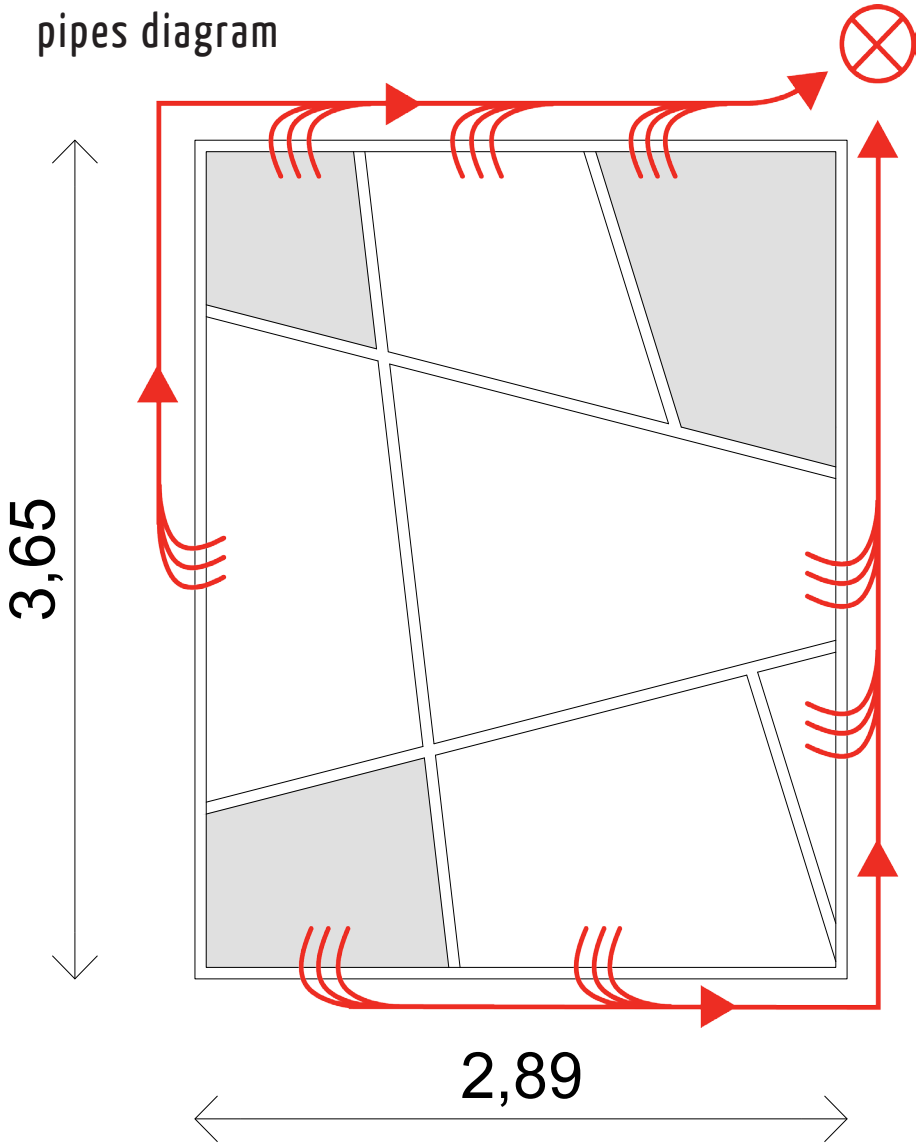


# pipes system concept

## individual element



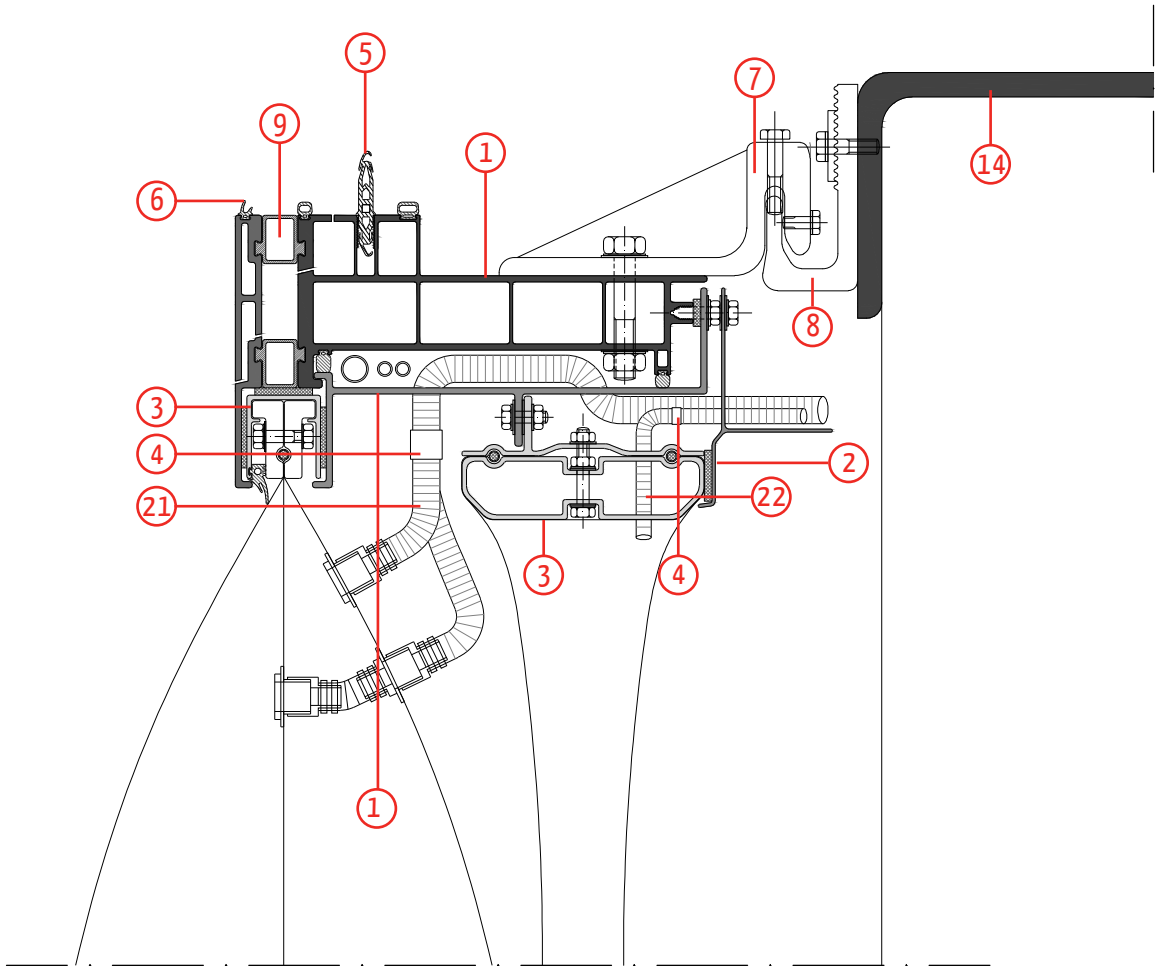

## pipes diagram



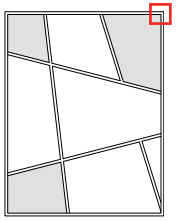
# details

1. aluminum extruded profile 4mm
2. aluminum extruded profile 2mm
3. GFRP extruded profile 3mm
4. valve
5. EPDM linking gasket
6. weather gasket
7. hook bracket
8. anchor
9. thermal break
10. anchor channels
11. steel decking floor sheet
12. aluminum stud
13. concrete floor 120mm for 90' fire delay
14. steel console (550x630mm)
15. fireproof boards 12.5mm
16. thick mineral fibre insulation 60mm
17. hard insulation
18. aluminum click cap 2mm
19. weather protection foil
20. suspended ceiling
21. inflation pipe ø20mm
22. deflation pipe ø10mm
23. main pipe ø50mm
24. L-shaped steel profile 4mm
25. railing
26. glass-fibre rod ø20mm (spacer)

## upper part connection



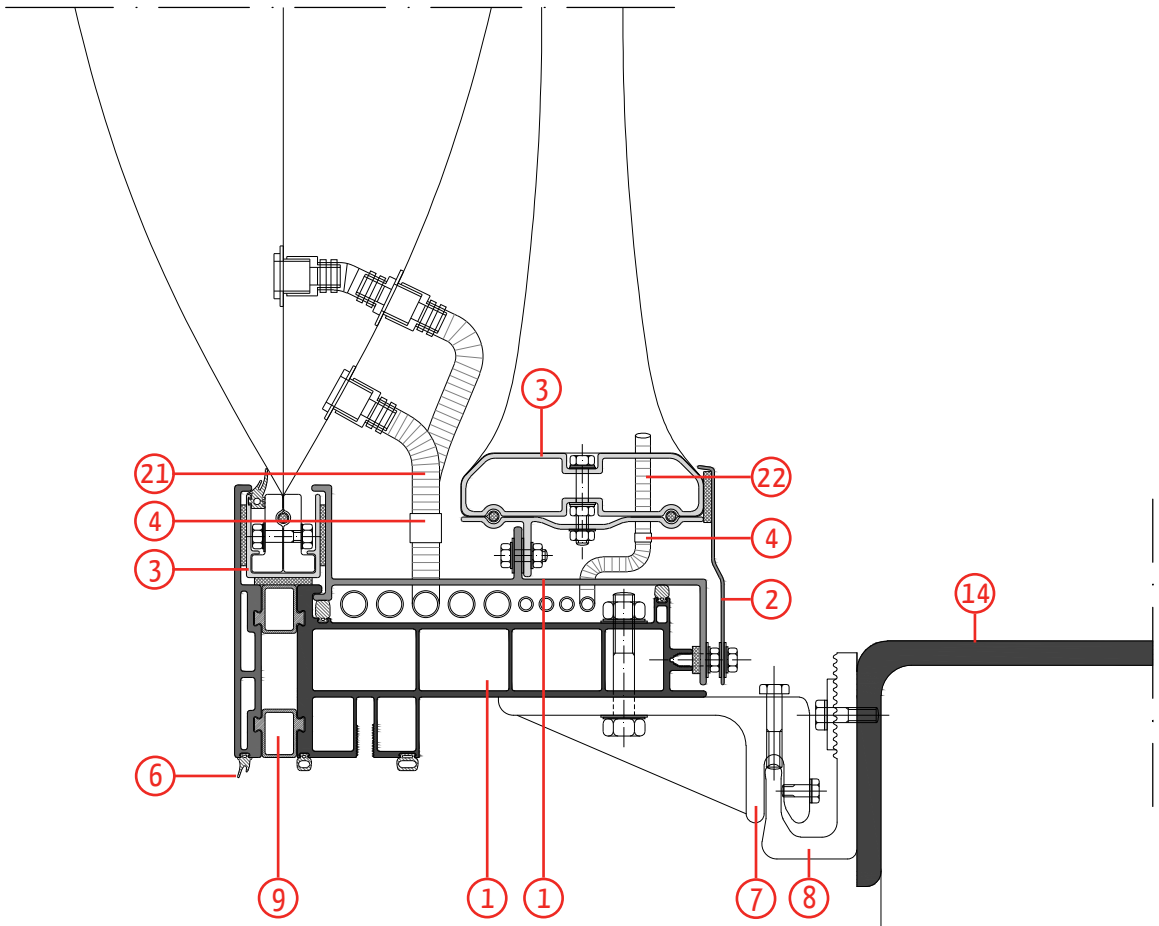

detail 1

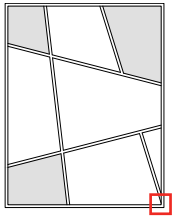


# details

## lower part connection

1. aluminum extruded profile 4mm
2. aluminum extruded profile 2mm
3. GFRP extruded profile 3mm
4. valve
5. EPDM linking gasket
6. weather gasket
7. hook bracket
8. anchor
9. thermal break
10. anchor channels
11. steel decking floor sheet
12. aluminum stud
13. concrete floor 120mm for 90' fire delay
14. steel console (550x630mm)
15. fireproof boards 12.5mm
16. thick mineral fibre insulation 60mm
17. hard insulation
18. aluminum click cap 2mm
19. weather protection foil
20. suspended ceiling
21. inflation pipe ø20mm
22. deflation pipe ø10mm
23. main pipe ø50mm
24. L-shaped steel profile 4mm
25. railing
26. glass-fibre rod ø20mm (spacer)



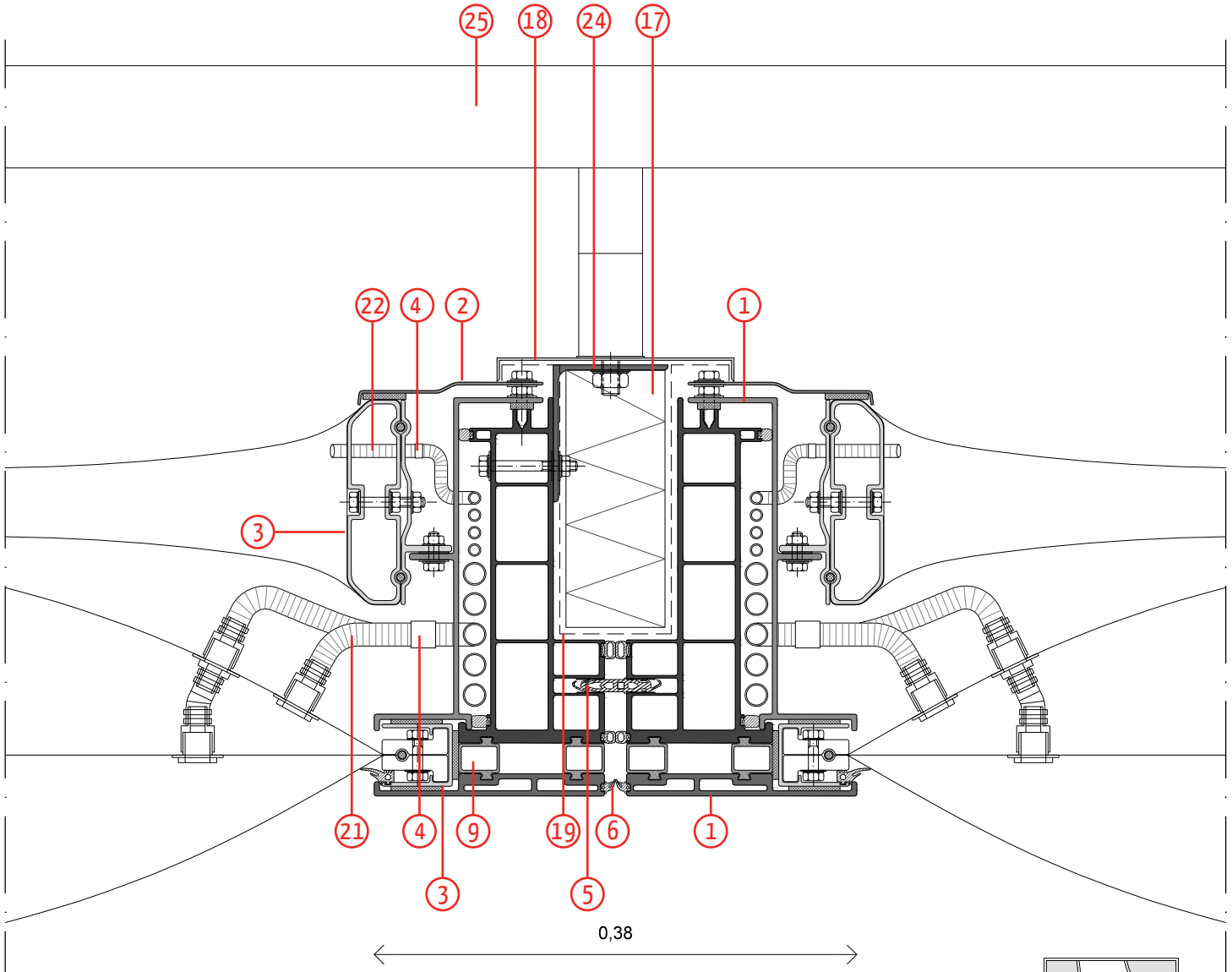



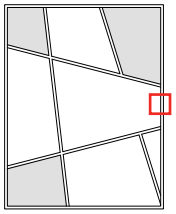
detail 2

# details

## side part connection

1. aluminum extruded profile 4mm
2. aluminum extruded profile 2mm
3. GFRP extruded profile 3mm
4. valve
5. EPDM linking gasket
6. weather gasket
7. hook bracket
8. anchor
9. thermal break
10. anchor channels
11. steel decking floor sheet
12. aluminum stud
13. concrete floor 120mm for 90' fire delay
14. steel console (550x630mm)
15. fireproof boards 12.5mm
16. thick mineral fibre insulation 60mm
17. hard insulation
18. aluminum click cap 2mm
19. weather protection foil
20. suspended ceiling
21. inflation pipe ø20mm
22. deflation pipe ø10mm
23. main pipe ø50mm
24. L-shaped steel profile 4mm
25. railing
26. glass-fibre rod ø20mm (spacer)



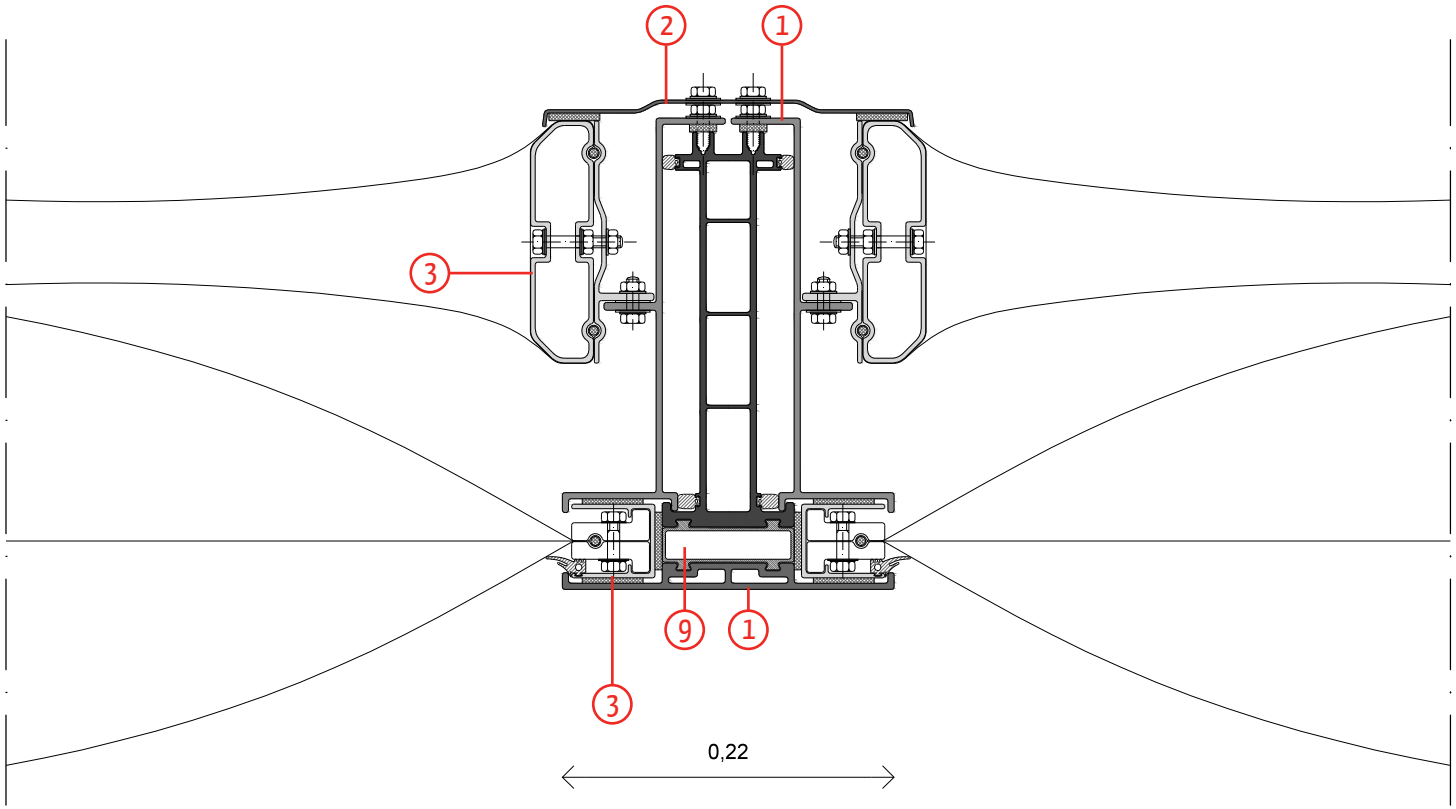



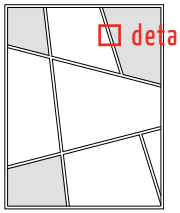
detail 3

# details

## cushions internal connection

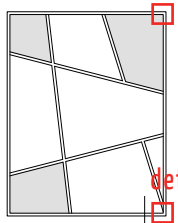
1. aluminum extruded profile 4mm
2. aluminum extruded profile 2mm
3. GFRP extruded profile 3mm
4. valve
5. EPDM linking gasket
6. weather gasket
7. hook bracket
8. anchor
9. thermal break
10. anchor channels
11. steel decking floor sheet
12. aluminum stud
13. concrete floor 120mm for 90' fire delay
14. steel console (550x630mm)
15. fireproof boards 12.5mm
16. thick mineral fibre insulation 60mm
17. hard insulation
18. aluminum click cap 2mm
19. weather protection foil
20. suspended ceiling
21. inflation pipe ø20mm
22. deflation pipe ø10mm
23. main pipe ø50mm
24. L-shaped steel profile 4mm
25. railing
26. glass-fibre rod ø20mm (spacer)



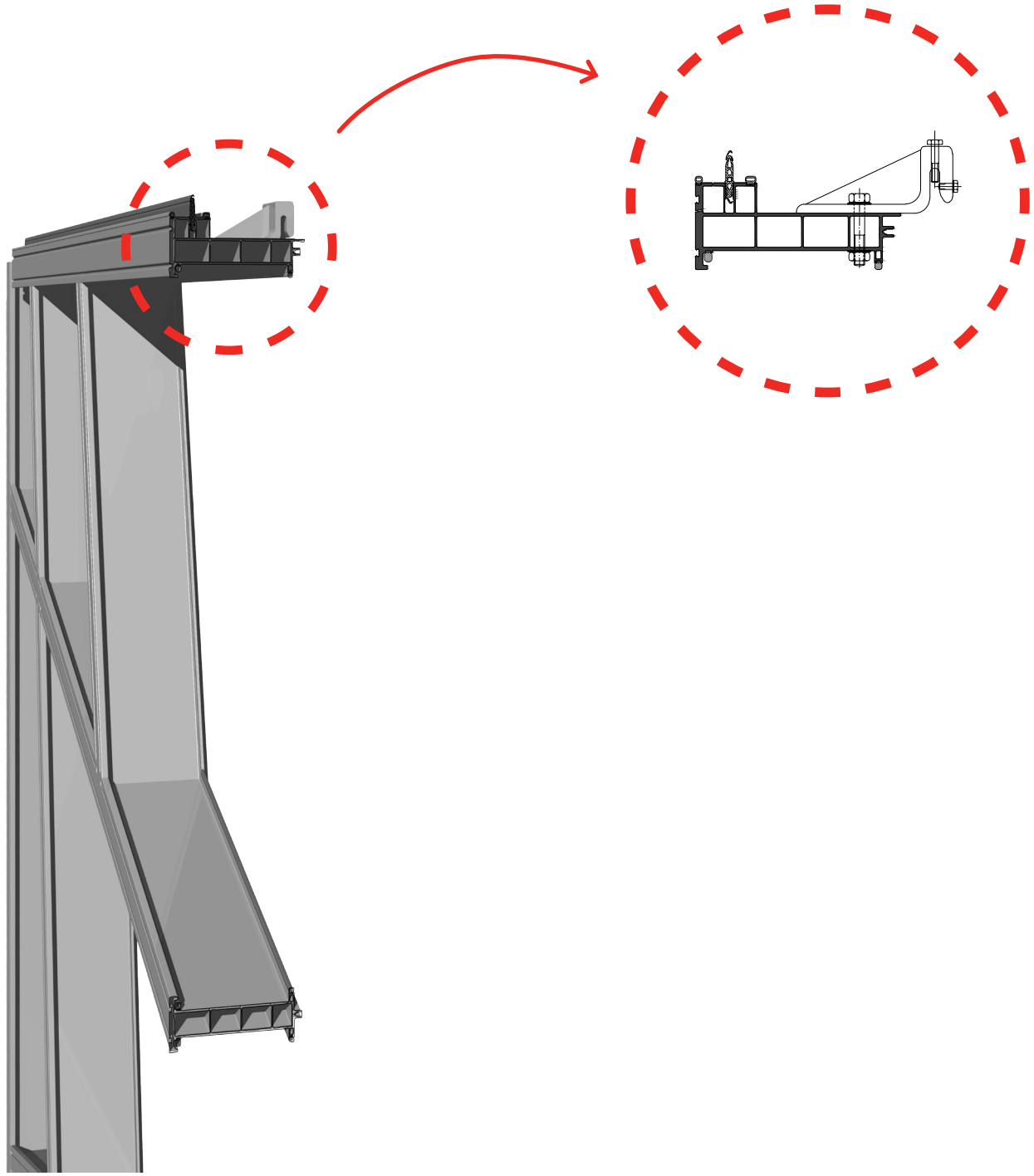
# detail

## connection to the building



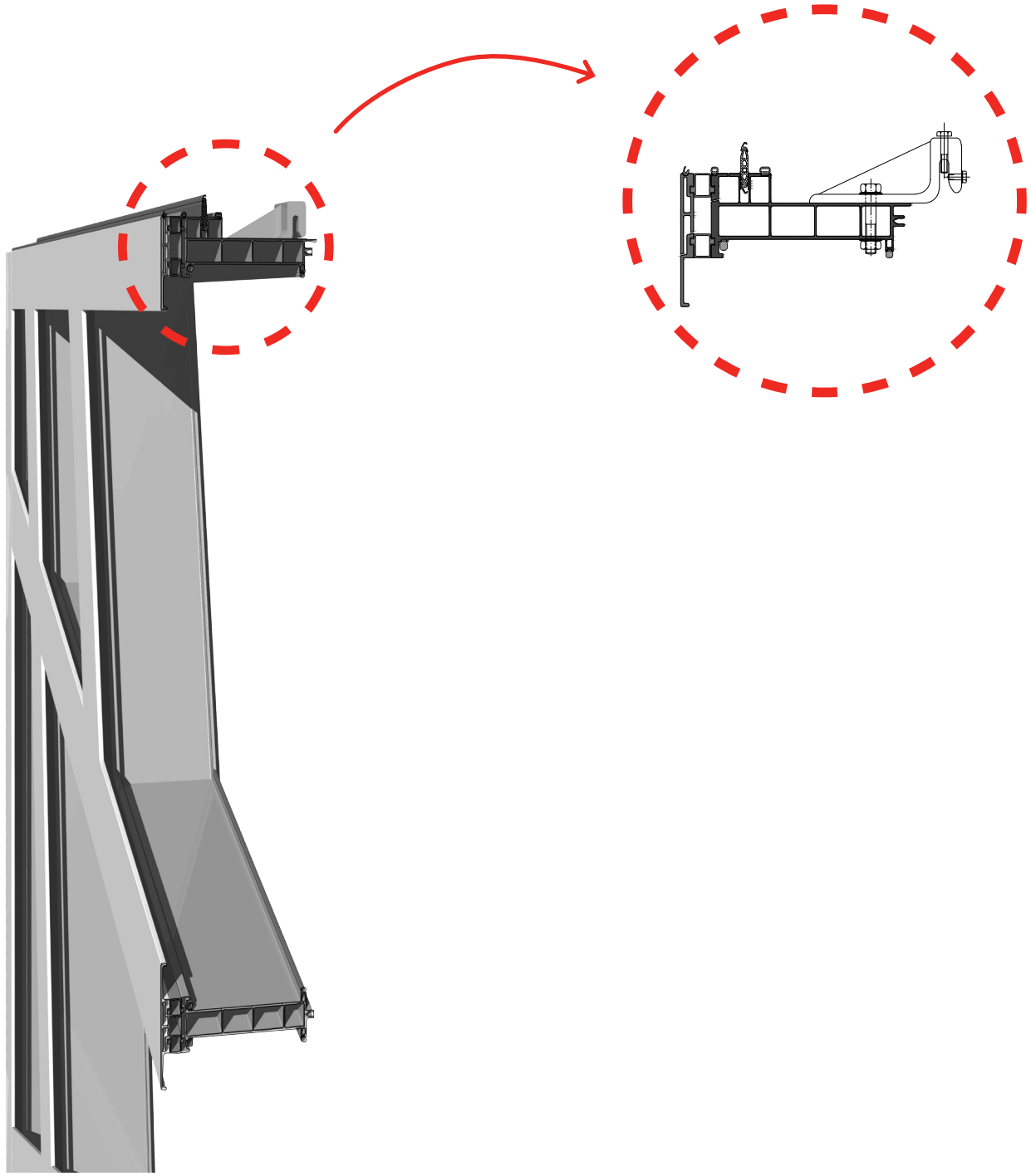
# assembly process

**1** main structural element



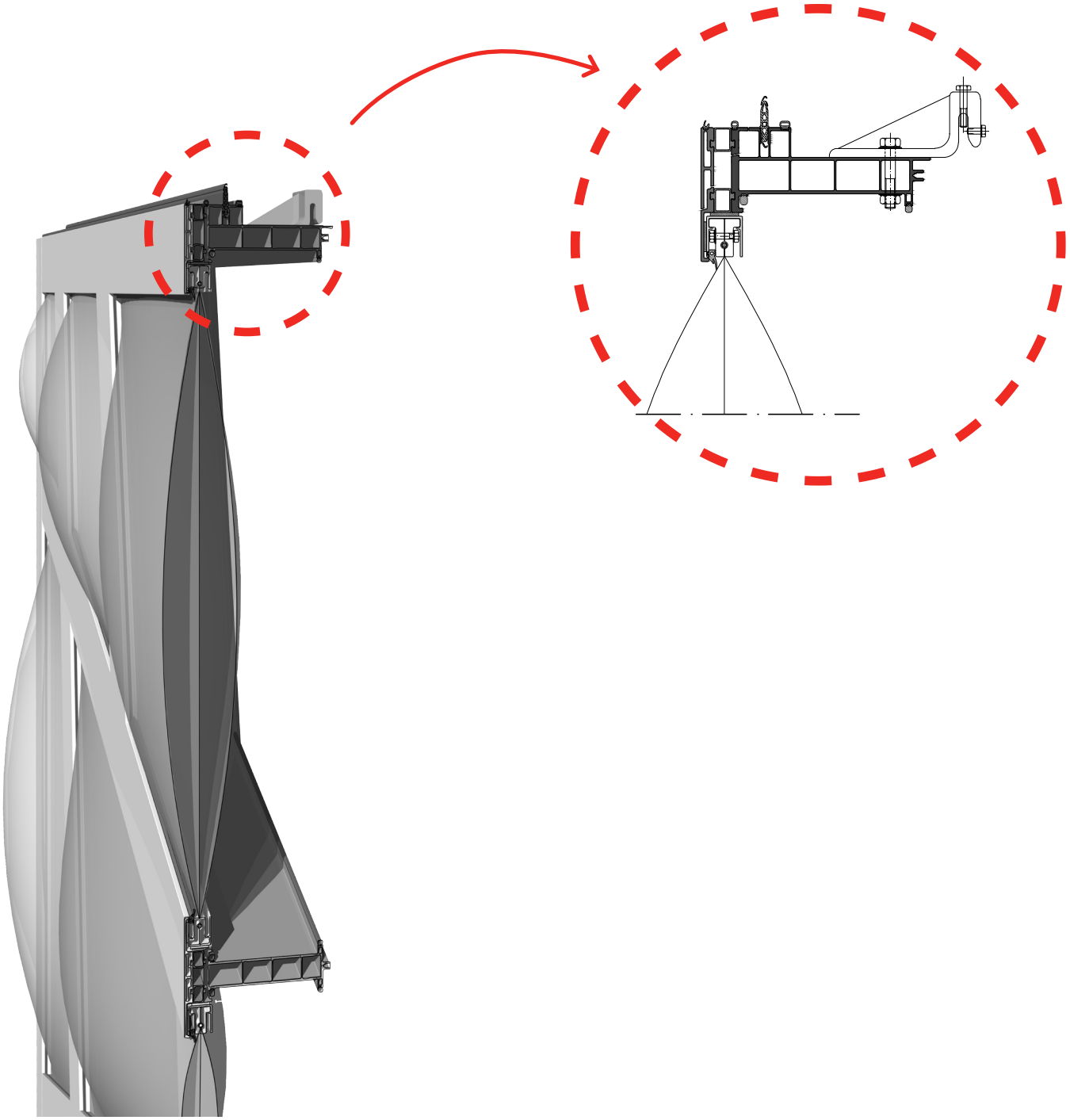
# assembly process

**2** external structural element
(thermal break)



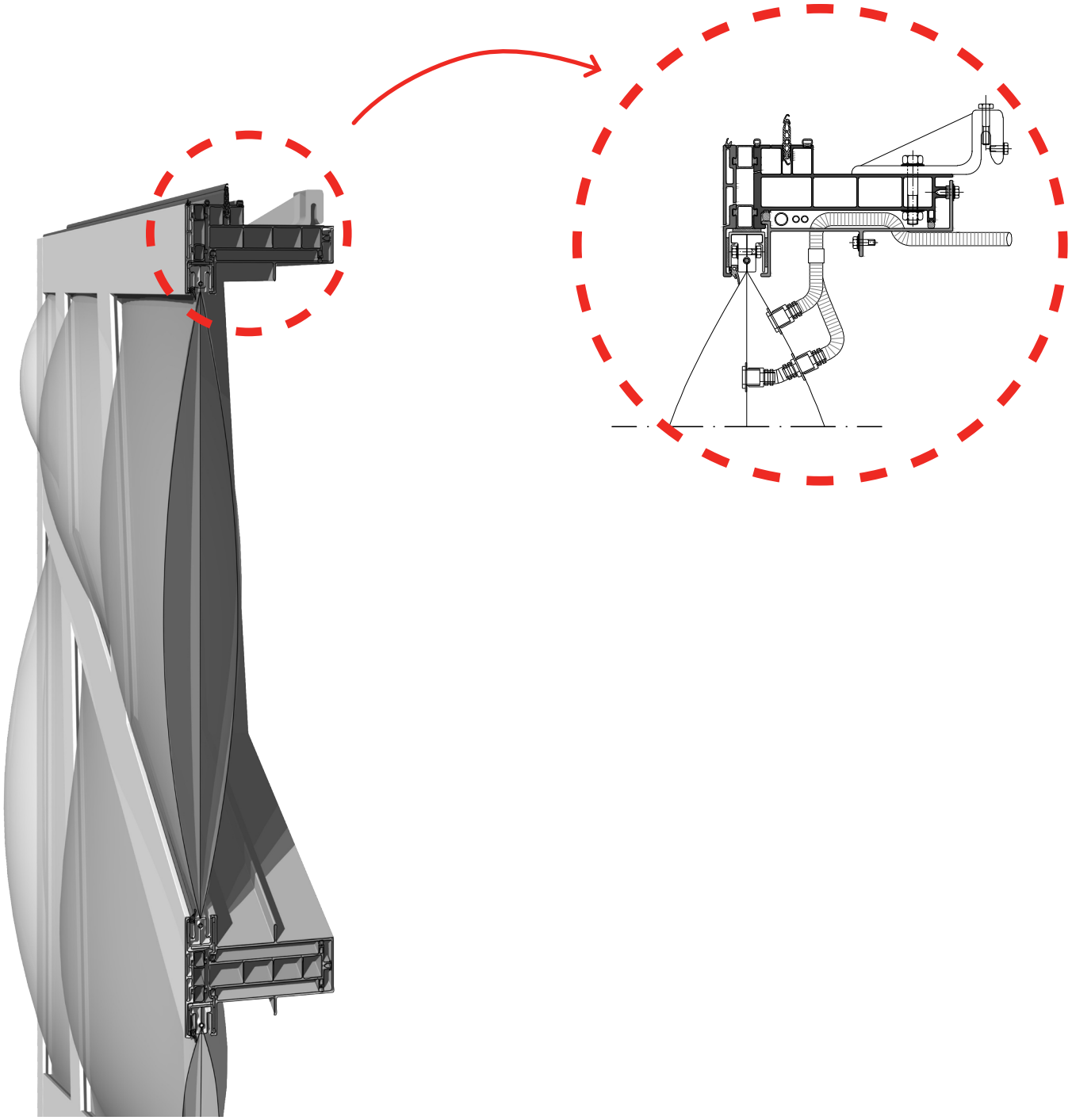
# assembly process

**3** inflated cushion



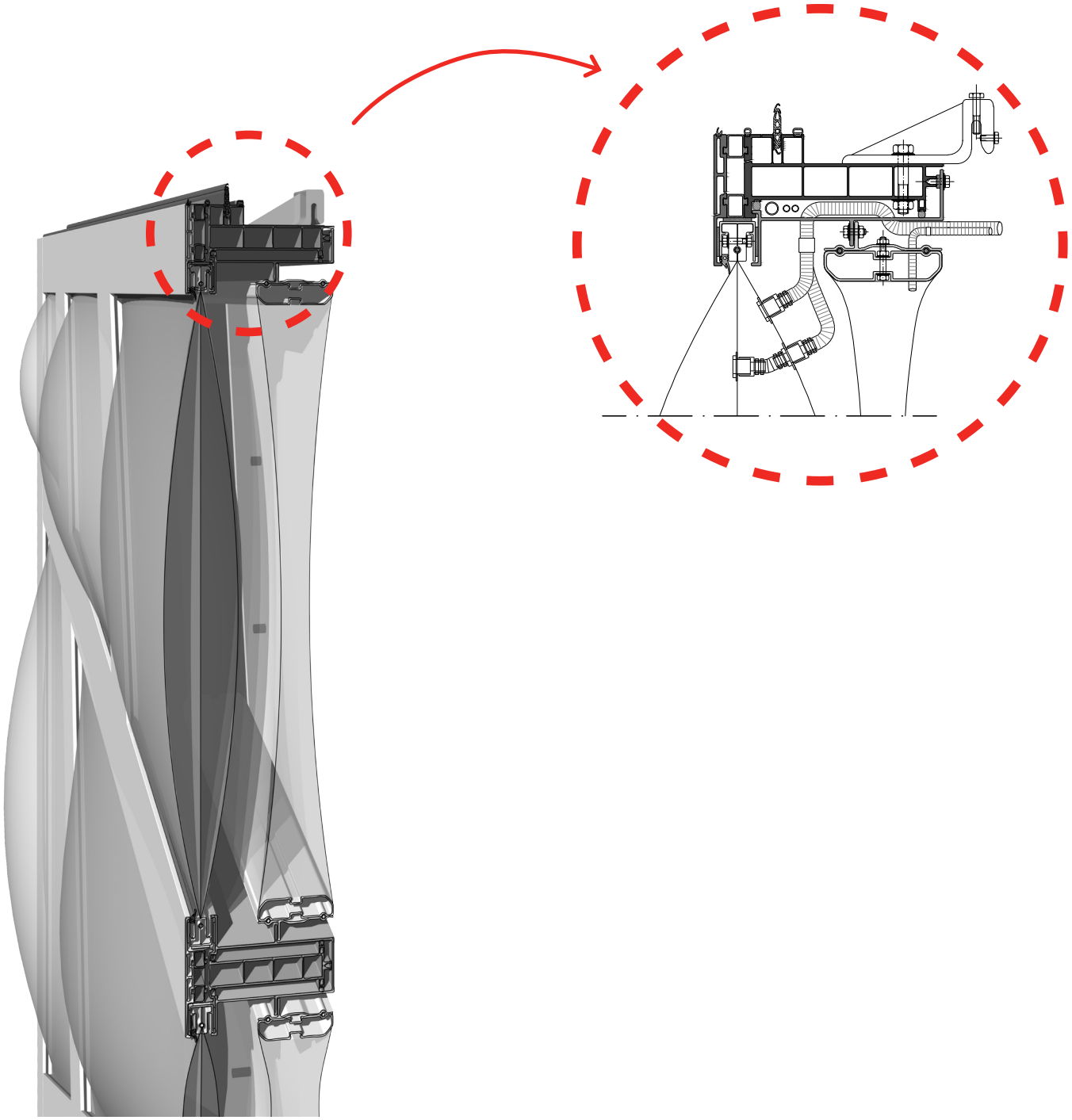
# assembly process

**4** second structural element



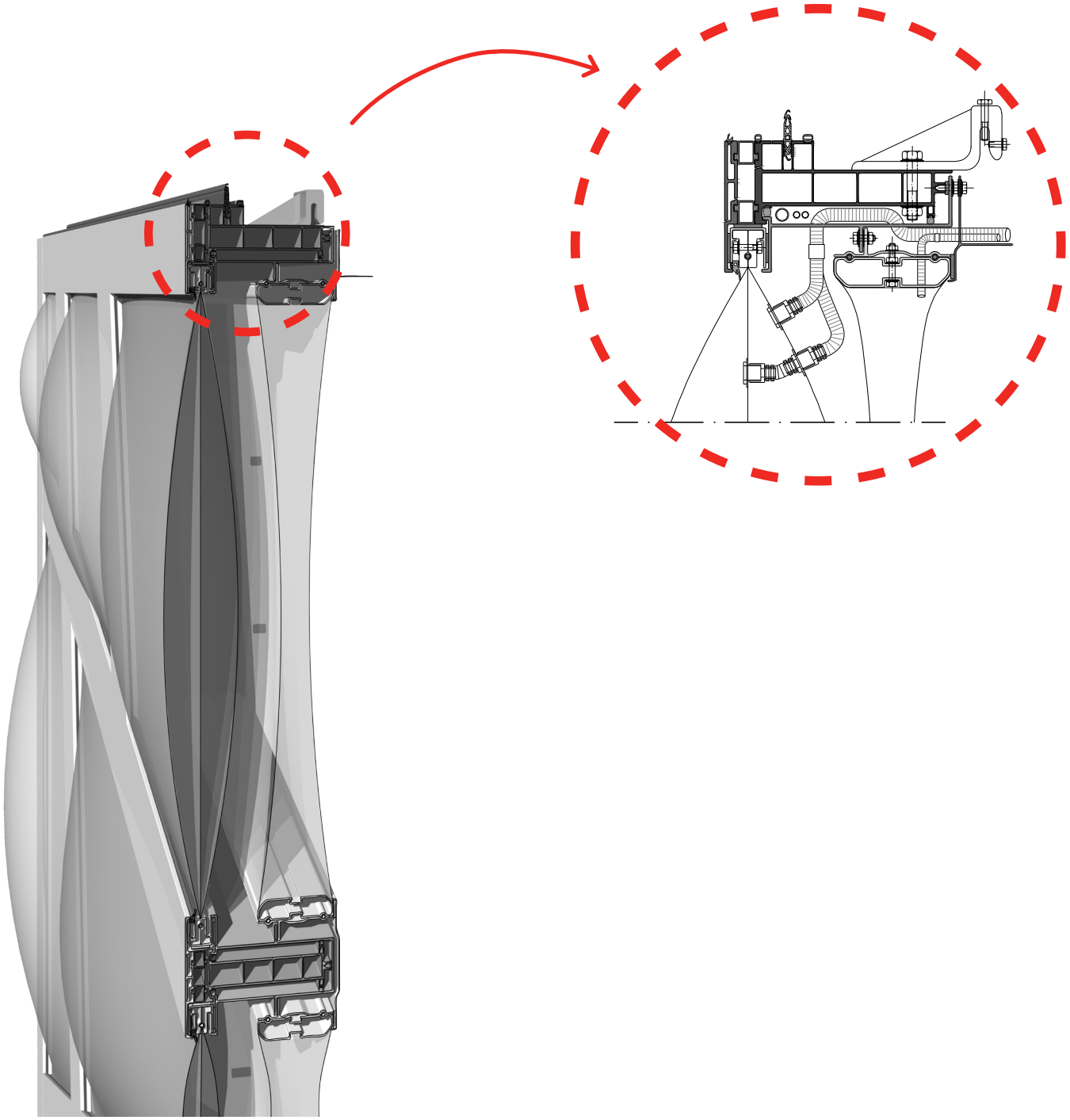
# assembly process

## 5 vacuum element



# assembly process

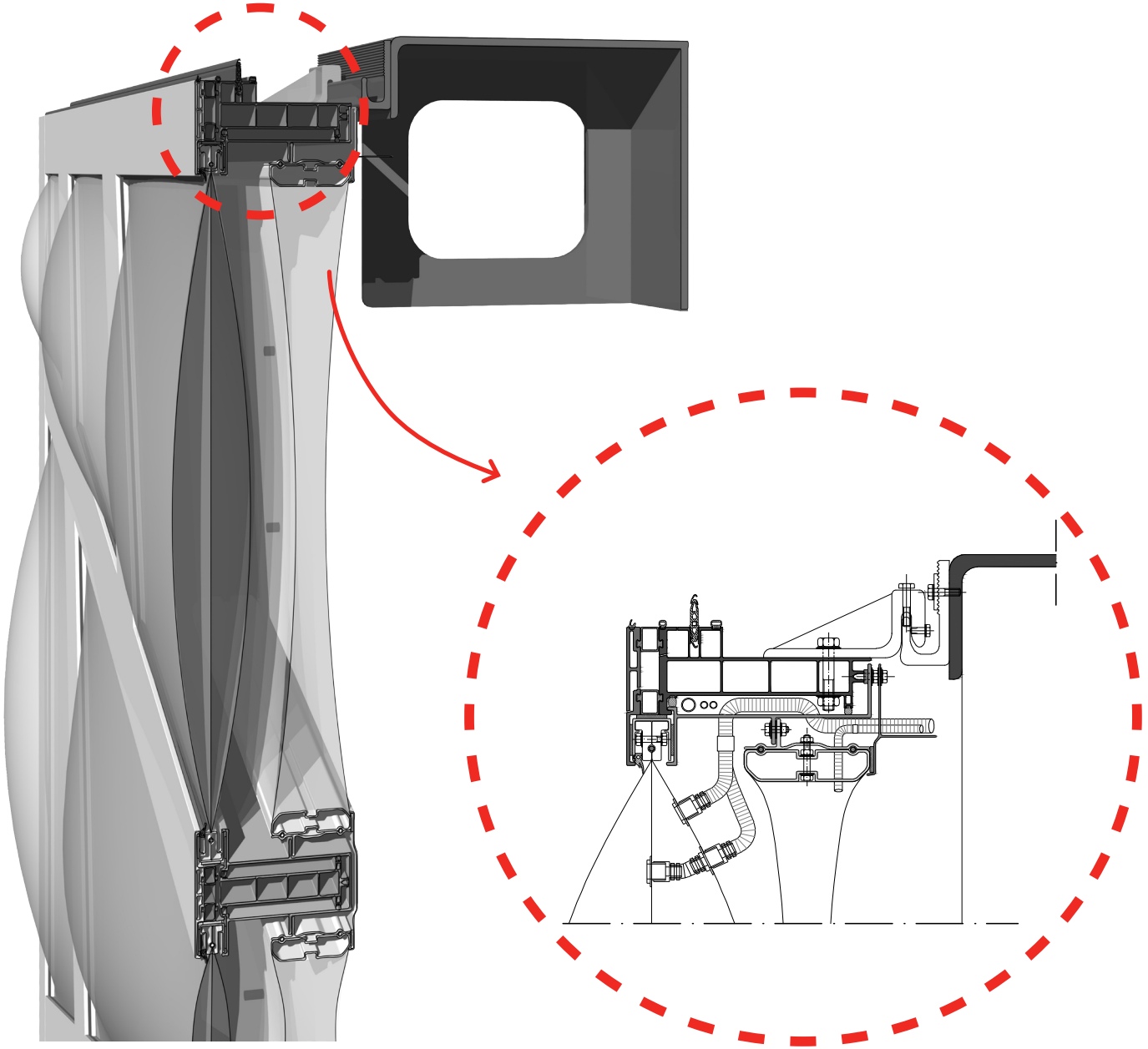
## 6 cover



# assembly process

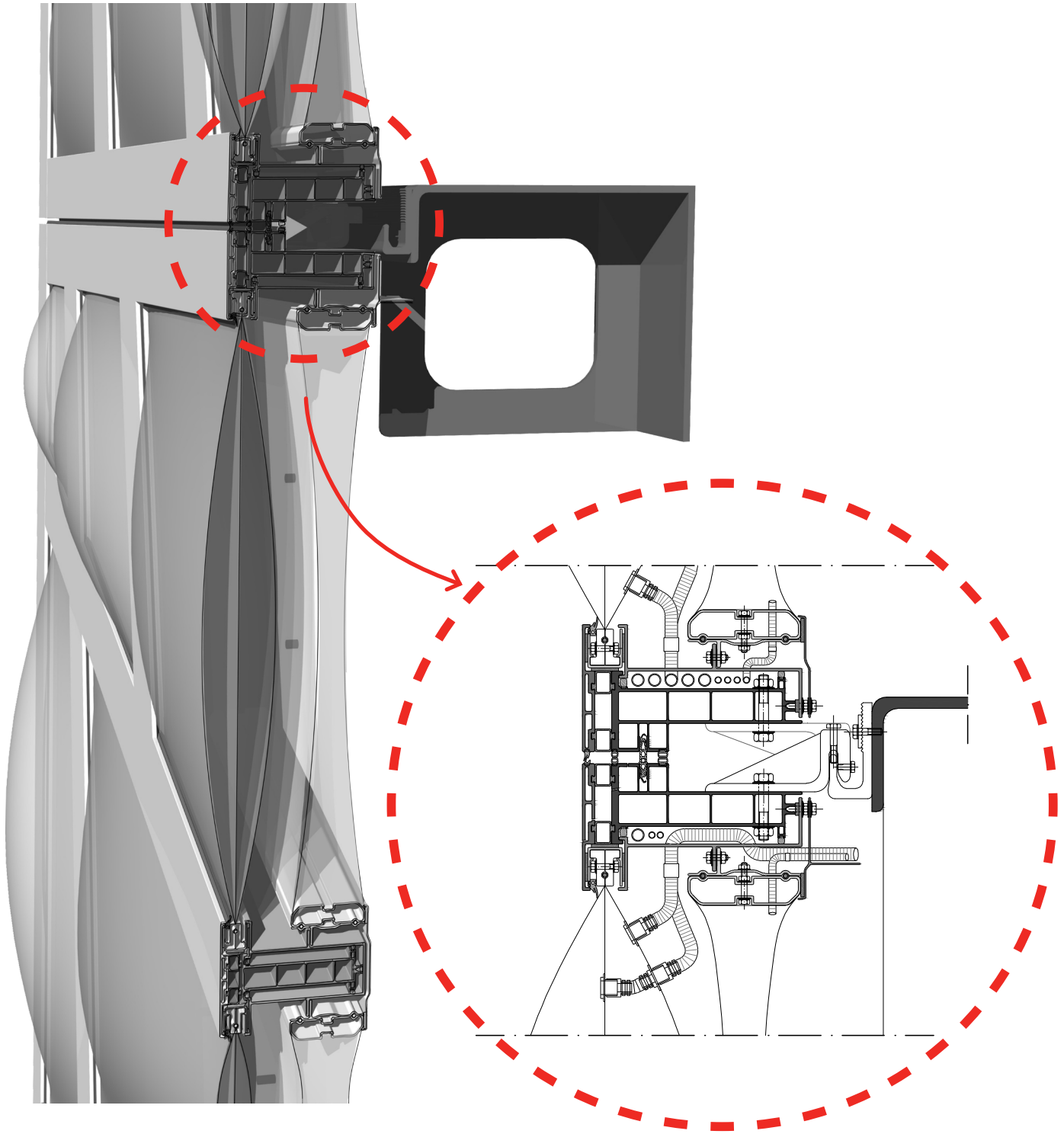
## 7

suspension of the panel (anchor/ hook)

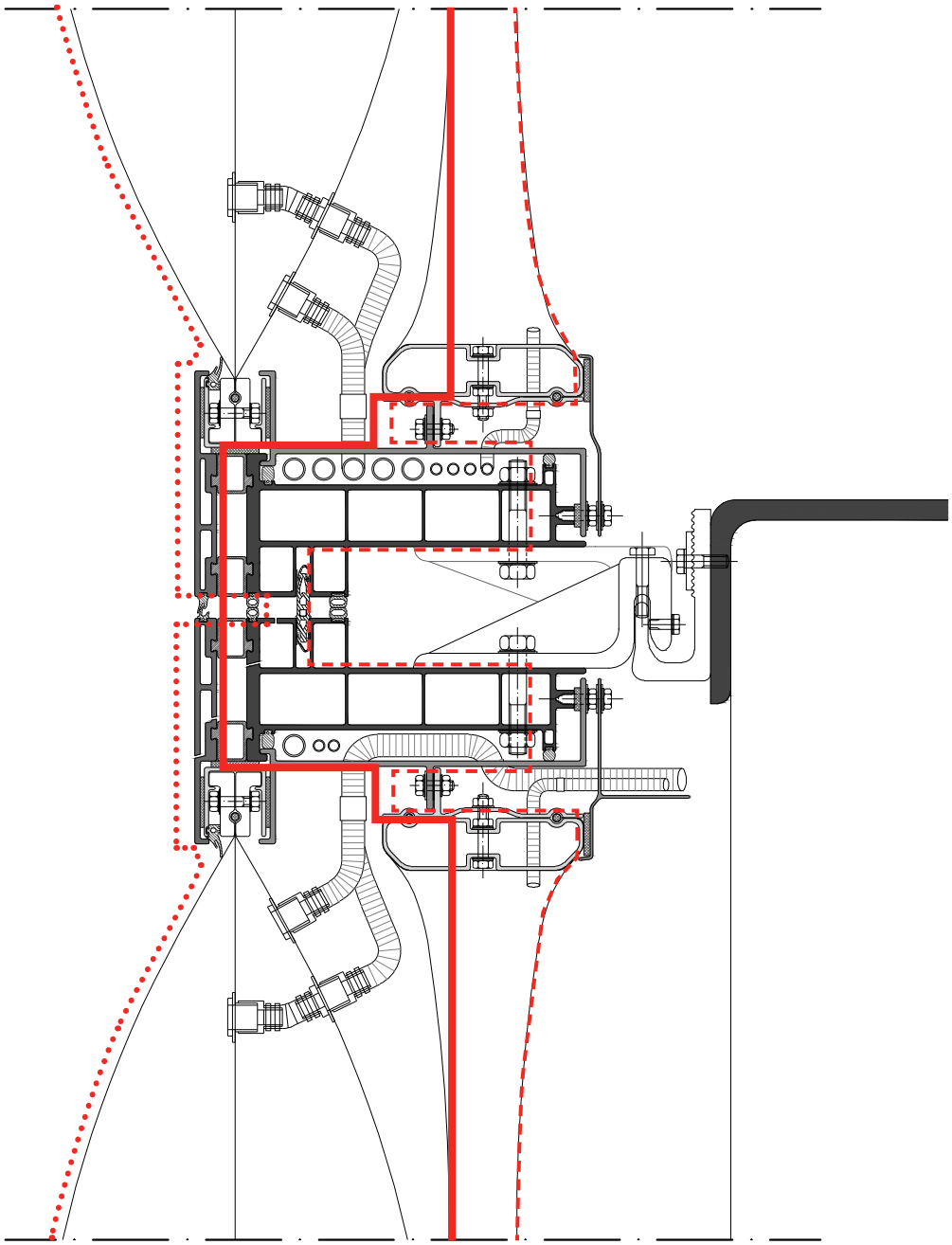


# assembly process

## 8 next panel on top



# lines of defense



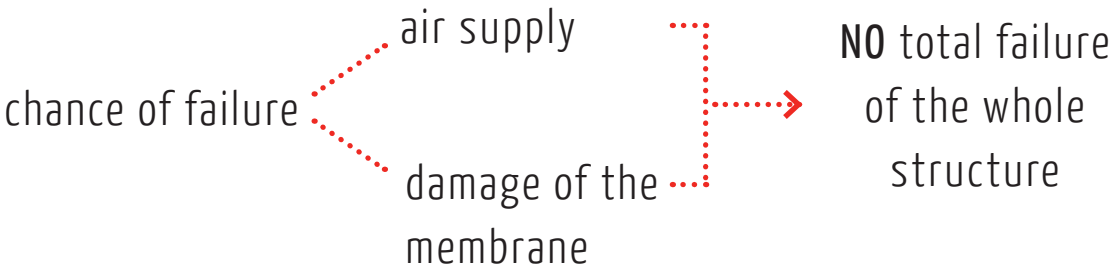
watertight line

thermal line

airtigtness line

# safety | maintenance

## 1. safety of cushion structures



# safety | maintenance

## 1. safety of cushion structures

chance of failure
- air supply
- damage of the membrane

→ NO total failure of the whole structure

## 2. fire safety

- self-distinguishing
- low flammability [class B1 / DIN 4102]

# safety | maintenance

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## 3. material's delicacy & safety barrier

- safety / explosion risk
- vandalism

# safety | maintenance

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## 2. fire safety

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- low flammability [class B1 / DIN 4102]

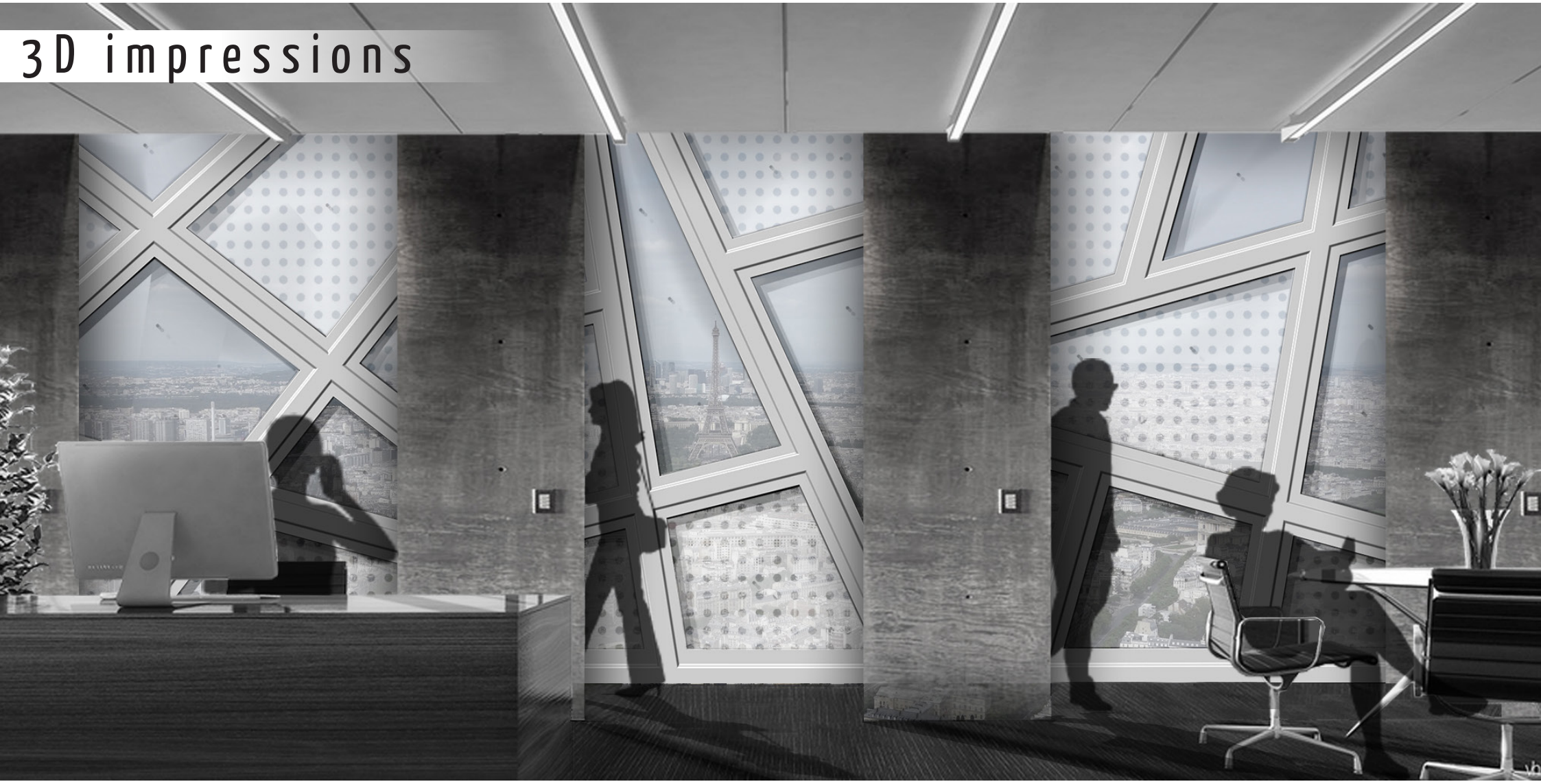
## 3. material's delicacy & safety barrier

- safety / explosion risk
- vandalism

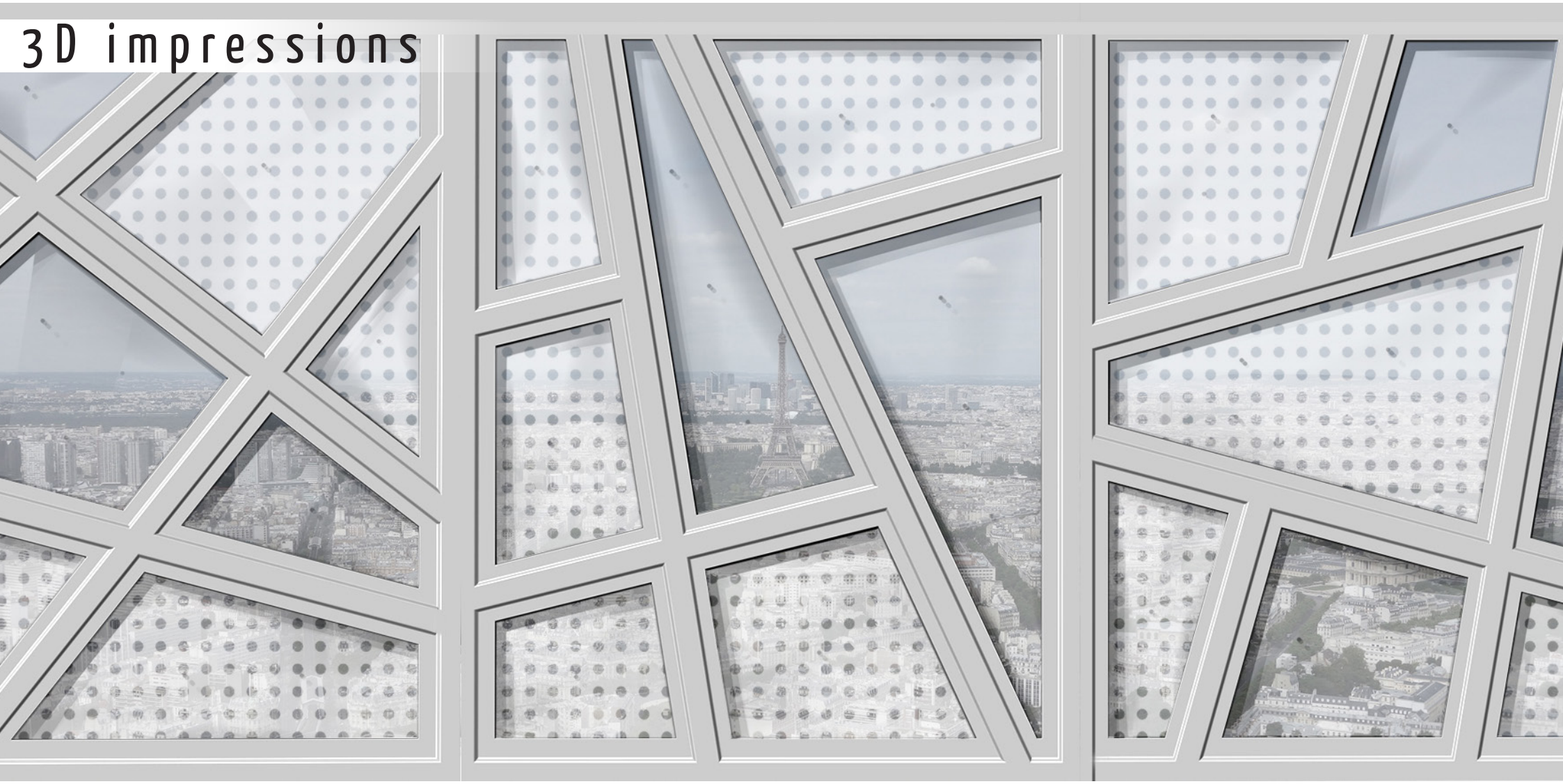
## 4. maintenance & replacement

- self-cleaning properties
- replacement from the inside

# 3D impressions



# 3D impressions



# 5

# conclusions

# research question

*How can an **adaptive**, **lightweight** and **flexible fabric** façade be designed, a façade that will be responsible for meeting the requirements and improving the **indoor comfort** in terms of **thermal** and **acoustical** insulation, as well as **sun shading** in a **high-rise** in Paris?*

# sub - questions

**1.** Which are the main **problems of high-rises** that should be tackled?

- wind
- construction / assembly process of the façade
- maintenance and replacement strategy

**2.** Which are the **most suitable fabrics/textiles** as a solution to the above problems? Do they meet the **building envelope requirements**?

**ETFE is suitable because:**

» transparent

» UV-resistant

» high tensile strength

» self-cleaning properties

» possible printing

» fire-resistant / self-distinguishing (fire class B1 [DIN 4102])

**3.** Which is the most **effective façade design** that meets all the requirements?

- thermal insulation
- acoustical insulation
- façade requirements (air / watertightness)
- efficient replacement strategy

**4.** How can the desired **adaptivity** be achieved? With what kind of **mechanisms**?

**adaptive integrated sun shading:**

» adjustable to users' needs (automatically / manually)


thank you