THIN GLASS SANDWICH

a thermal study of regular and semiregular tessellations used in bi-directional sandwiches

MARC A.J. DEN HEIJER

RESISTANCE

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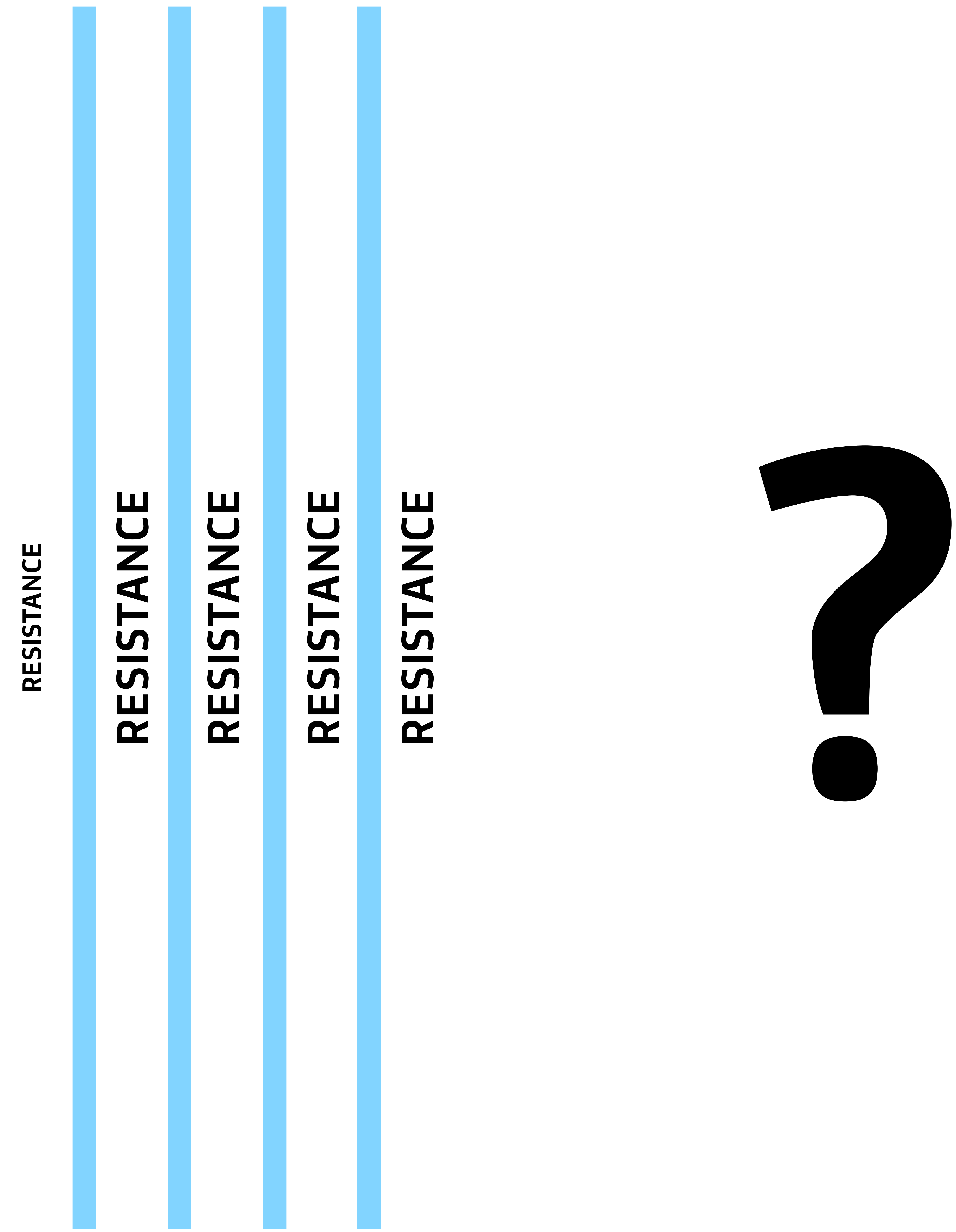
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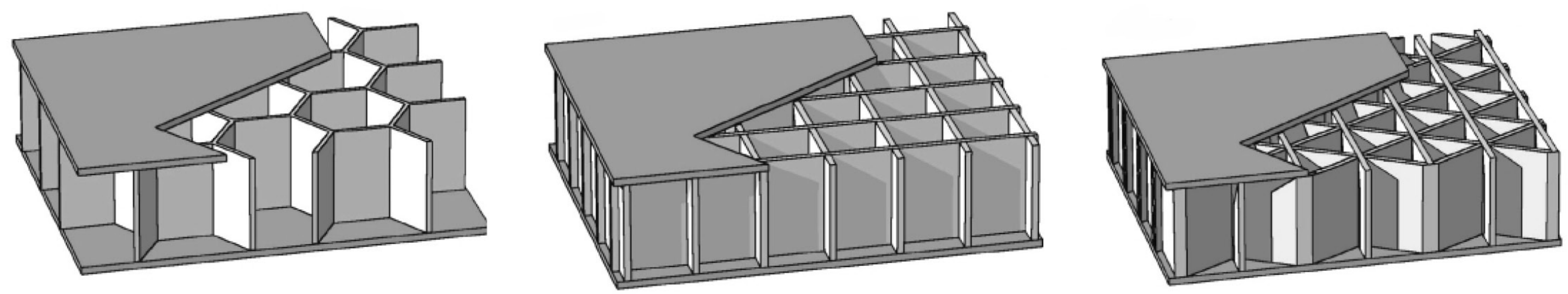


SANDWICH ELEMENTS

Pingle et al. (2011)

TO WHAT EXTENT CAN A THIN GLASS SANDWICH COUNTERBALANCE ITS DECREASED THERMAL PERFORMANCE BY REDUCING EMBODIED ENERGY DURING PRODUCTION?

Literature review

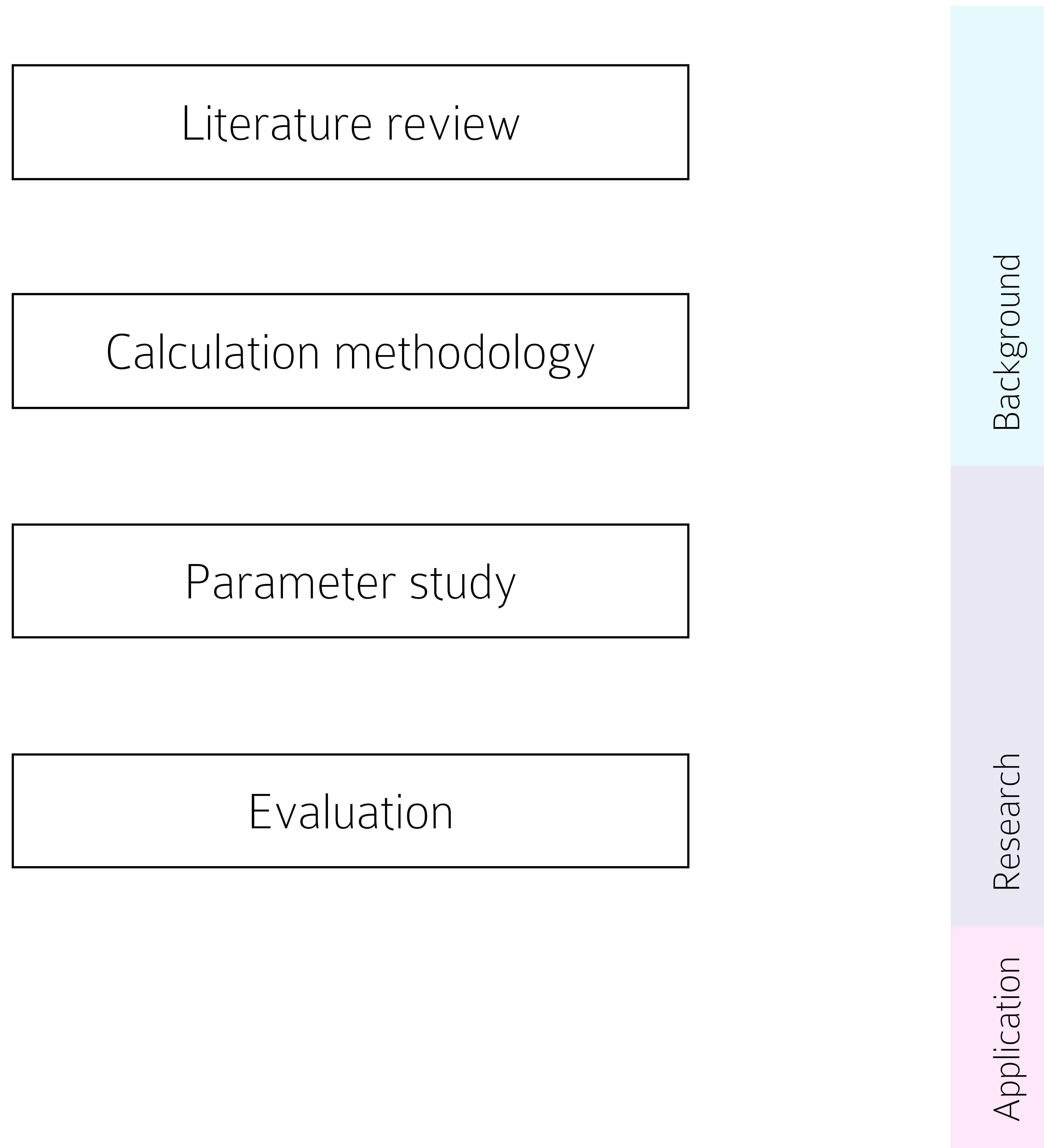
Literature review

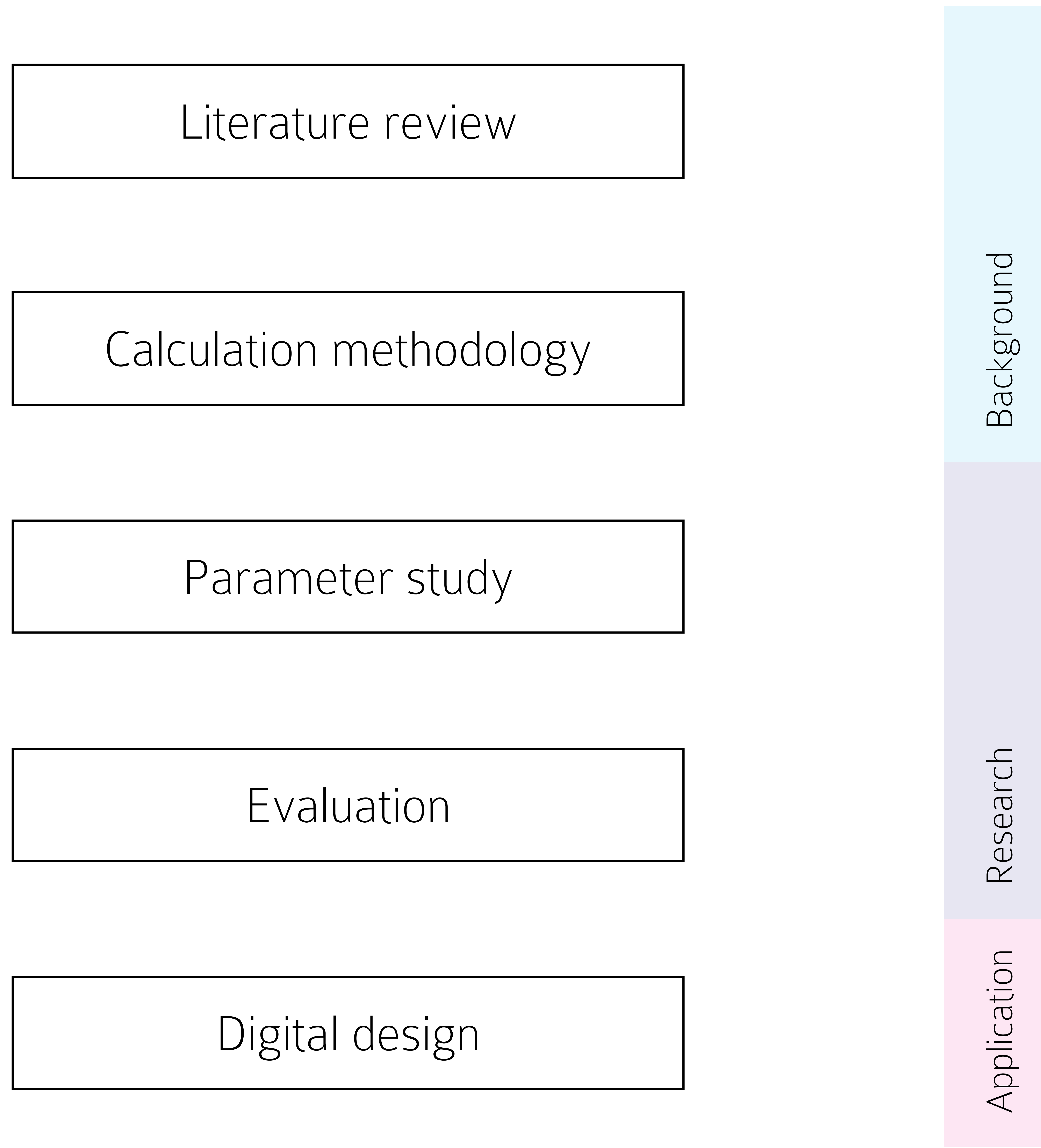
Calculation methodology

Literature review

Calculation methodology

Parameter study


Literature review
Calculation methodology
Parameter study
Evaluation
Background
Research
Application


Literature review
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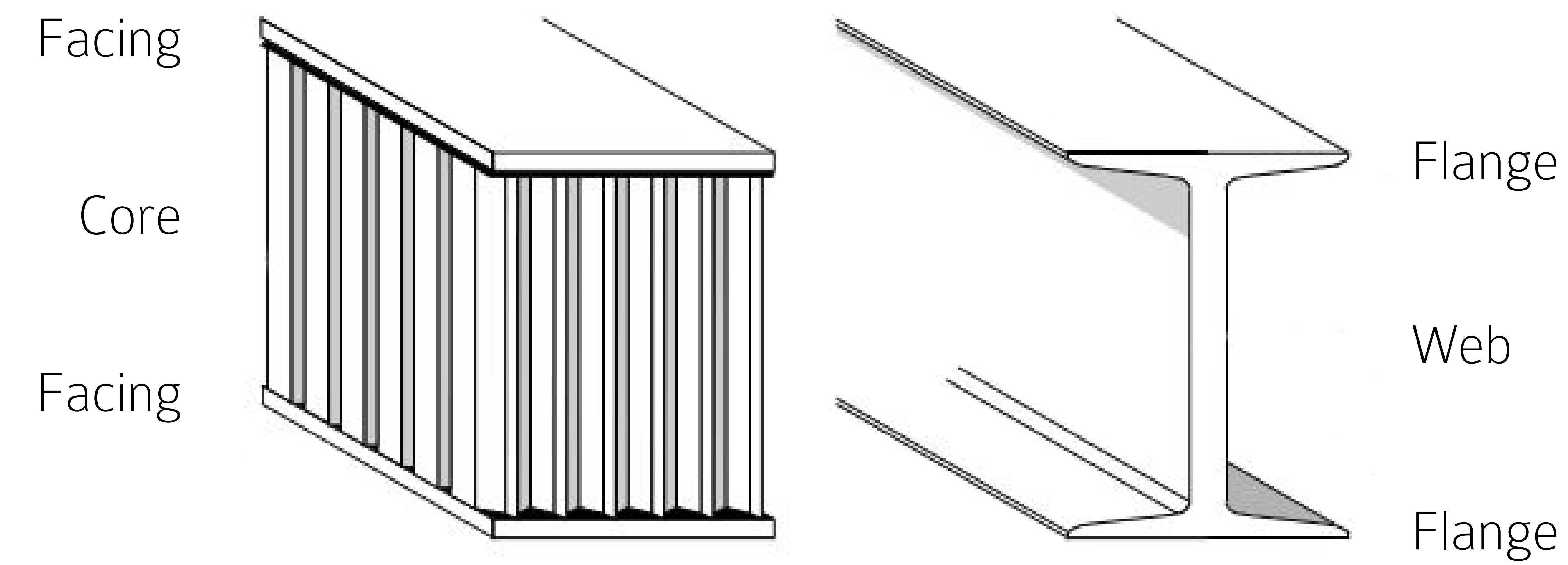
Application

LITERATURE REVIEW

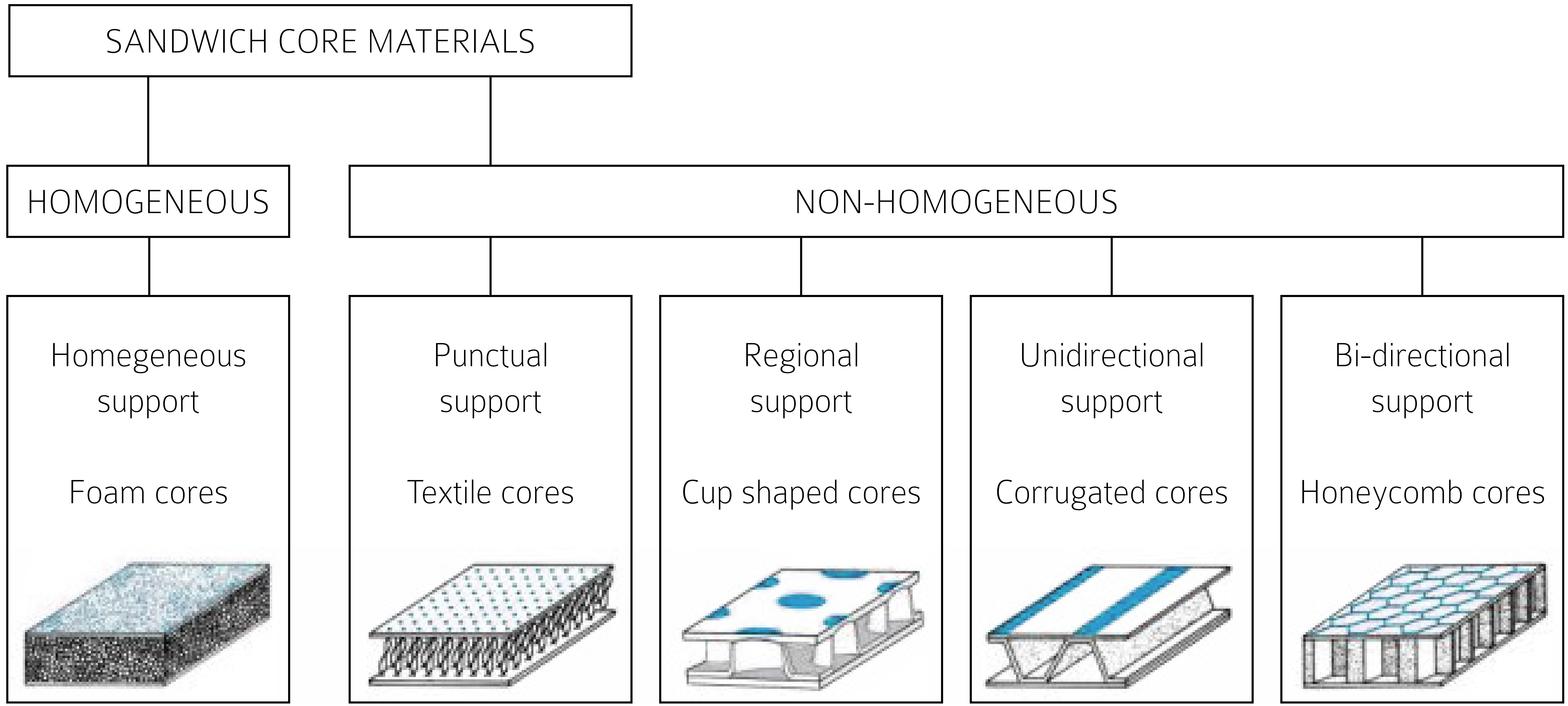

SODA-LIME GLASS

ALUMINOSILICATE GLASS



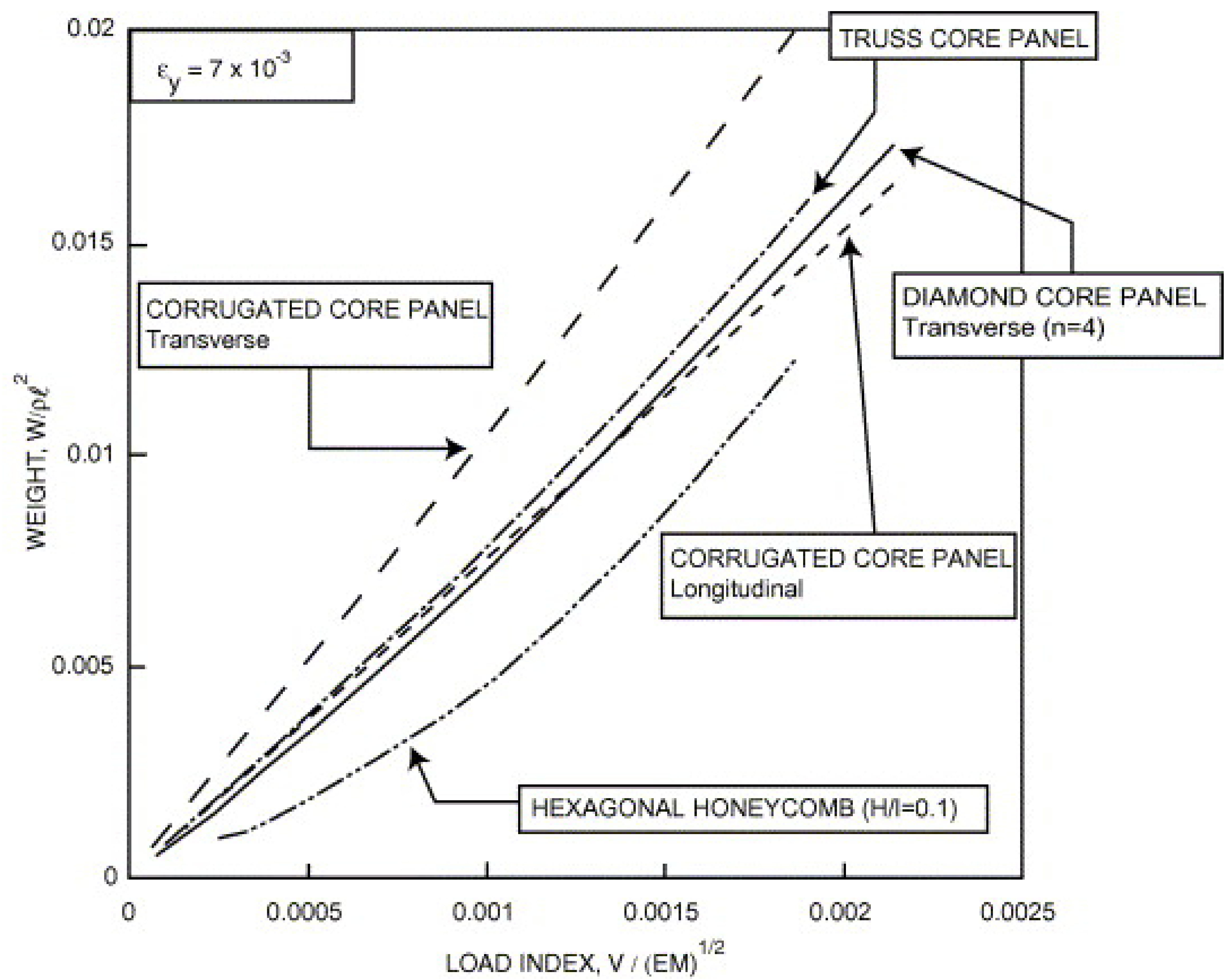
SANDWICH AND I-BEAM

comparison by Hexcel (2000)



SANDWICH TYPOLOGIES

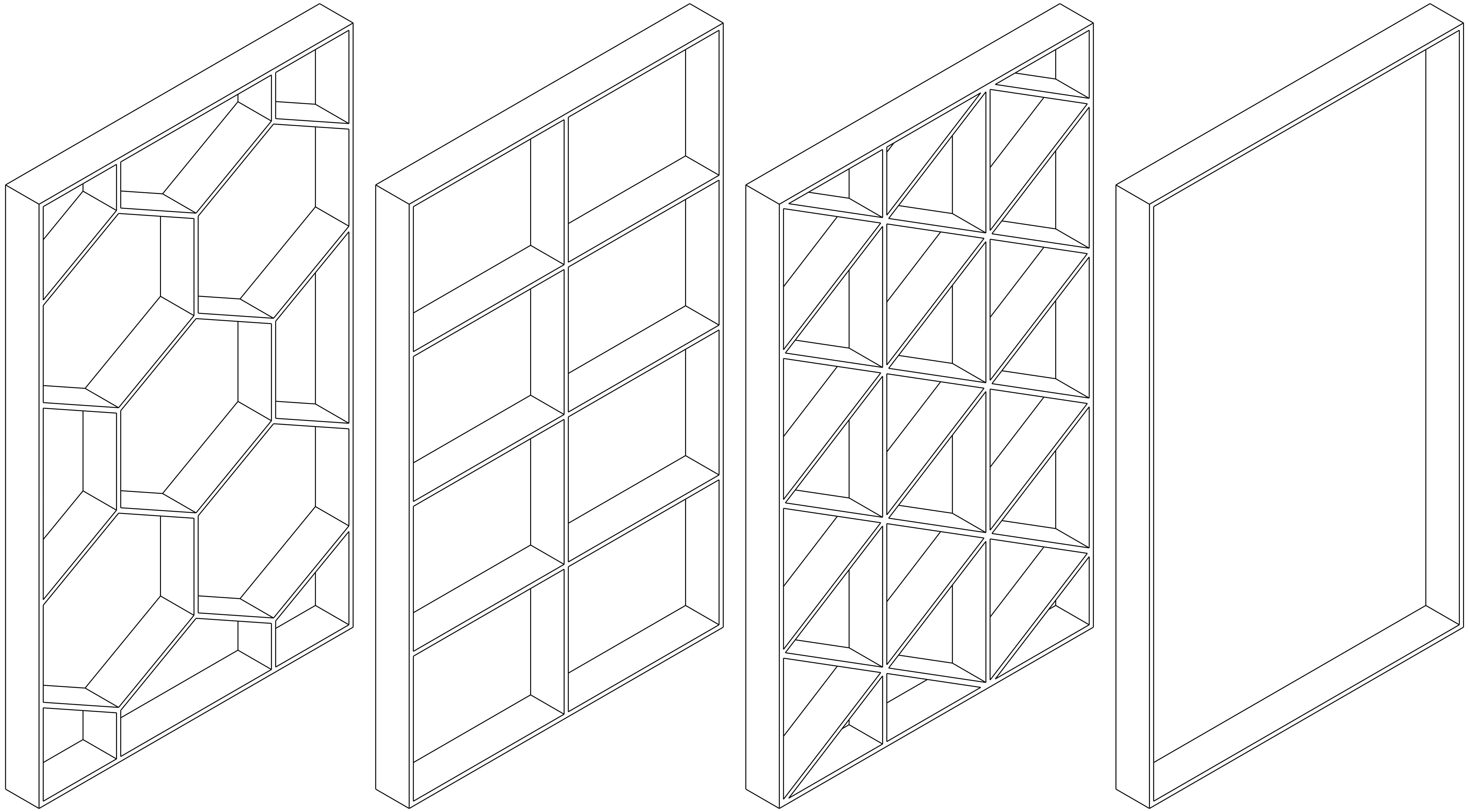
classification by Econcore (n.d.)



STRENGTH AND STIFFNESS

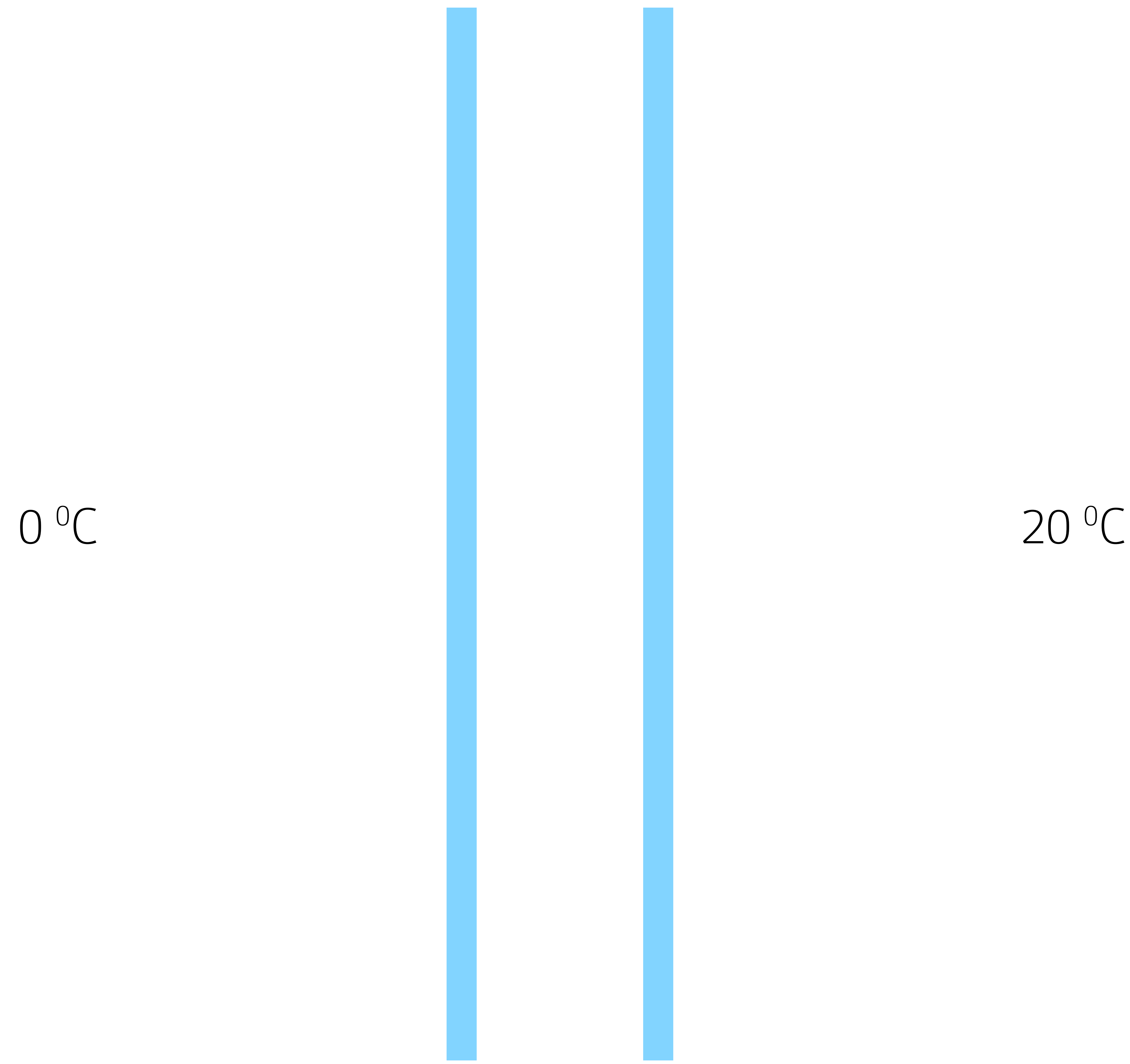
weight-load ratio of sandwich typologies (Valdevit, Huchinson, & Evans, 2004)

CALCULATION METHODOLOGY

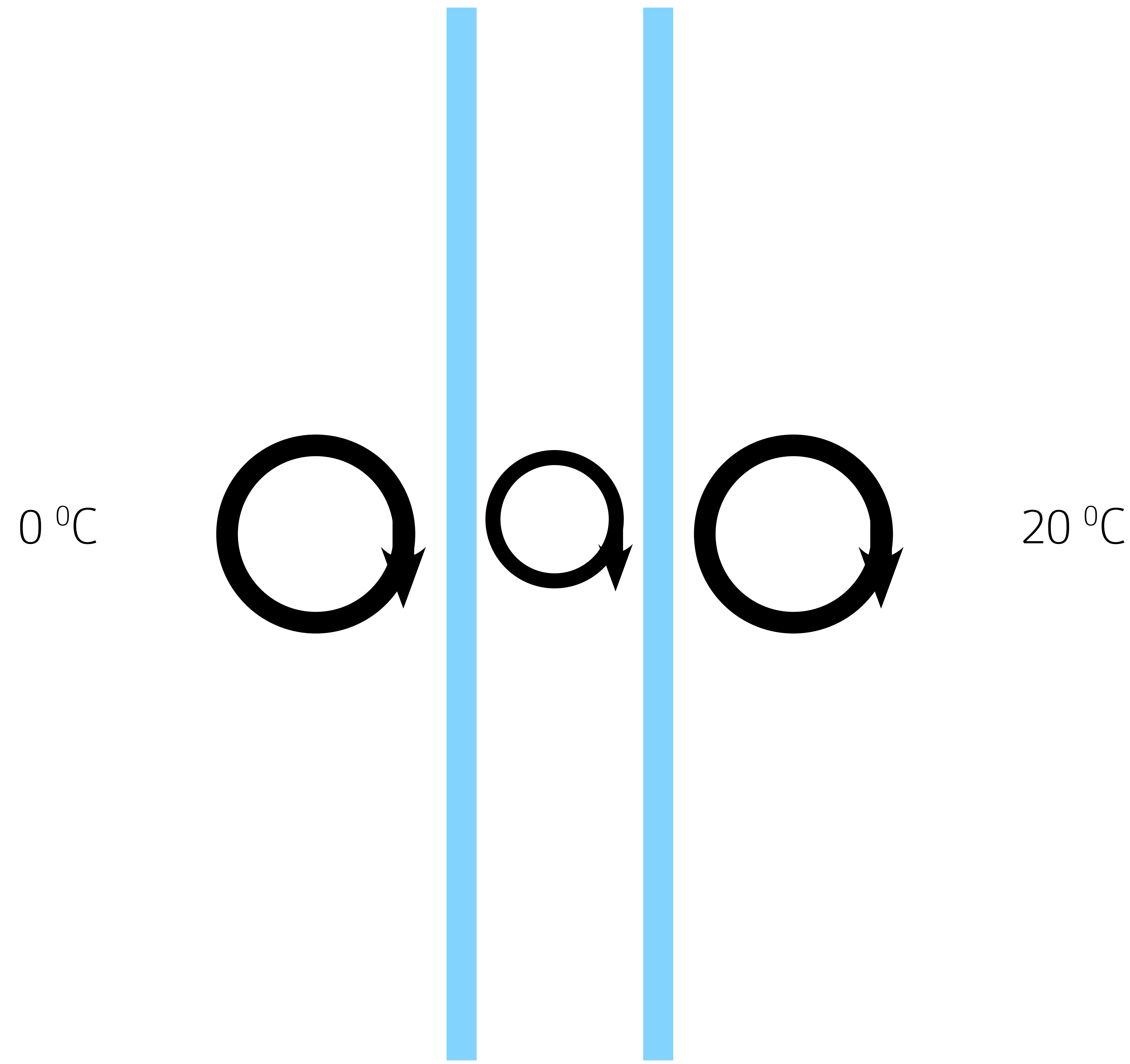


BASIC PROTOTYPES

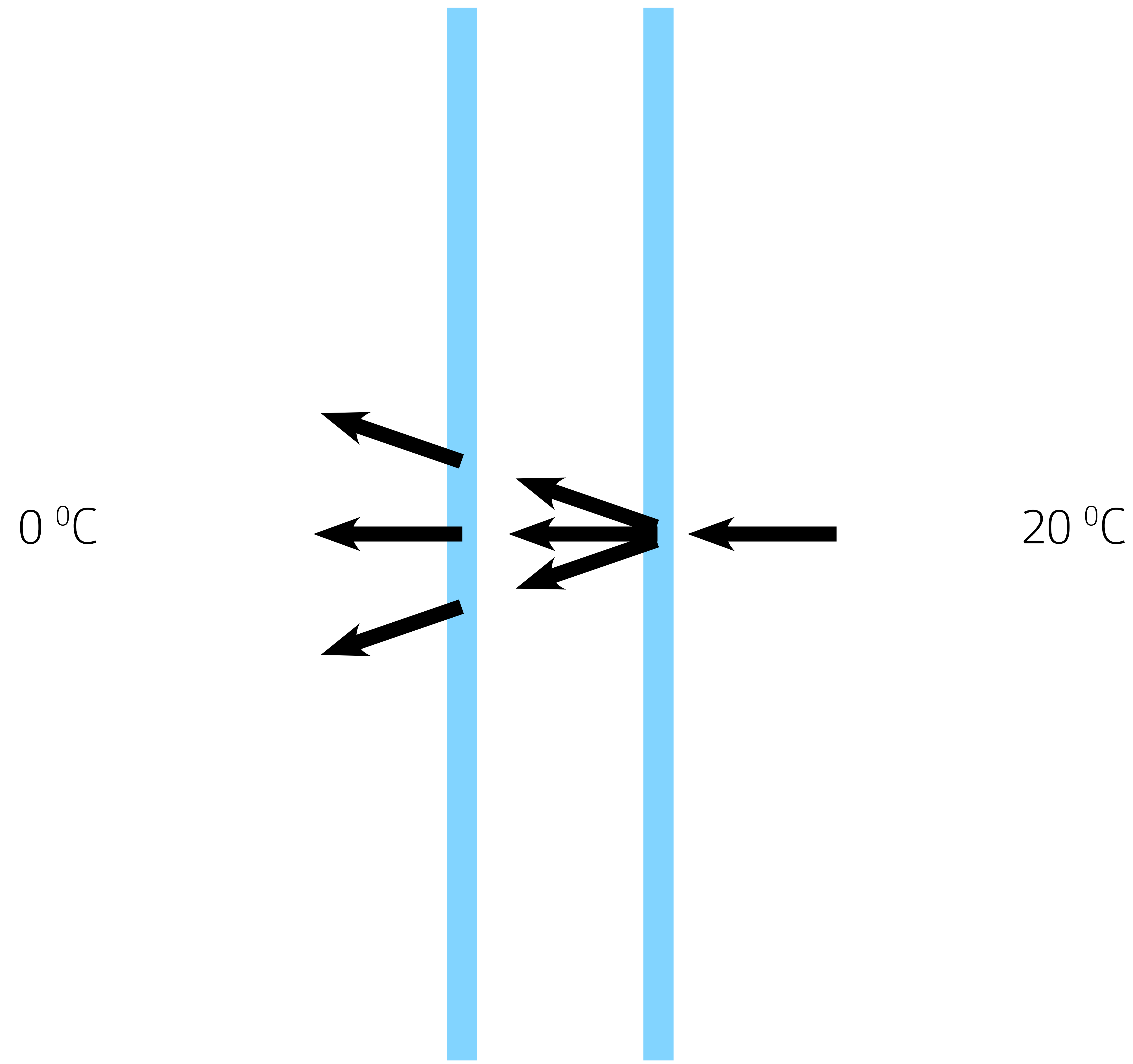
250x250x16mm, uncoated glass, air-filled cavity, PETG ribs 2mm



HEAT TRANSFER

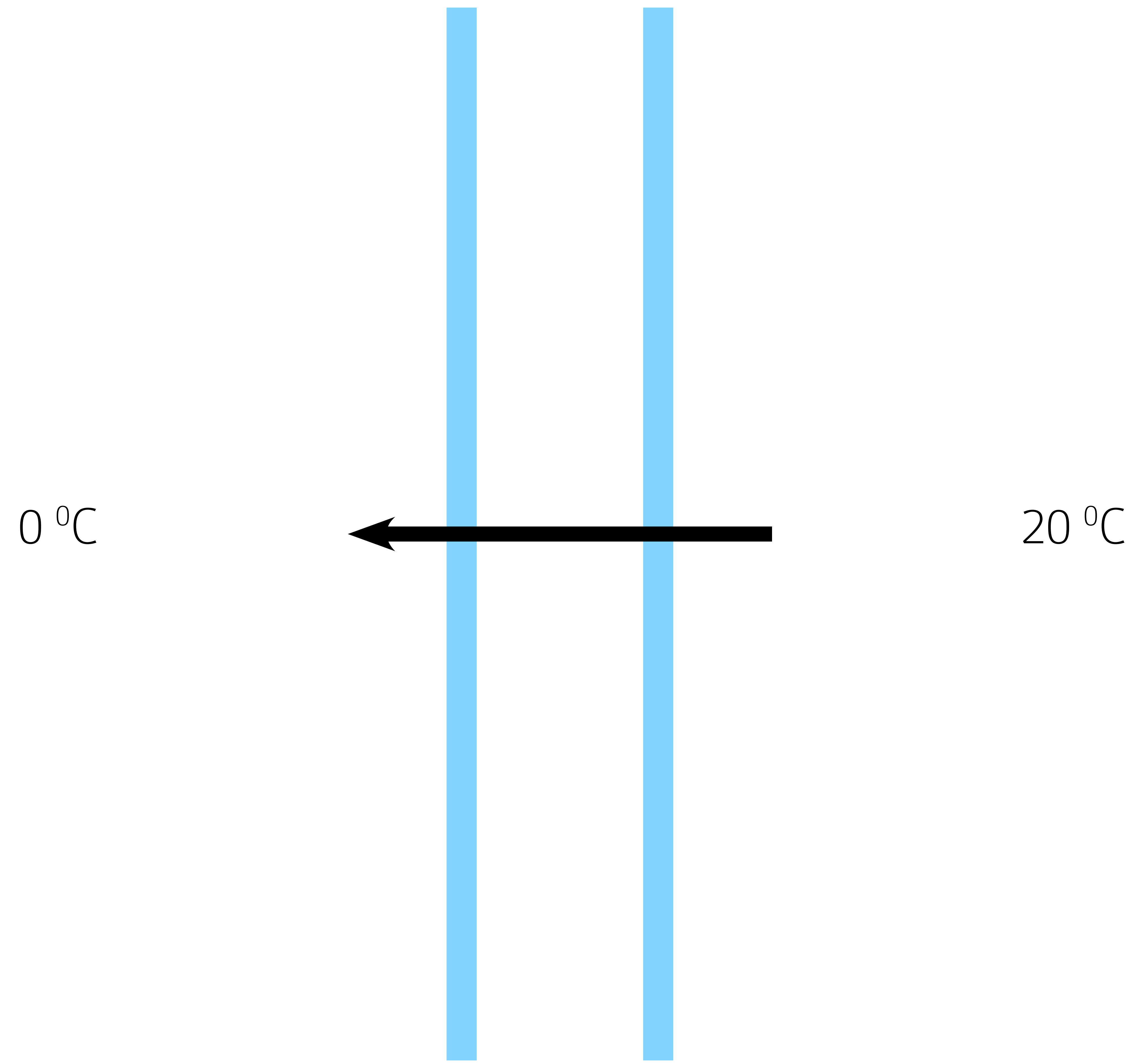


CONVECTION



RADIATION

Background



CONDUCTION

$$R_{\mathrm{g}} = \frac{1}{h_{\mathrm{a}} + h_{\mathrm{r}}}$$

CAVITY RESISTANCE

according to NEN-EN-ISO6946

$$R_g = \frac{1}{h_a + h_r}$$

Direction of heat flow	h_a [a] W/(m²·K)
Horizontal	$0{,}73 \times (\Delta T)^{1/3}$
Upwards	$1{,}14 \times (\Delta T)^{1/3}$
Downwards	$0{,}09 \times (\Delta T)^{0{,}187} d^{-0{,}44}$

[a] Or, if larger, 0,025/d.

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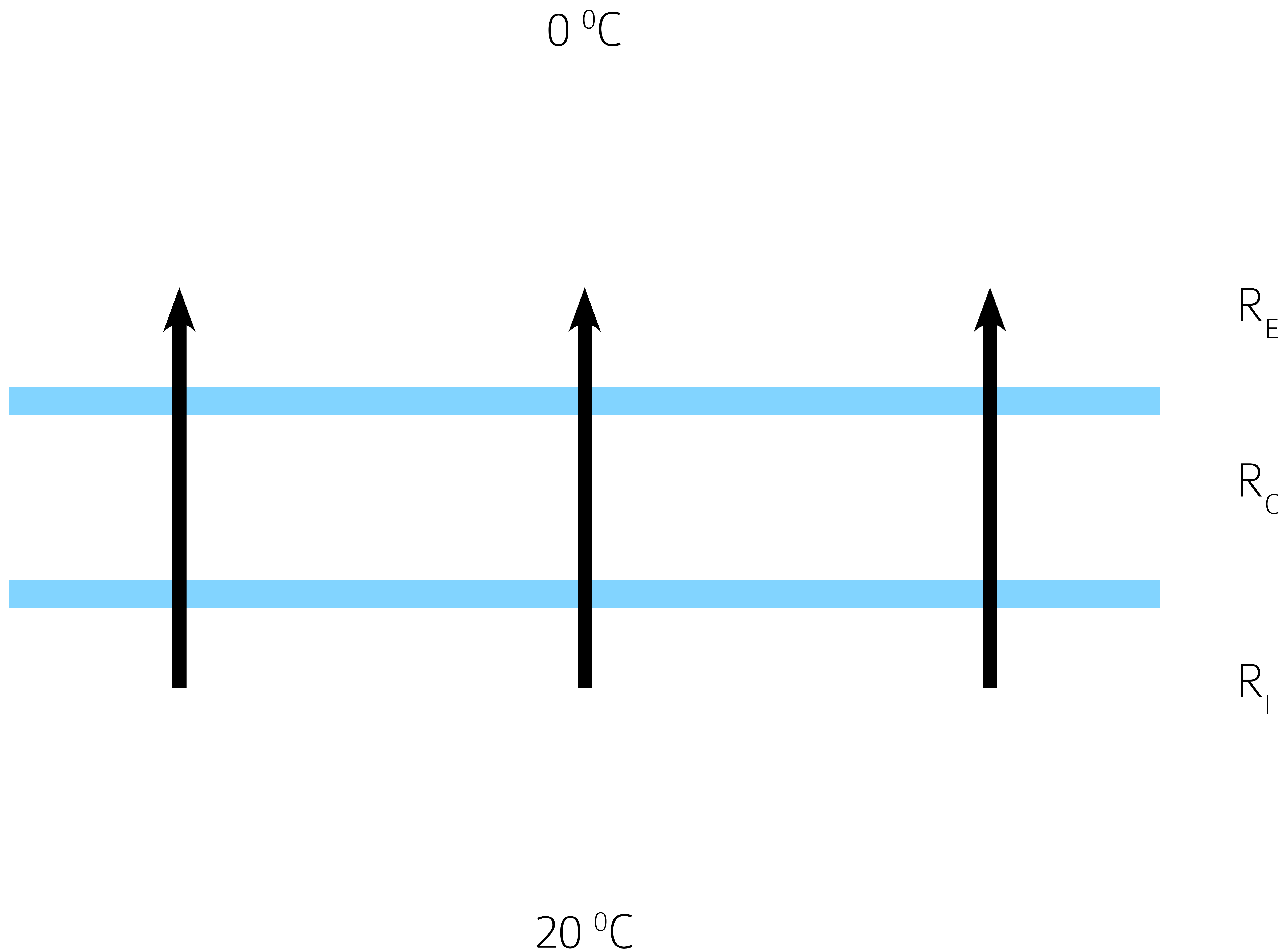
[a] Or, if larger, 0,025/d.

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 2 + \frac{2}{\left(1 + \sqrt{1 + d^2/b^2} - d/b\right)}} \qquad b = D_H = \frac{4A}{P}$$

Mean temperature °C	h_{r0} W/(m²·K)
−10	4,1
0	4,6
10	5,1
20	5,7
30	6,3

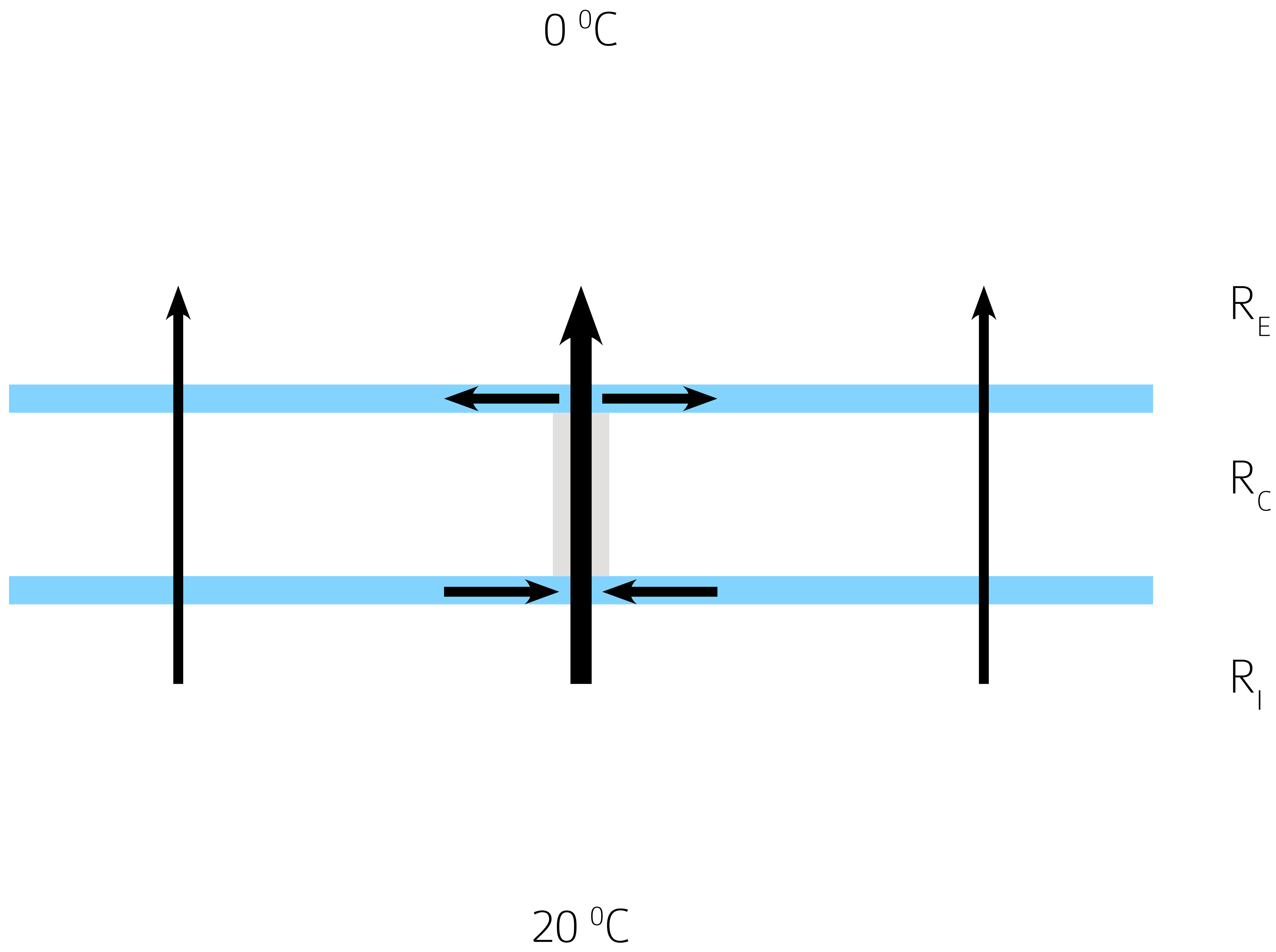
CAVITY RESISTANCE

according to NEN-EN-ISO6946



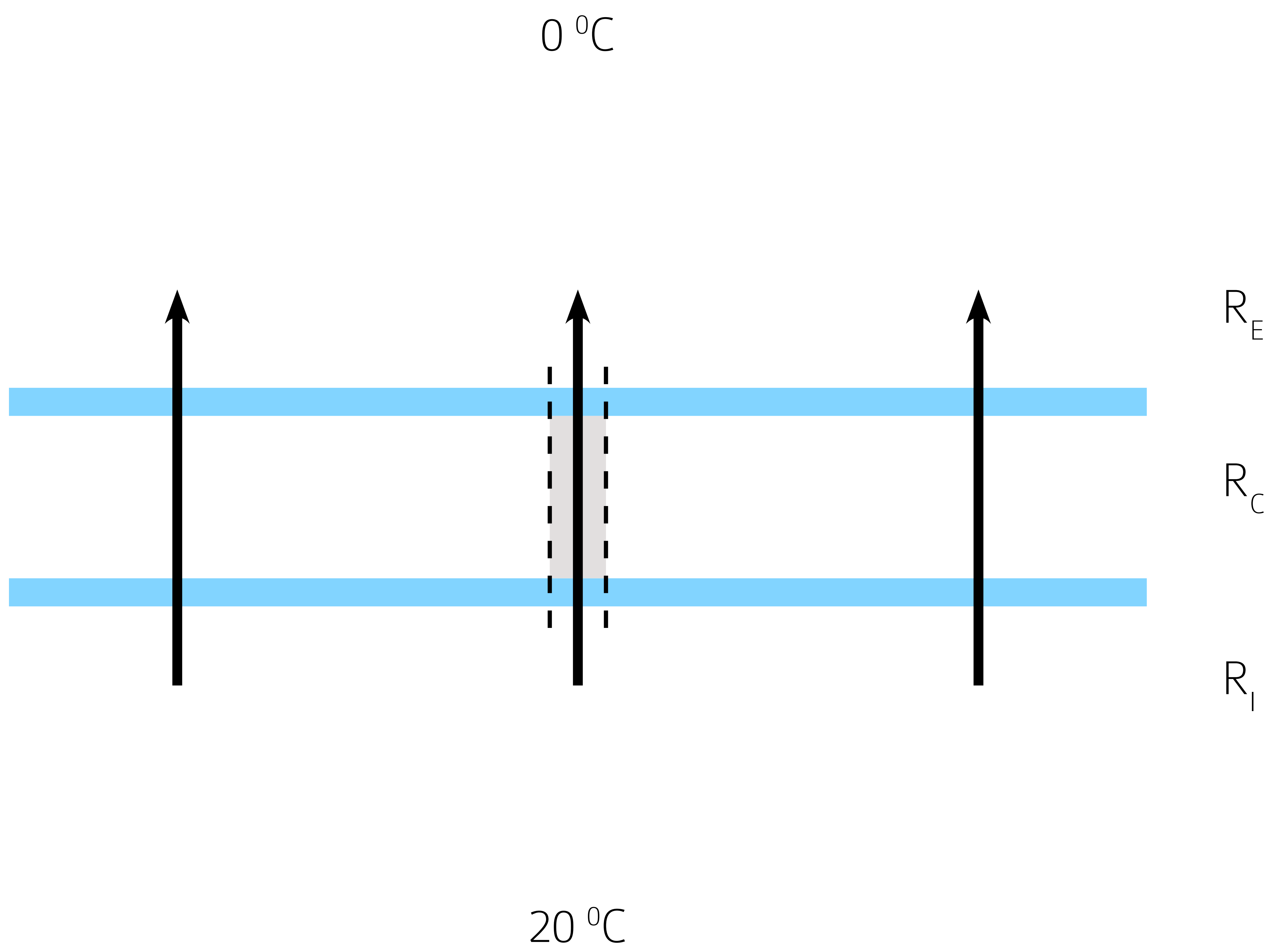
CAVITY

without thermal bridge



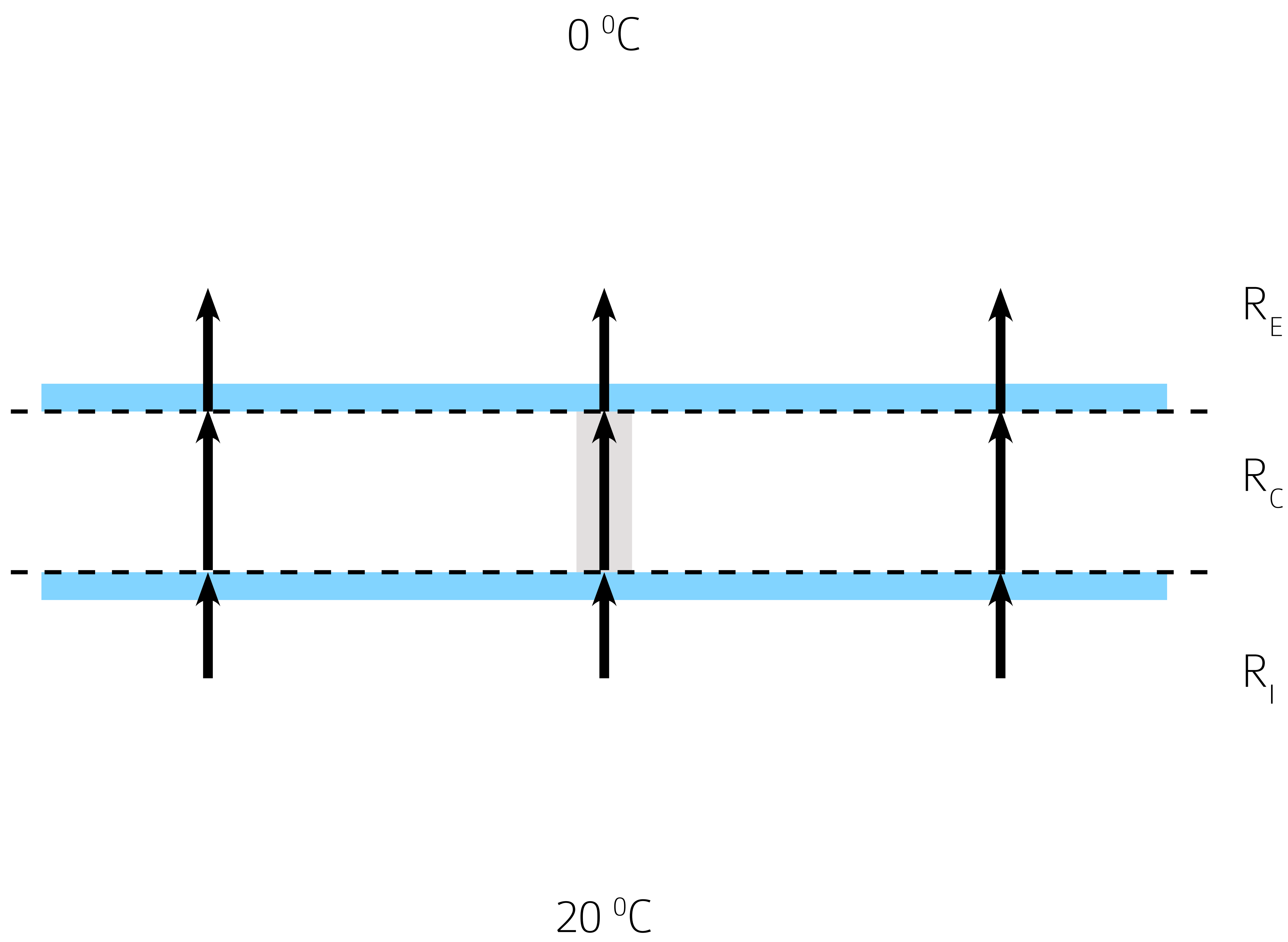
CAVITY

with thermal bridge



SIMPLE ANALYTICAL CALCULATION

minimum U-value by Zeegers (2006)

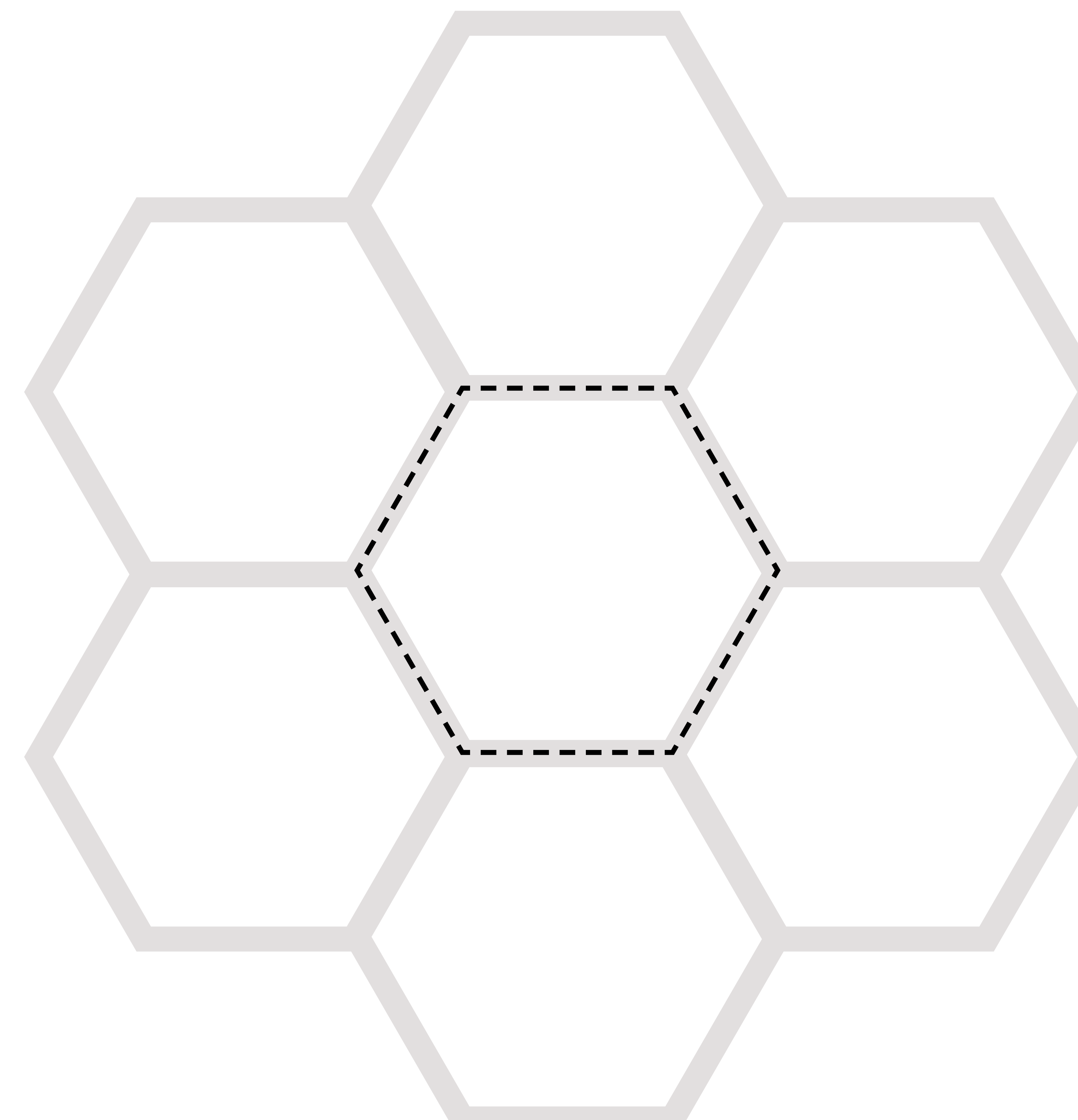


SIMPLE ANALYTICAL CALCULATION

maximum U-value by Zeegers (2006)

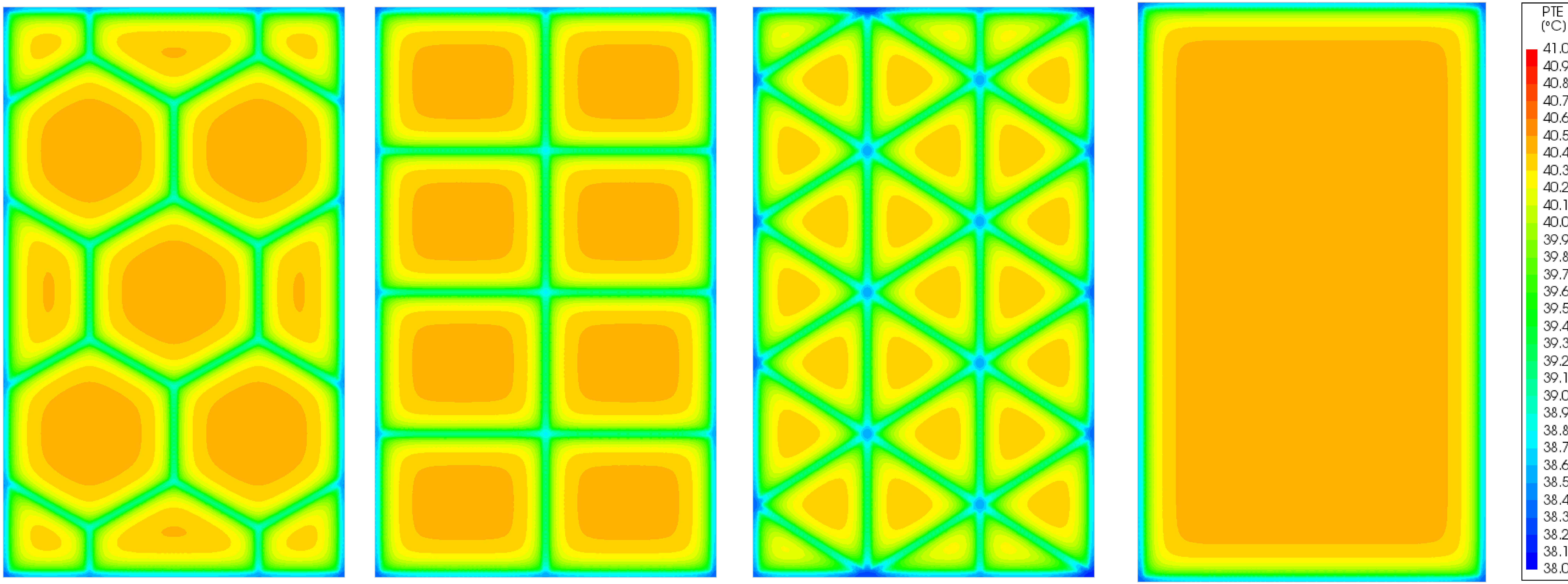
Background

$$U_{\mathrm{eff}} \approx \frac{U_{\mathrm{cop}} S_{\mathrm{cop}} + \psi^{(c)}_{\mathrm{edge}} l_{\mathrm{p}}}{S_{\mathrm{cop}} + S_{\mathrm{edge}}}$$



DETAILED ANALYTICAL CALCULATION

by Tenpierik, Van der Spoel, & Cauberg (2007)



NUMERICAL ANALYSIS

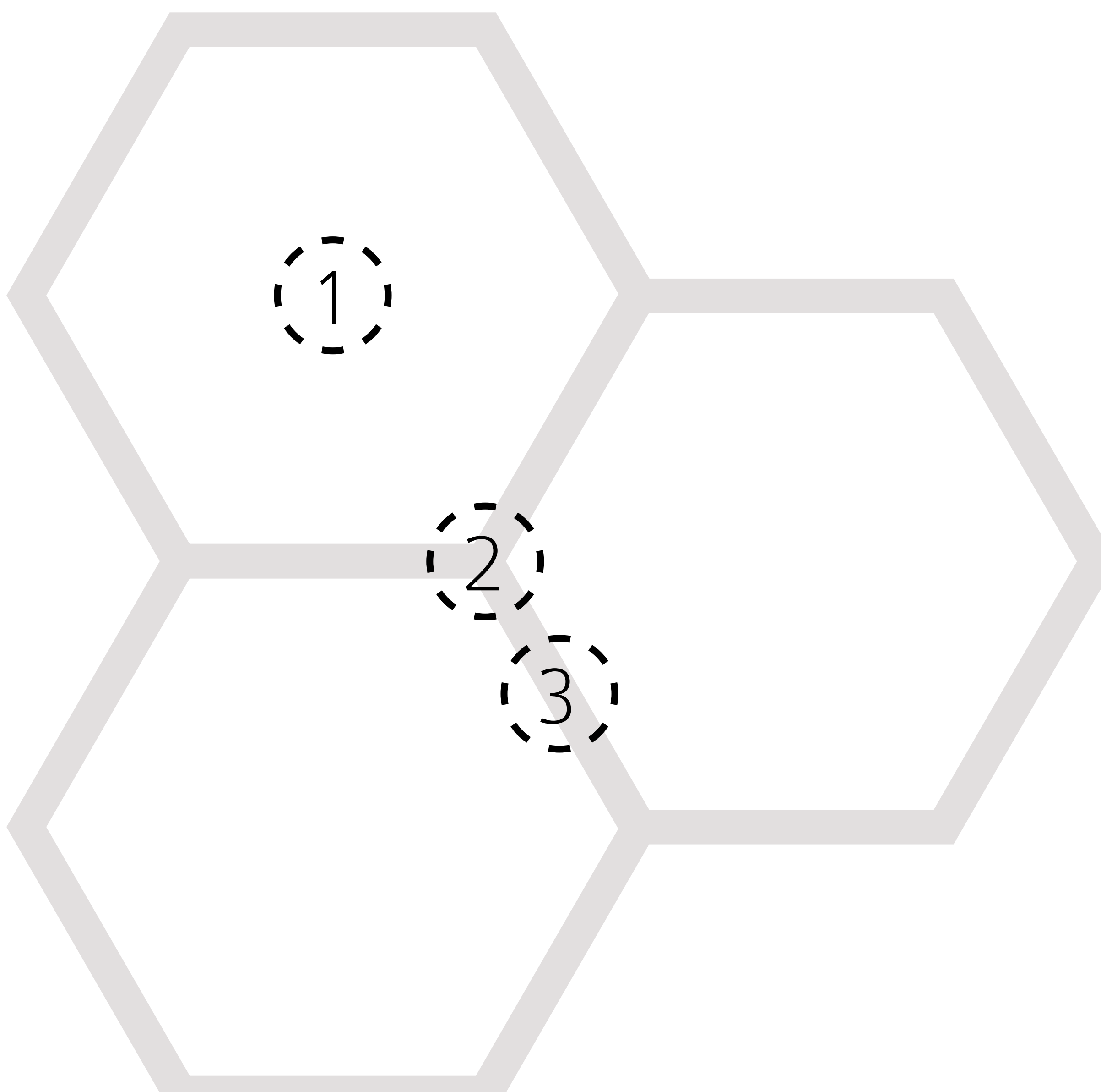
23°C - 48°C and boundary resistance at both sides of 0.1304 m^2K/W

	U (W/m²K)		
	Simple	Detailed	Numerical
Hexagon	2.453	2.473	2.472
Square	2.445	2.463	2.452
Triangle	2.488	2.533	2.481
Empty	2.456	2.454	2.454

COMPARISON CALCULATION METHODS

boundary resistance at both sides of 0.13 m²K/W


Eltek
Squirrel
1000 series
Eltek
Eltek
Squirrel
1000 series
Eltek



	U (W/m²K)		
	Cell	Knot	Element
Hexagon	2.46	2.37	2.54
Square	2.55	2.45	2.61
Triangle	2.39	2.50	2.53
Empty	2.54		

PHYSICAL MEASUREMENTS

boundary resistance at both sides of 0.13 m^2K/W

	U (W/m²K)			
	Physical	Simple	Detailed	Numerical
Hexagon	2.37-2.54	2.453	2.473	2.472
Square	2.45-2.61	2.445	2.463	2.452
Triangle	2.39-2.53	2.488	2.533	2.481
Empty	2.54	2.456	2.454	2.454

PHYSICAL MEASUREMENTS VERSUS ANALYTICAL CALCULATION

boundary resistance at both sides of 0.13 m^2K/W

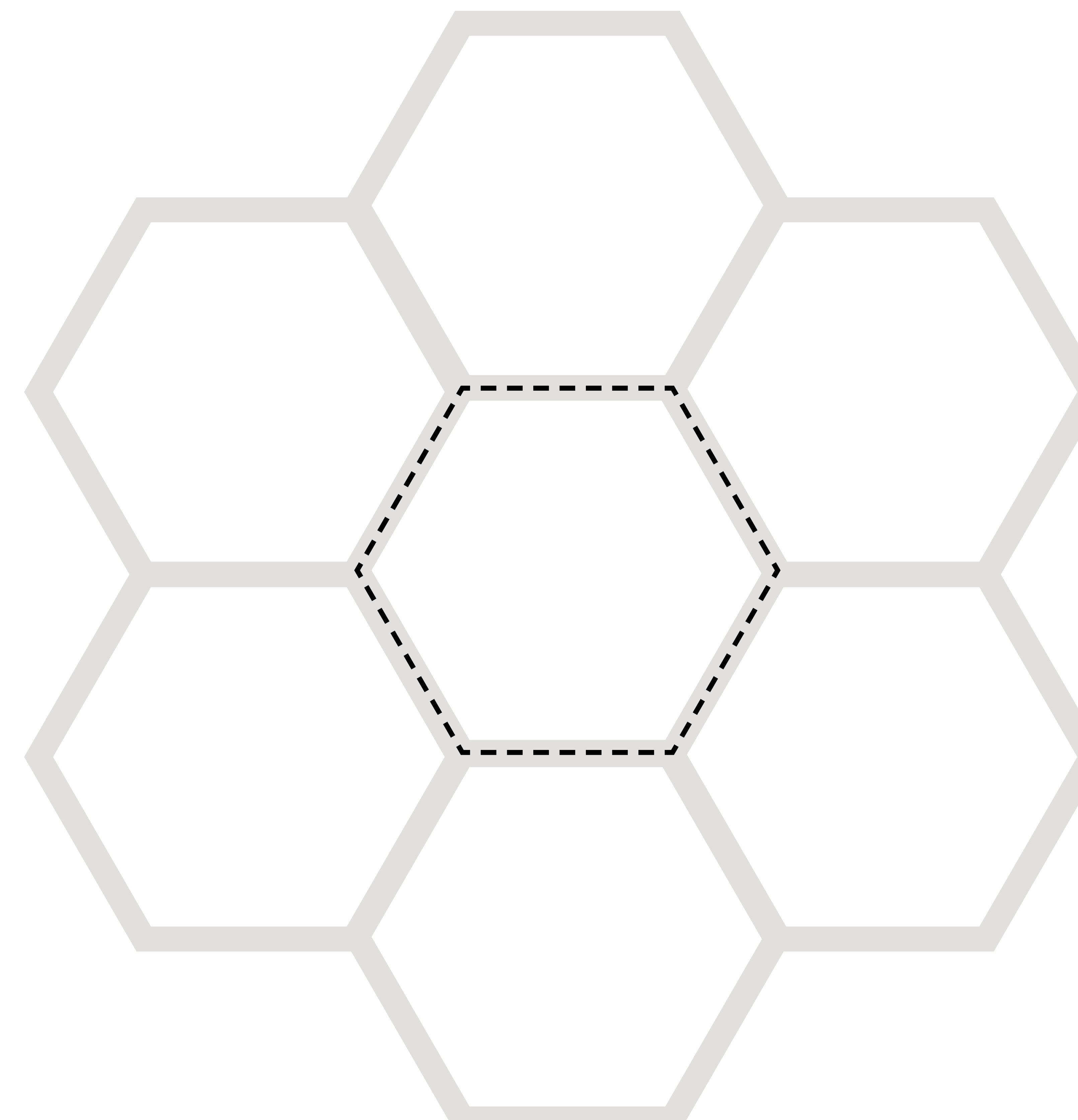
PARAMETER STUDY

	PETG	PA	PLA
Density (kg/m^3)	1260 - 1280	1090 - 1100	1240 - 1270
Young's modulus (GPa)	2.01 - 2.11	1.60 - 1.68	3.30 - 3.60
Tensile strength (MPa)	60 - 66	40 - 47	47 - 70
Compressive strength (MPa)	57.5 - 63.5	55.0 - 46.7	66.0 - 86.4
Thermal conductivity (W/mK)	0.29	0.24	0.15
Resistance UV radiation	Fair	Fair	Good
Recycleble	True	True	True
Embodied energy (MJ/kg)	89 - 98	210 - 232	52 - 58

MATERIAL CHOICE

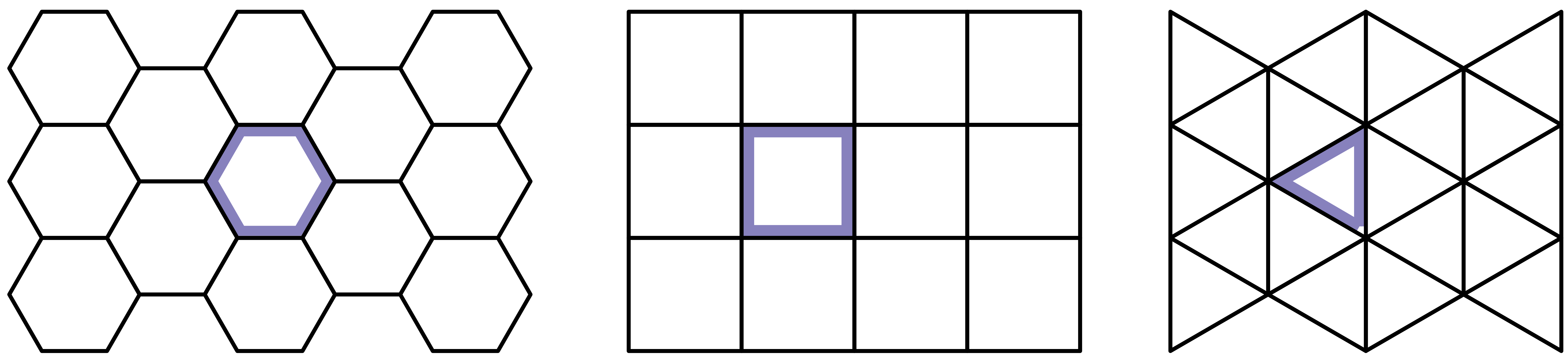
information based on CES (2018)

$$U_{\text{eff}} \approx \frac{U_{\text{cop}} S_{\text{cop}} + \psi^{(c)}_{\text{edge}} l_{\text{p}}}{S_{\text{cop}} + S_{\text{edge}}}$$

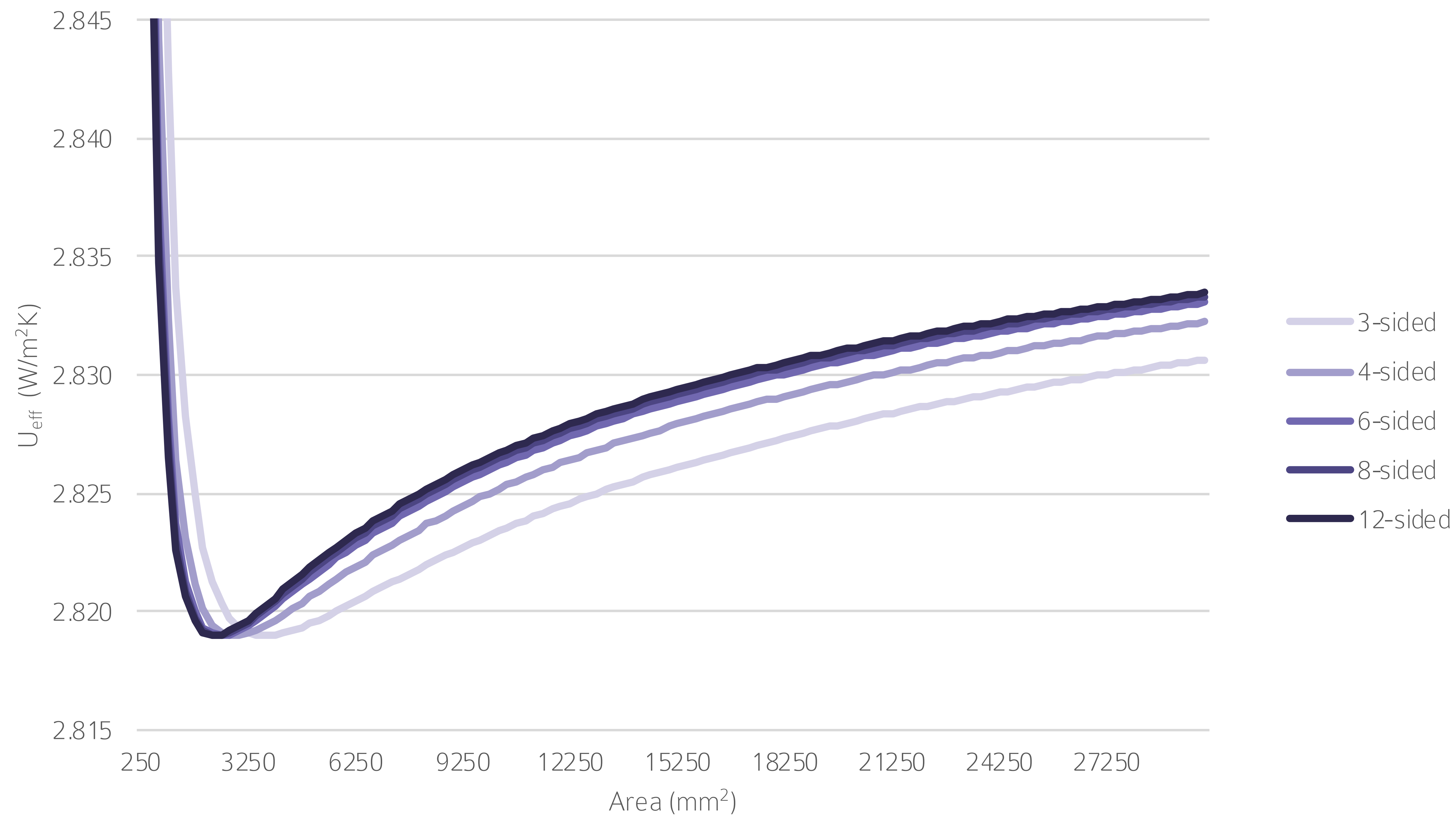


SETUP

boundary resistance 0.04 and 0.13 m^2K/W temperatures 0^oC and 20^oC



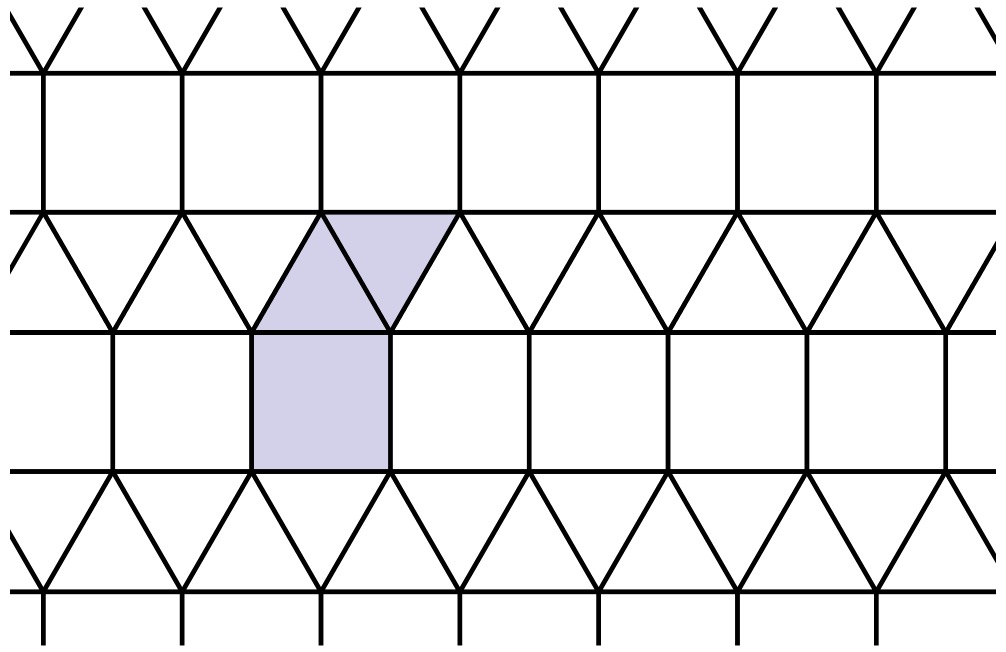
REGULAR TESSELATIONS

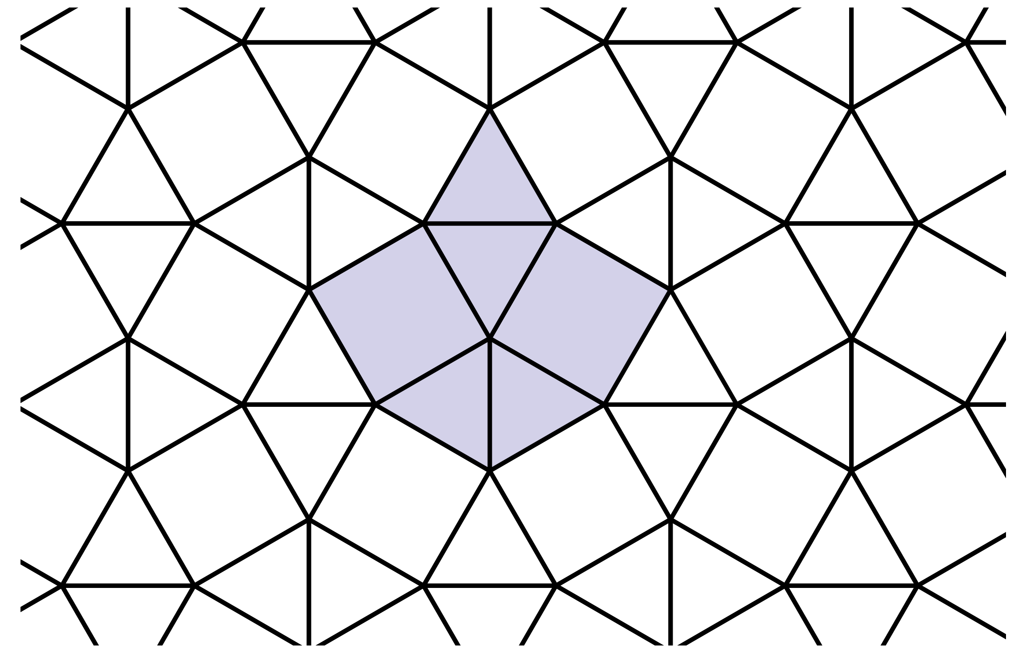


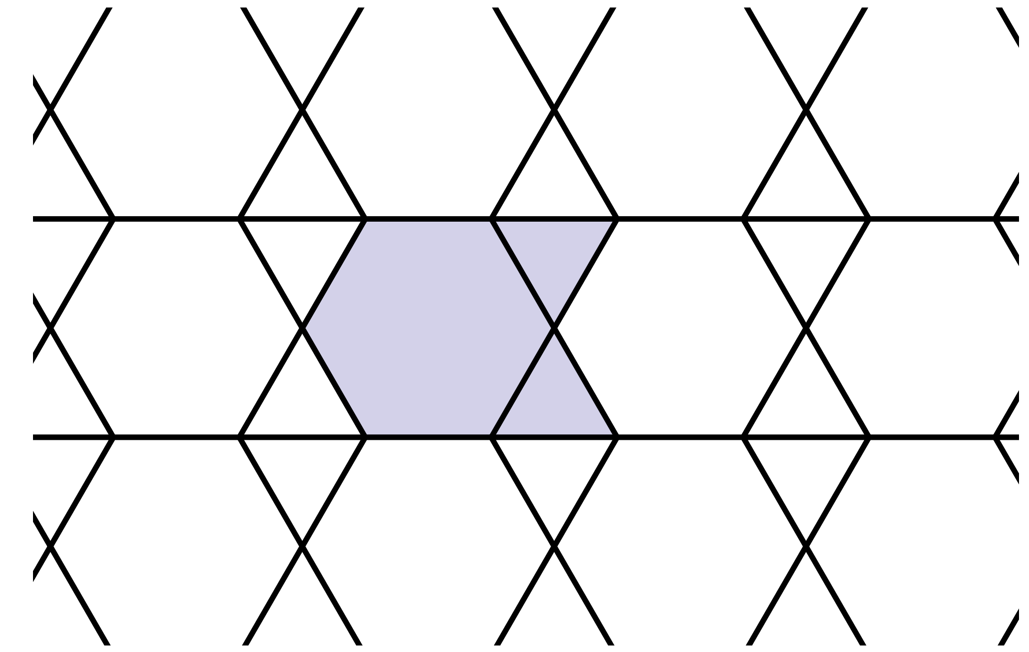
Polygon	3-sided	4-sided	6-sided	8-sided	12-sided
Area (mm^2)	3750	3000	2500	2500	2250

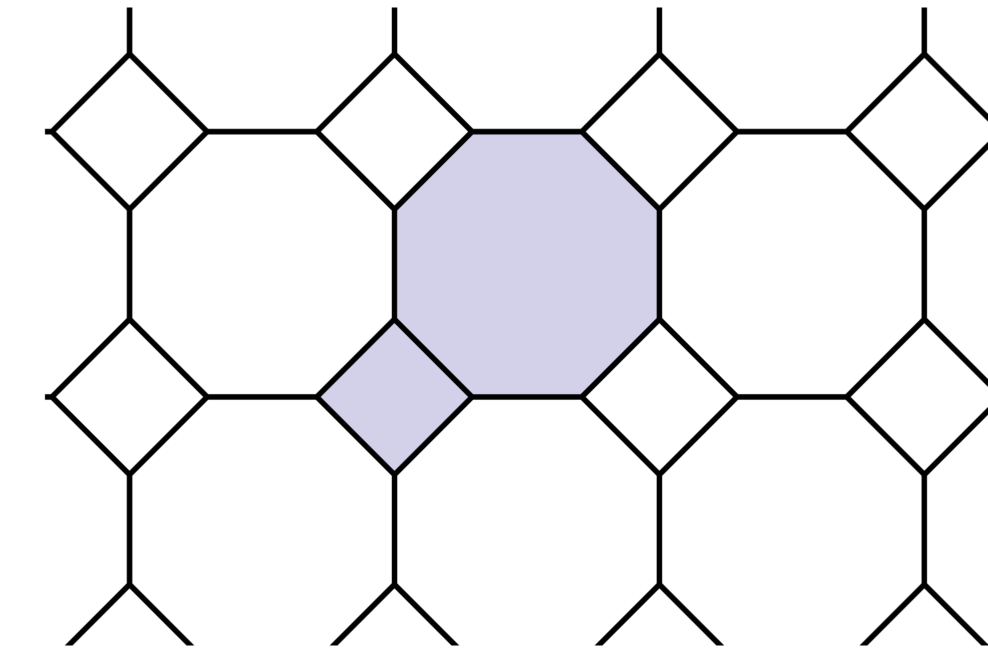
RELATION BETWEEN SIZE OF POLYGONS AND U-VALUE

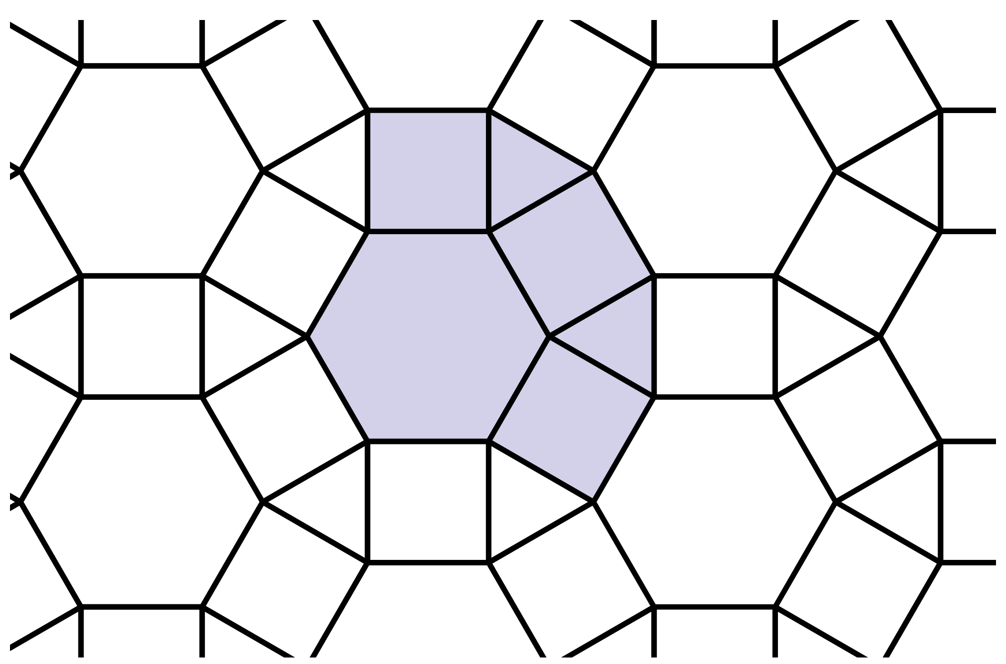
bottom at 2.819 W/m^2K

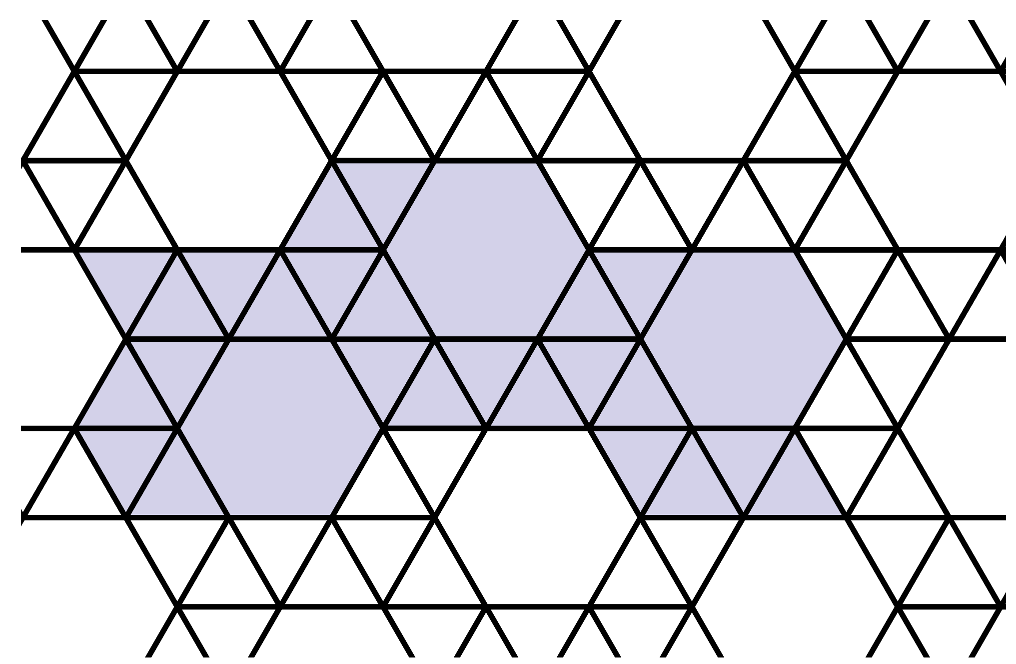

Pattern A 3.3.3.4.4

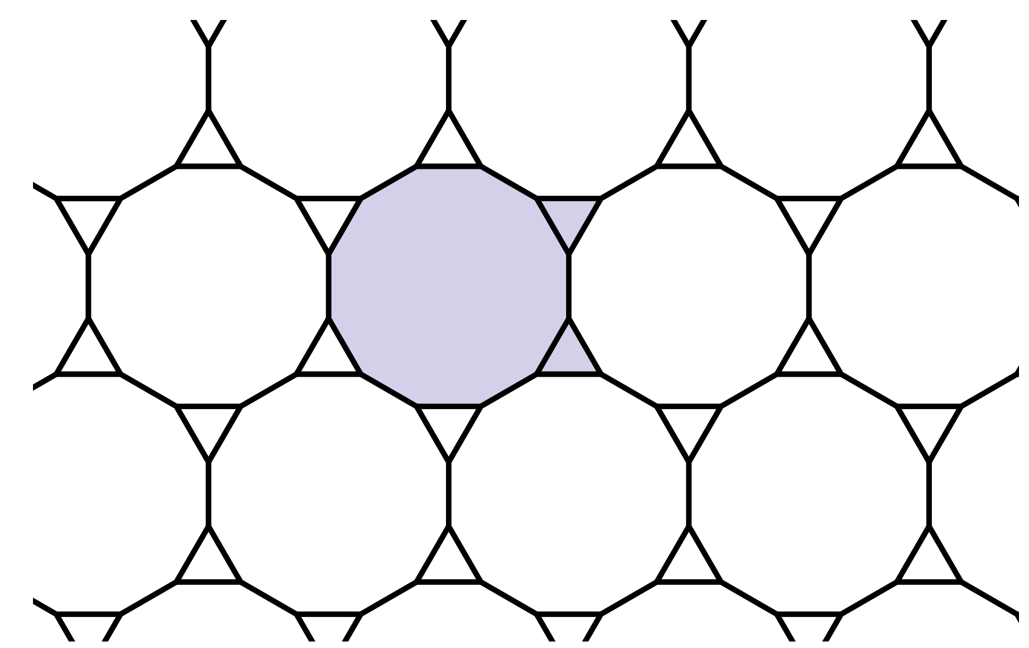

Pattern B 3.3.4.3.4

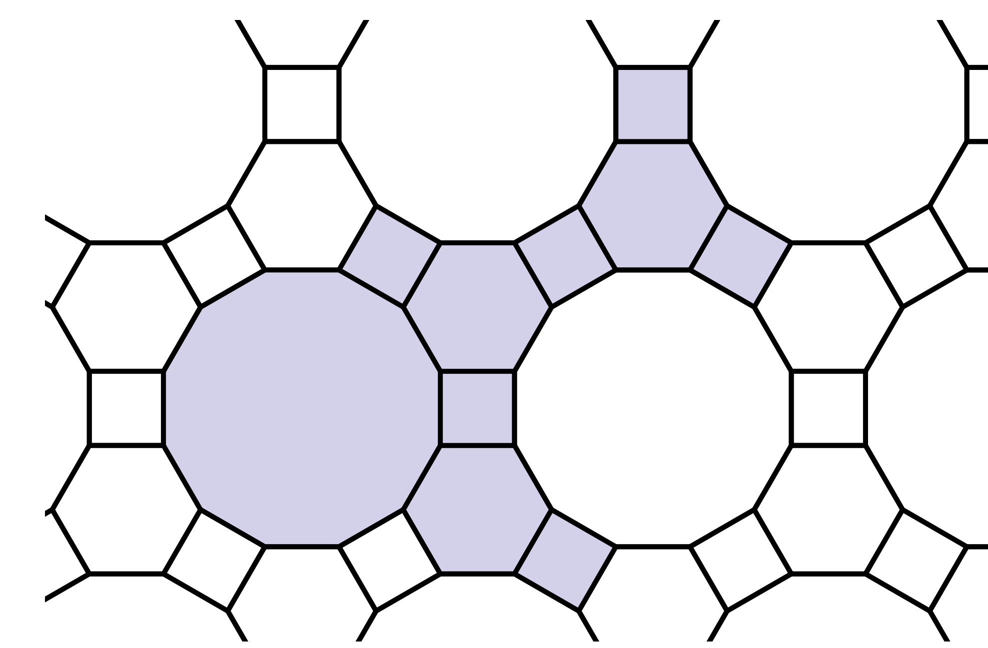

Pattern C 3.6.3.6


Pattern D 4.8.8

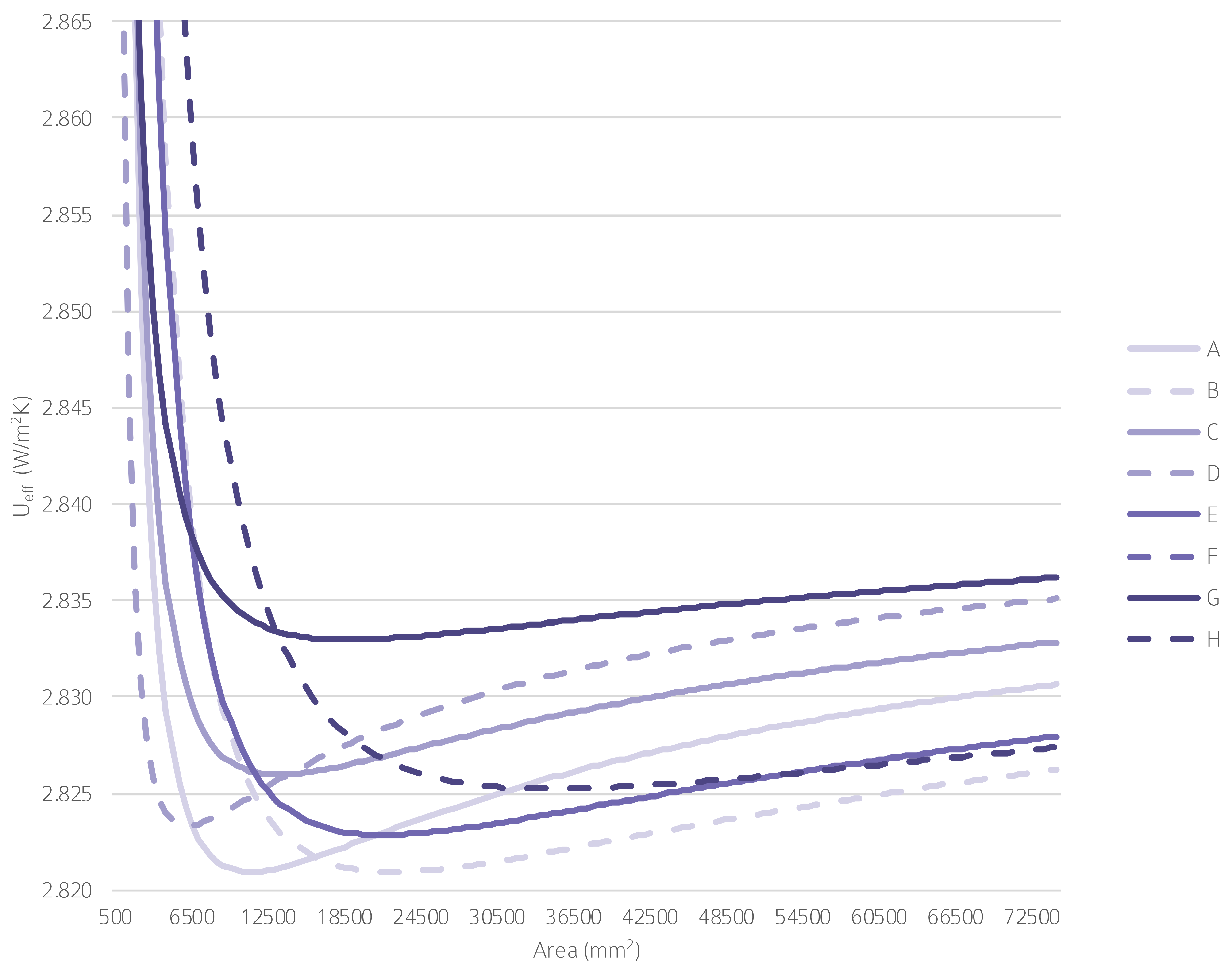

Pattern E 3.4.6.4


Pattern F 3.3.3.3.6

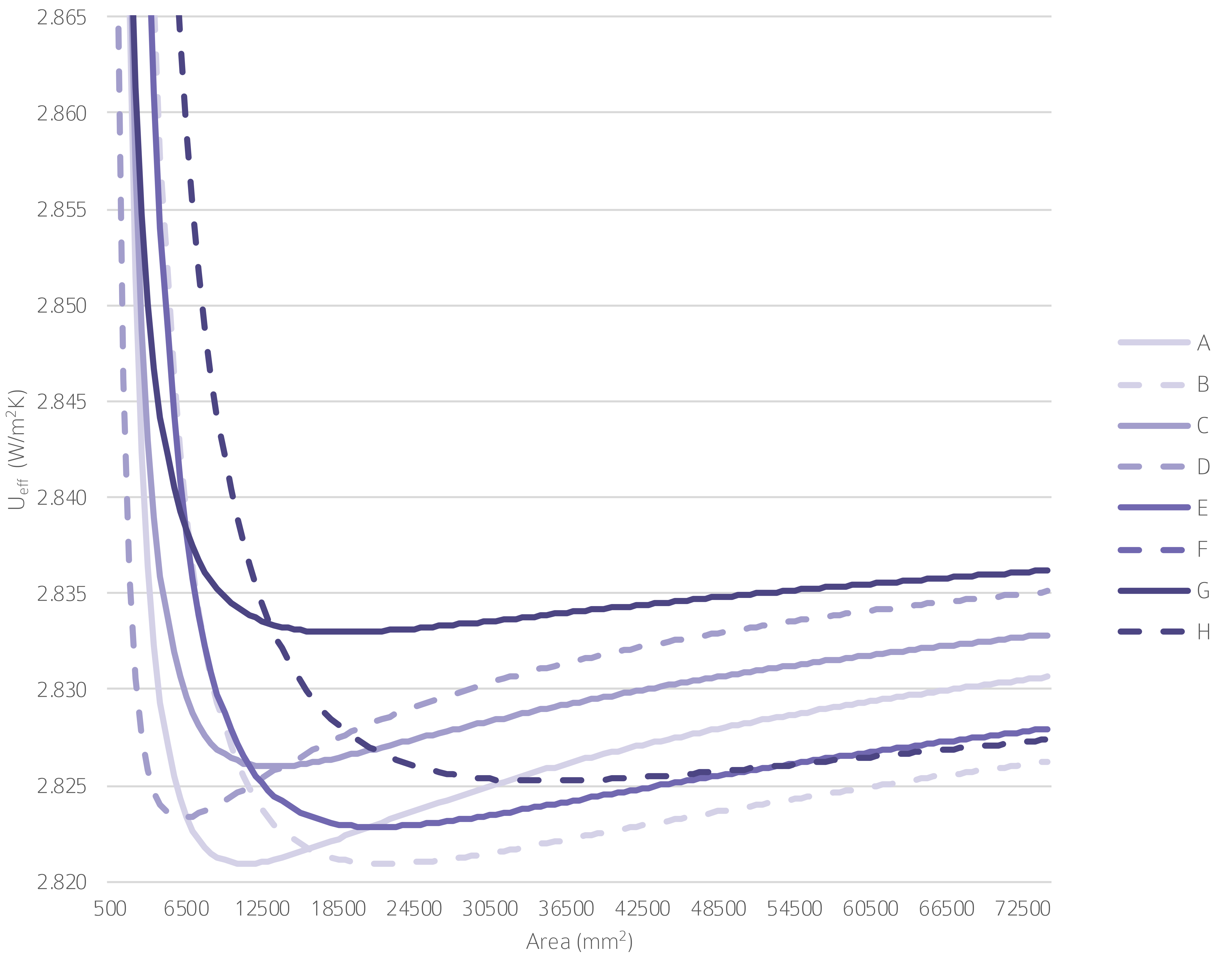

Pattern G 3.12.12

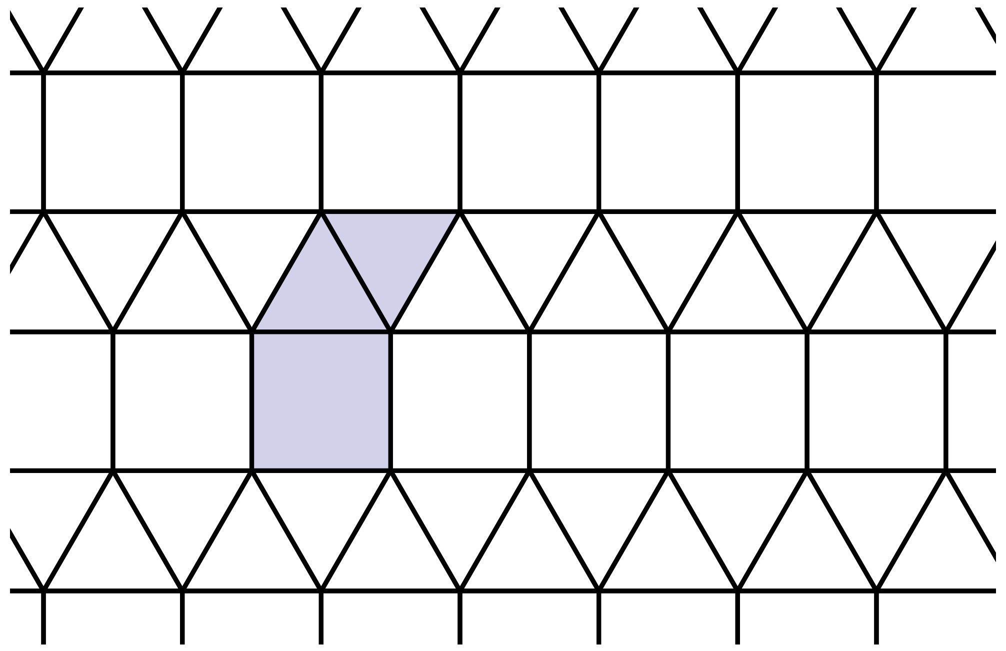

Pattern H 4.6.12

SEMIREGULAR TESSELATIONS

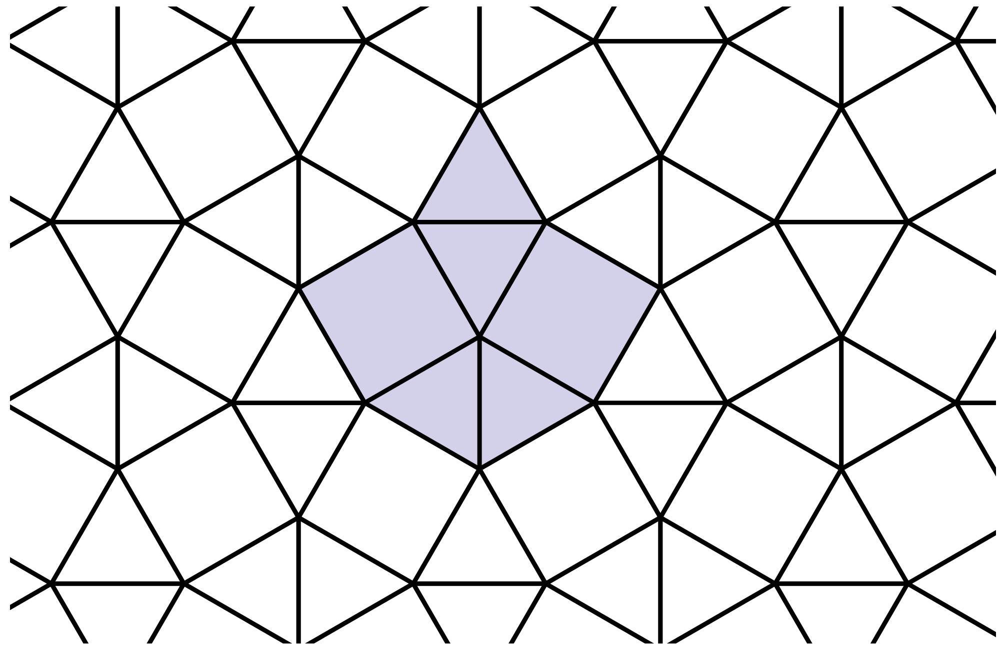


RELATION BETWEEN SIZE OF REPEATING PATTERN AND U-VALUE



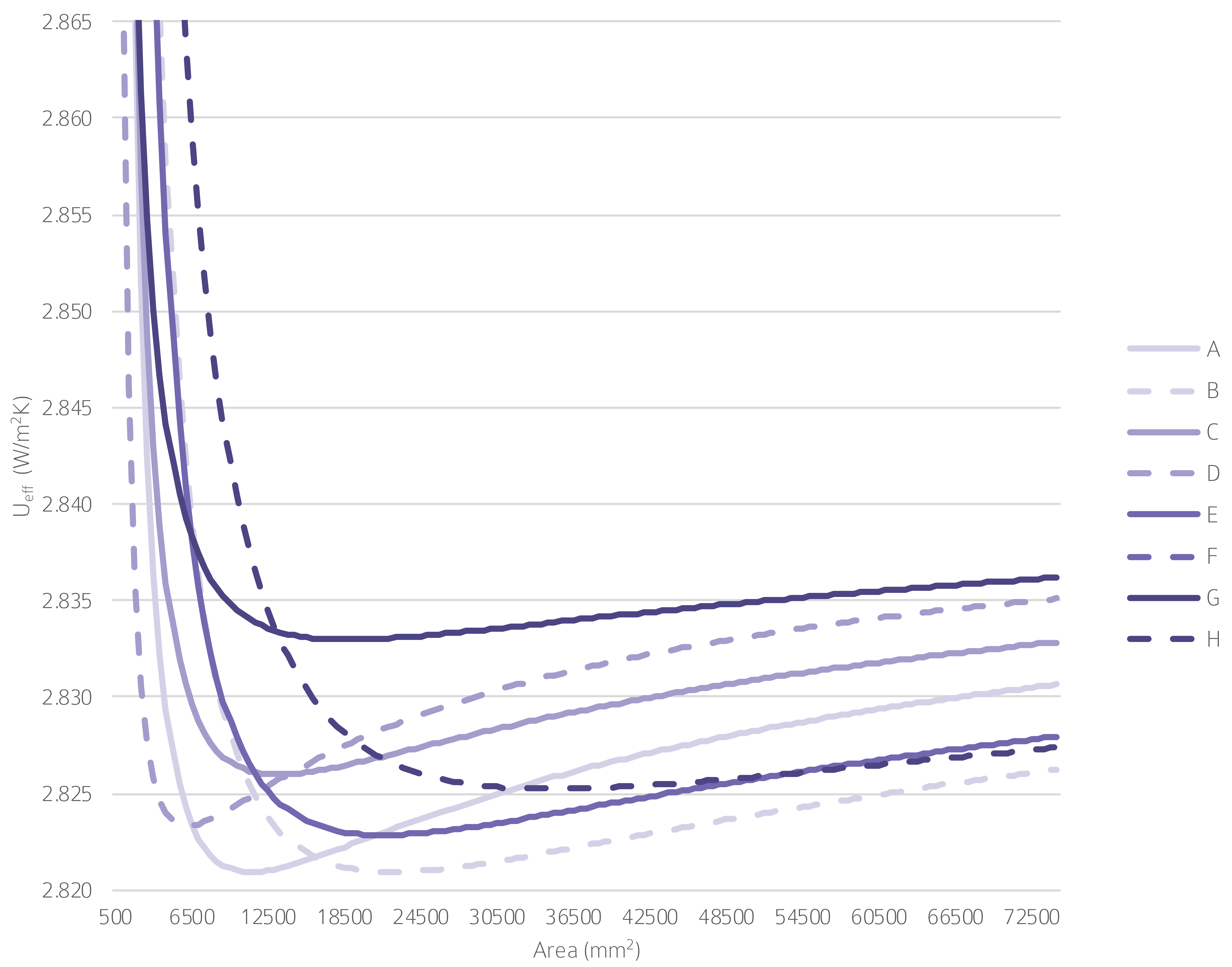


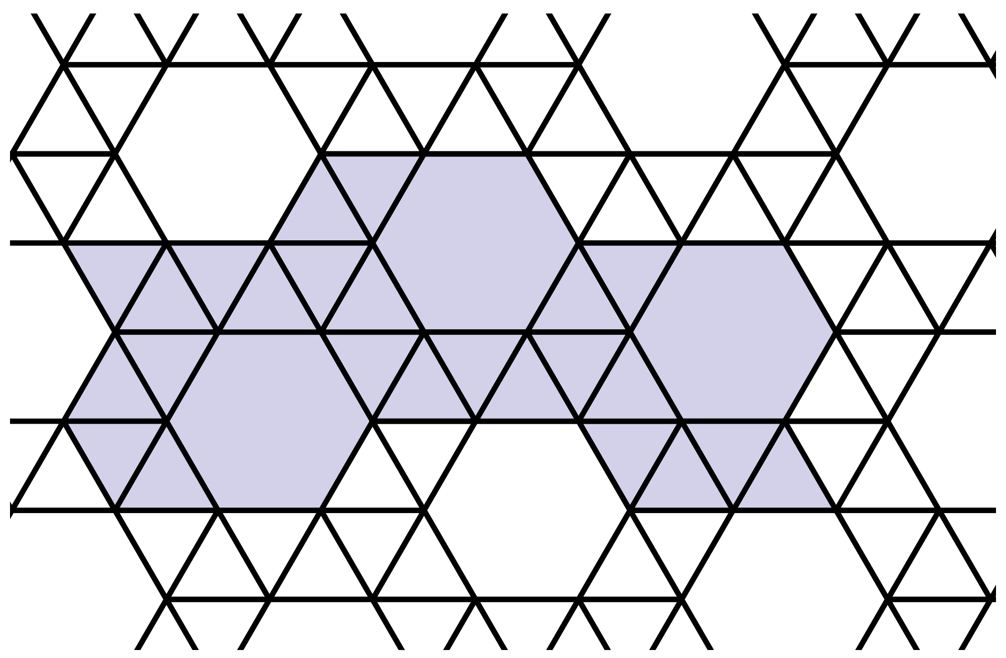
Pattern A 3.3.3.4.4



Pattern B 3.3.4.3.4

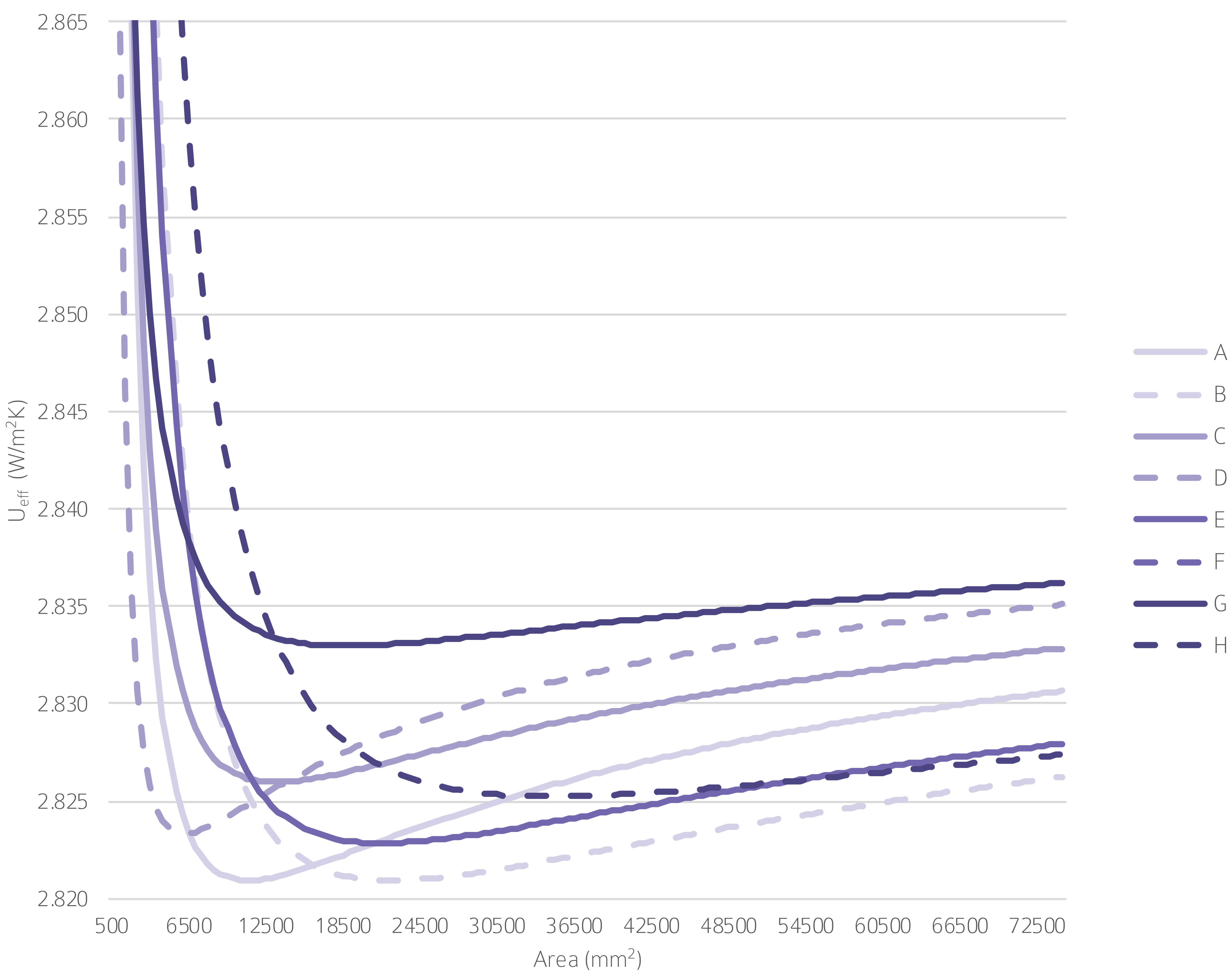
RELATION BETWEEN SIZE OF REPEATING PATTERN AND U-VALUE

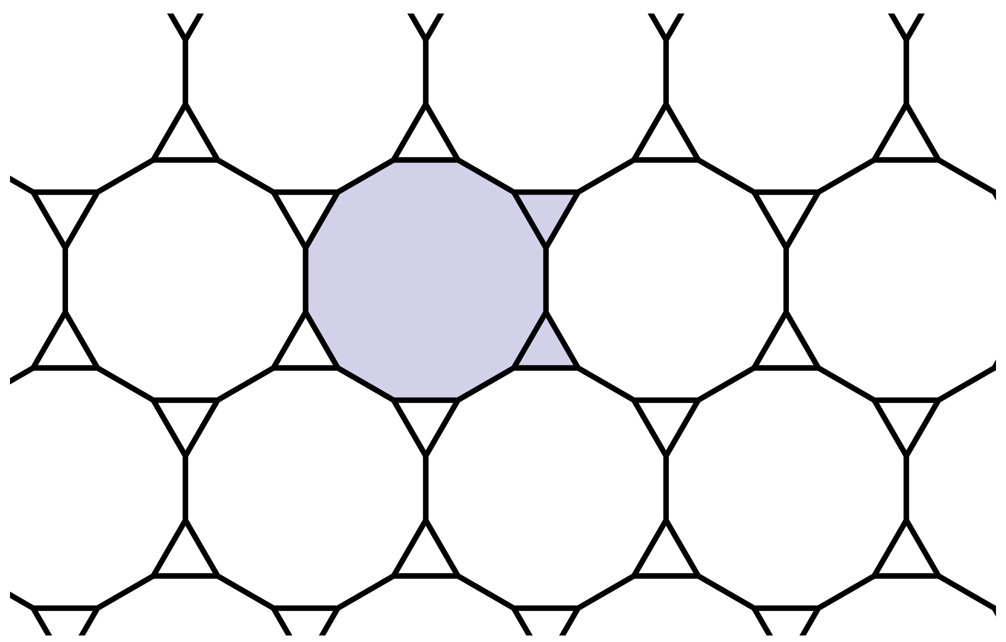




Pattern F 3.3.3.3.6

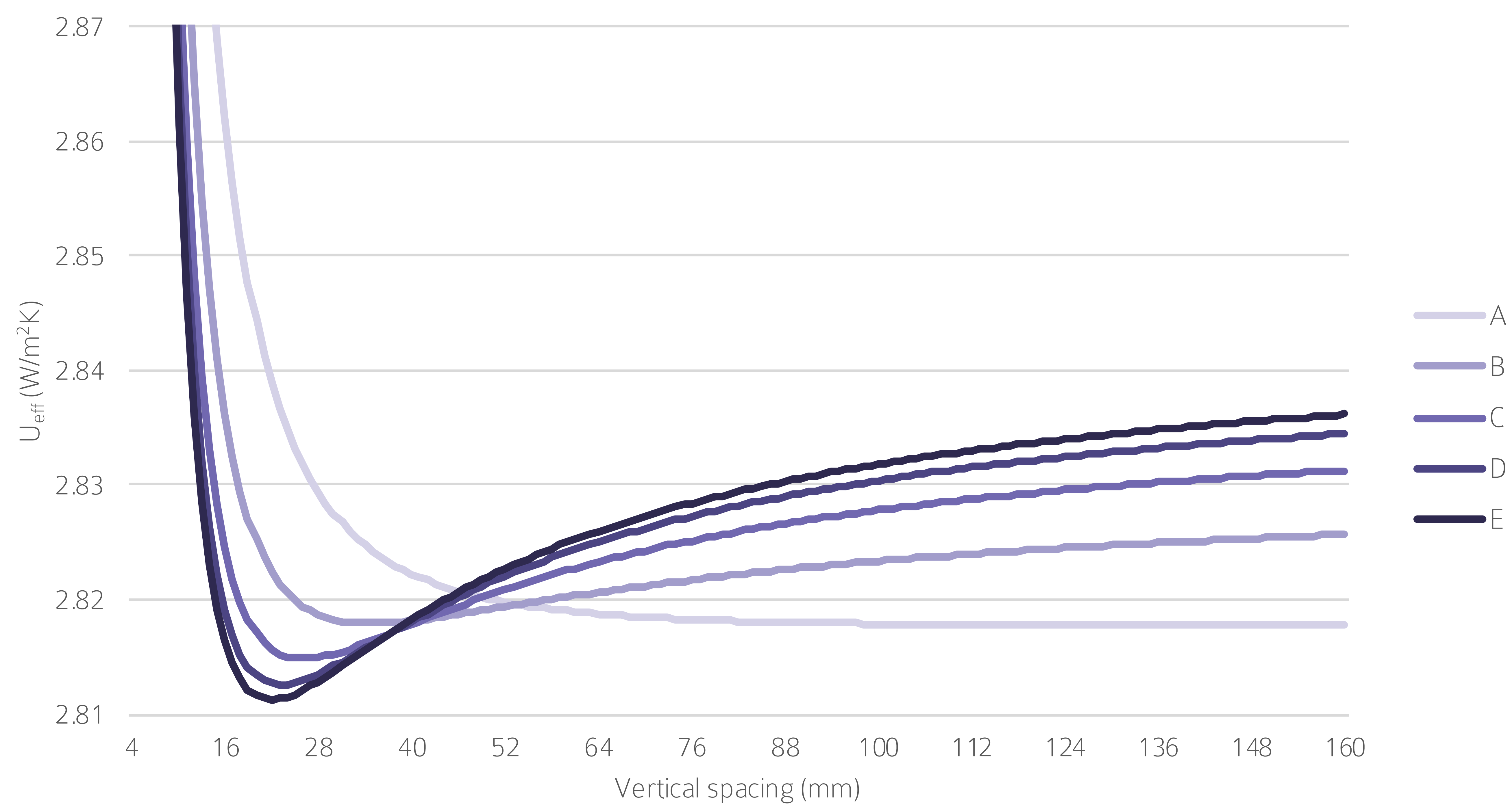
RELATION BETWEEN SIZE OF REPEATING PATTERN AND U-VALUE





Pattern G 3.12.12

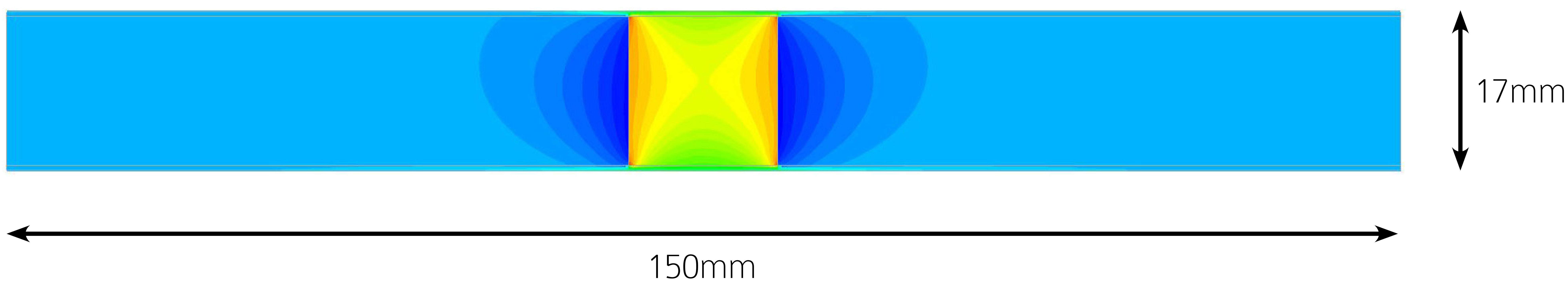
RELATION BETWEEN SIZE OF REPEATING PATTERN AND U-VALUE



Rectangle	A	B	C	D	E
Width (mm)	40	80	160	320	640
Height (mm)	132	34	26	23	22
U (W/m²K)	2.818	2.818	2.815	2.813	2.811

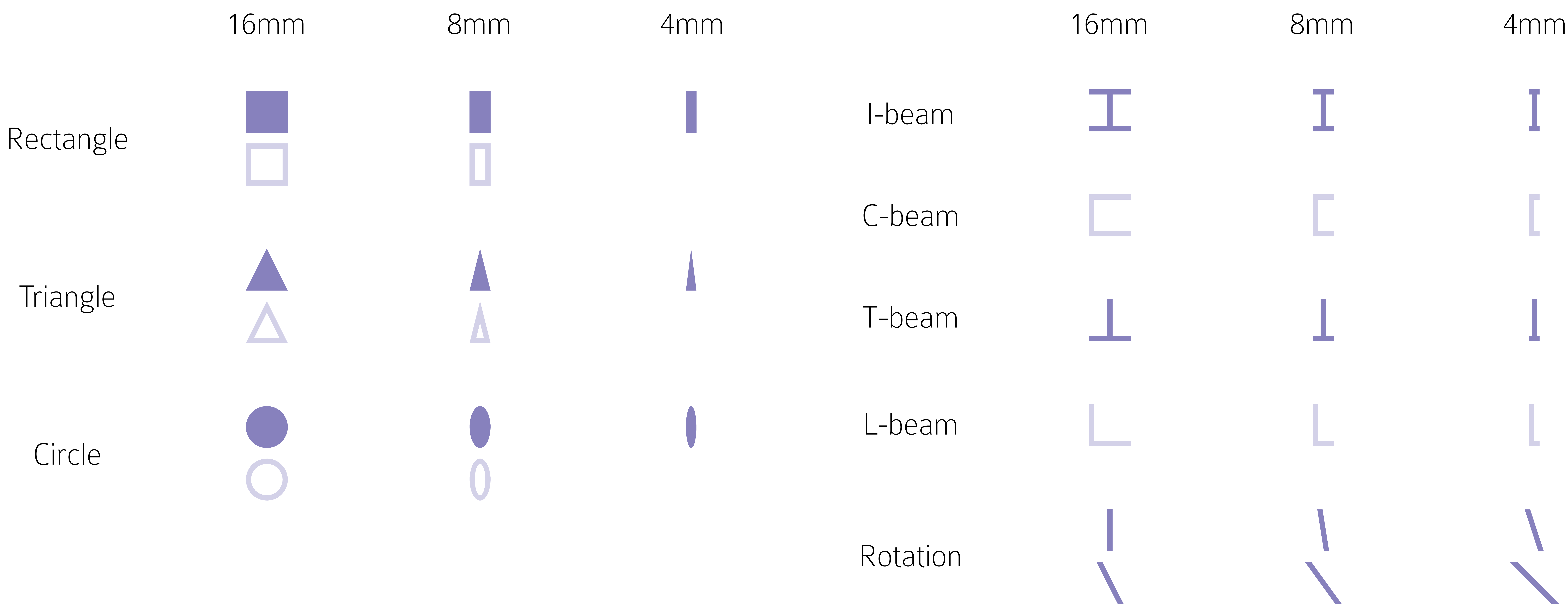
RELATION BETWEEN ELONGATION OF RECTANGLE AND U-VALUE

$$\psi = (q_2 * l_2 - q_1 * l_1) / \Delta T$$

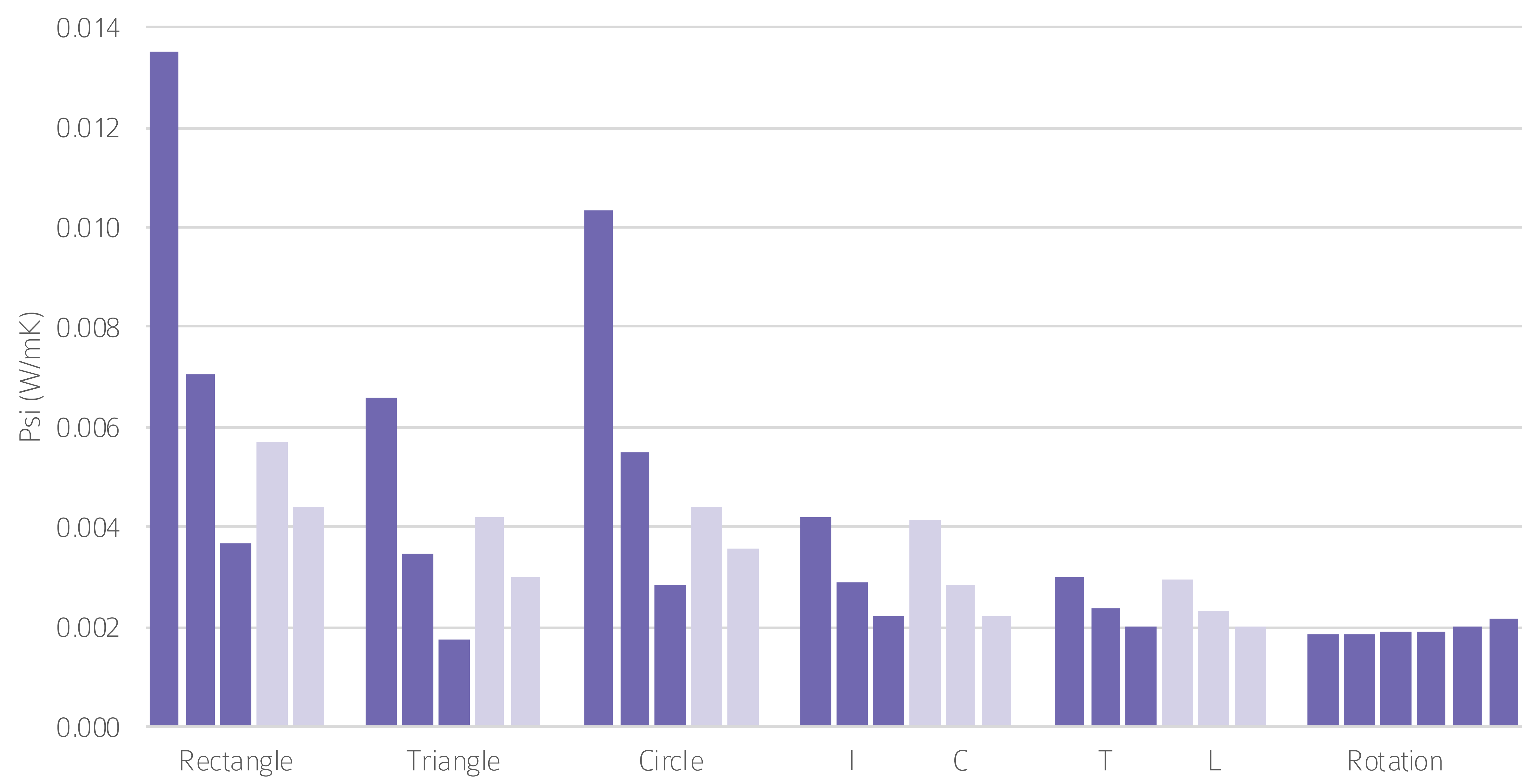


THERMAL BRIDGE

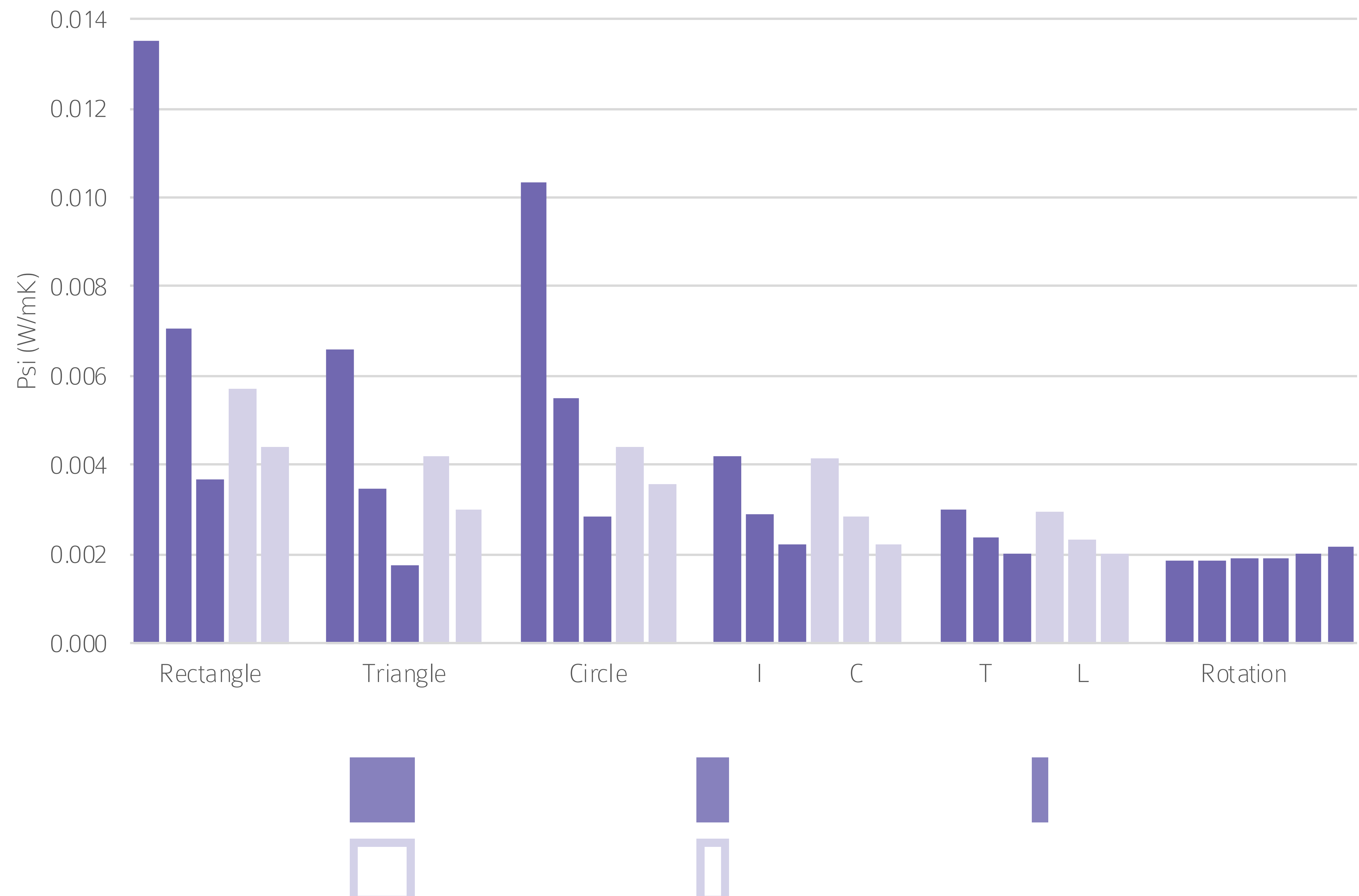
boundary resistance 0.04 and 0.13 m^2K/W temperatures 0^oC and 20^oC



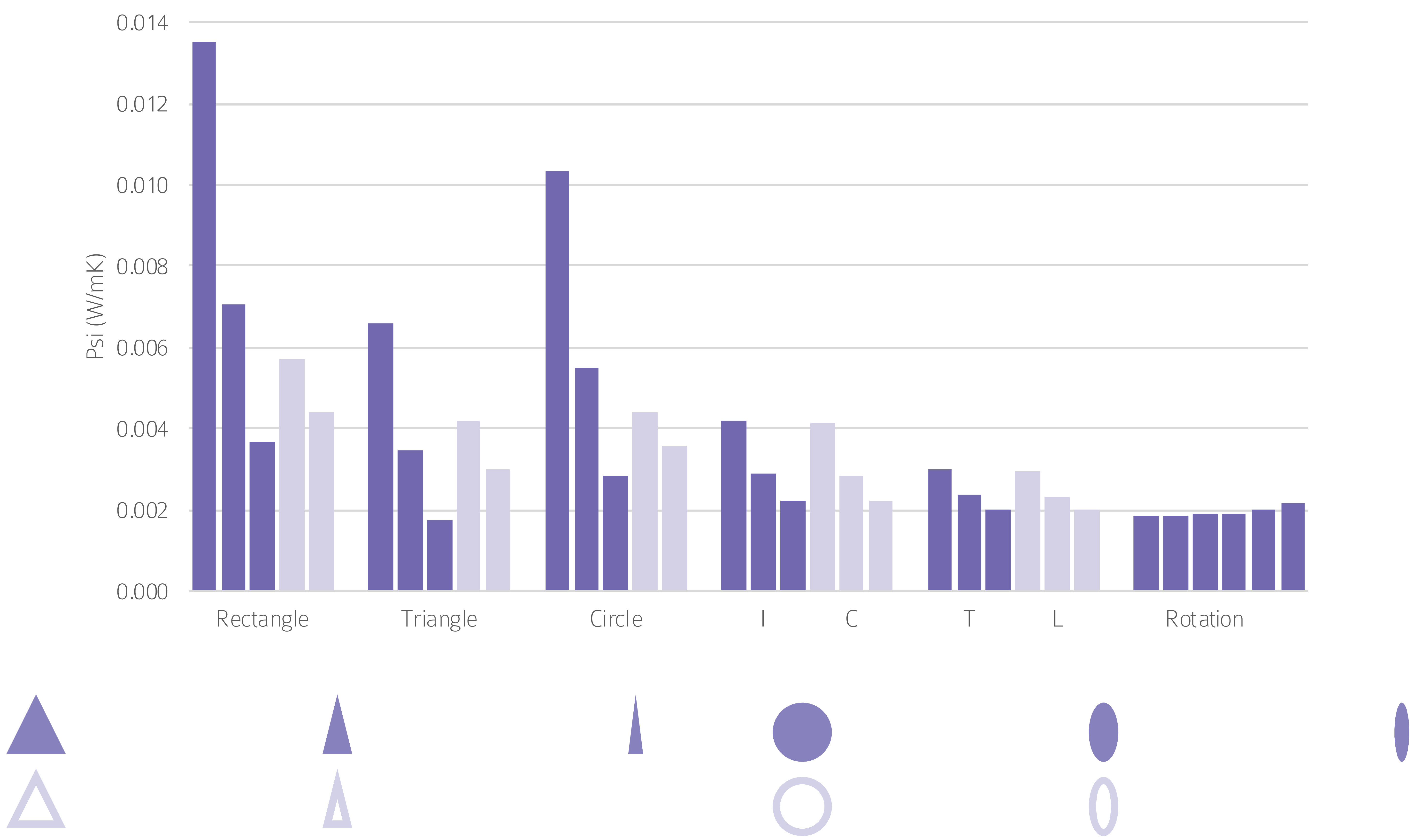
SELECTION OF SPACERS



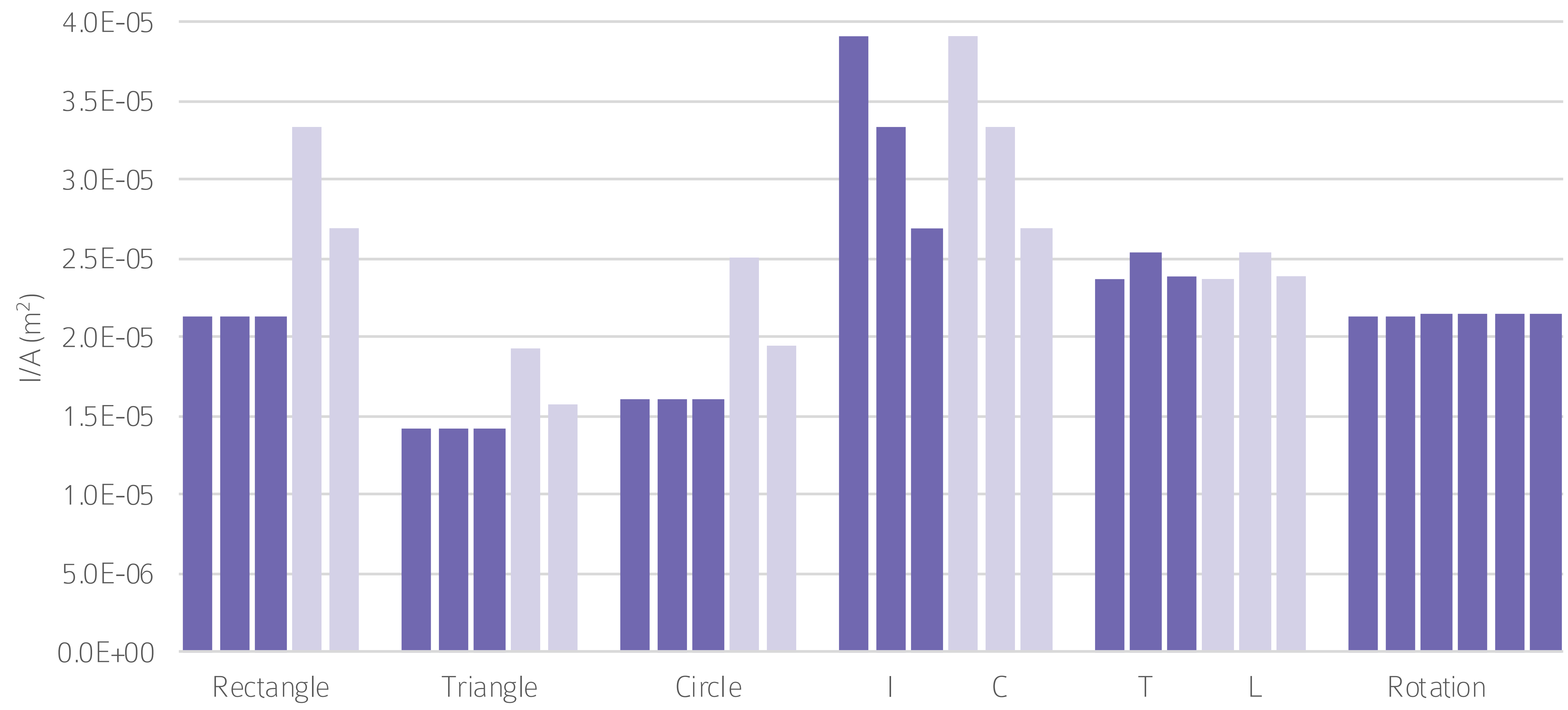
LINEAR THERMAL TRANSMITTANCE



LINEAR THERMAL TRANSMITTANCE



LINEAR THERMAL TRANSMITTANCE



SECOND MOMENT OF AREA / AREA

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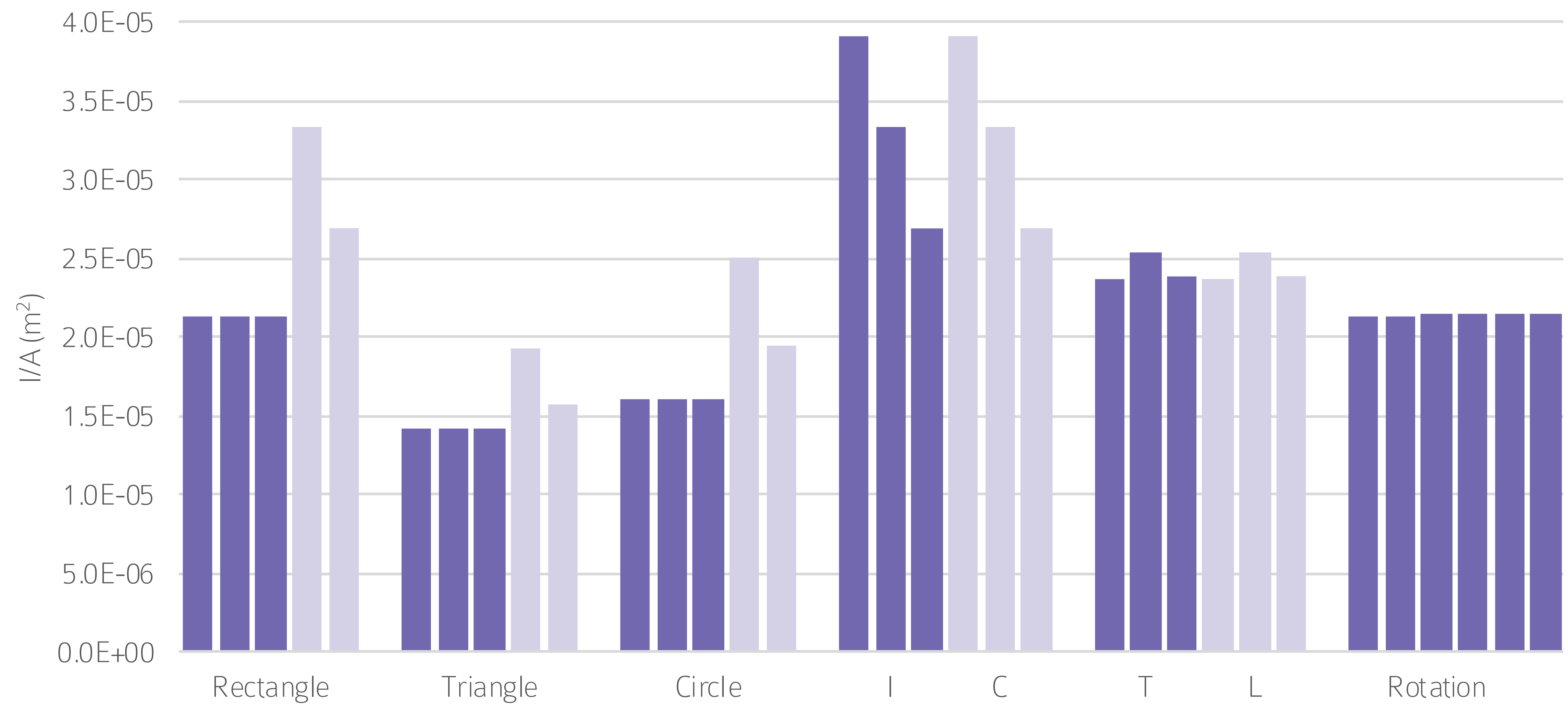

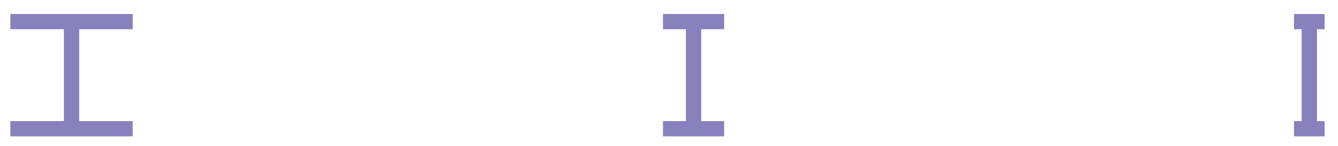

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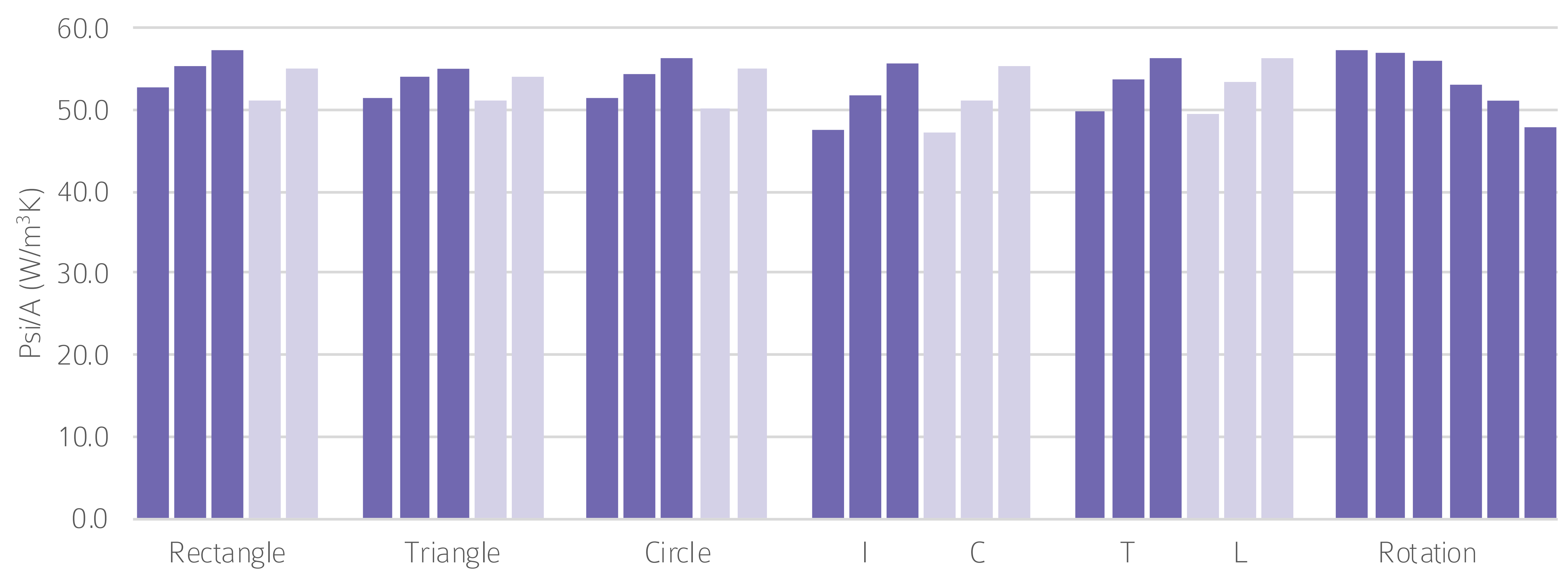
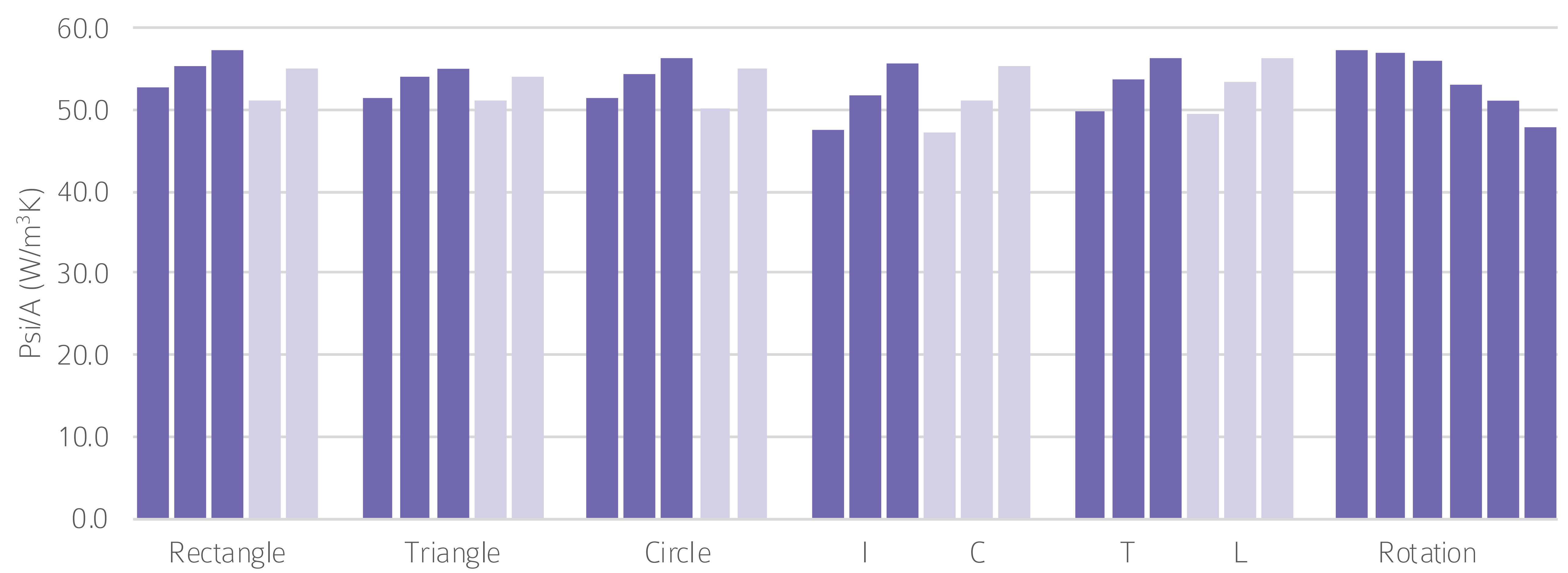


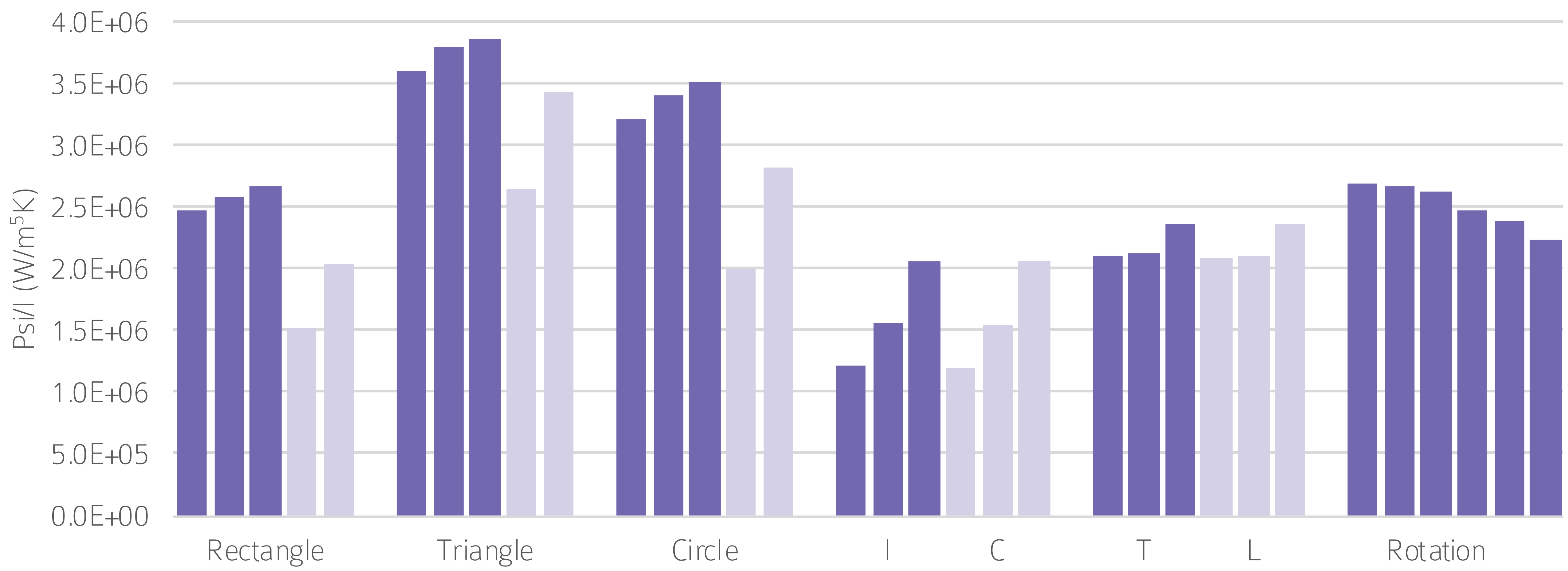
LINEAR THERMAL TRANSMITTANCE / AREA

Research

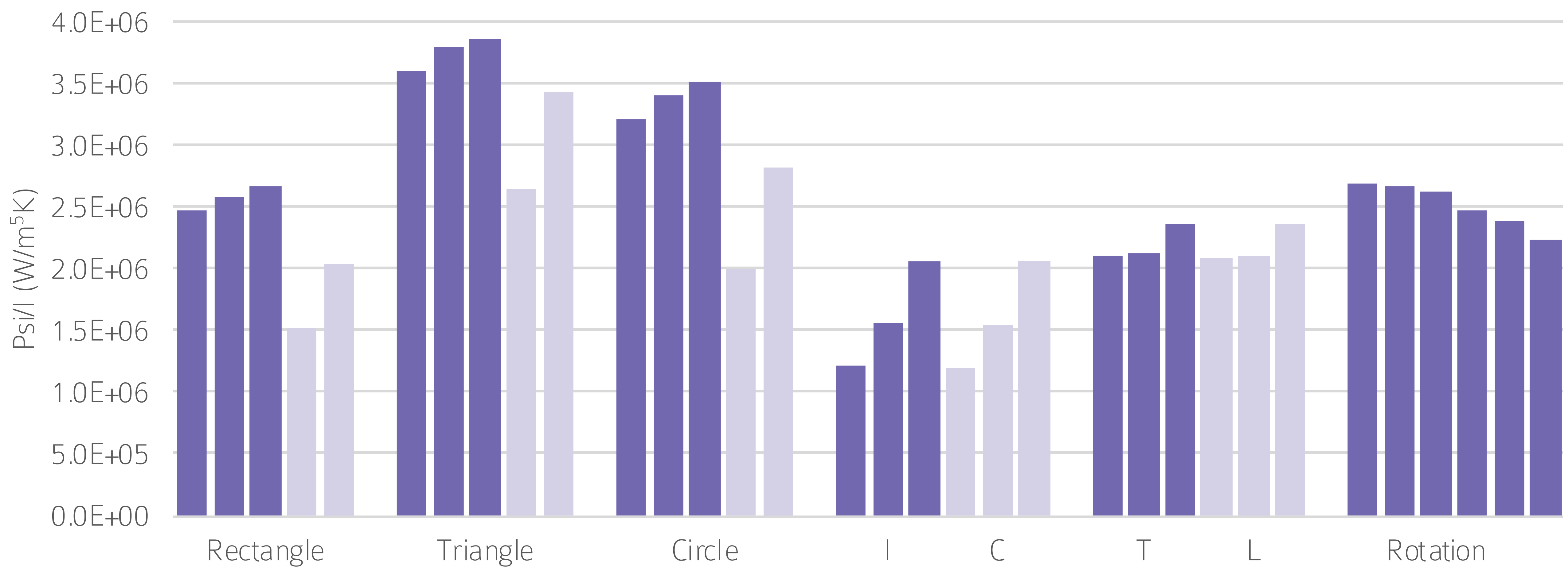


LINEAR THERMAL TRANSMITTANCE / AREA

Research

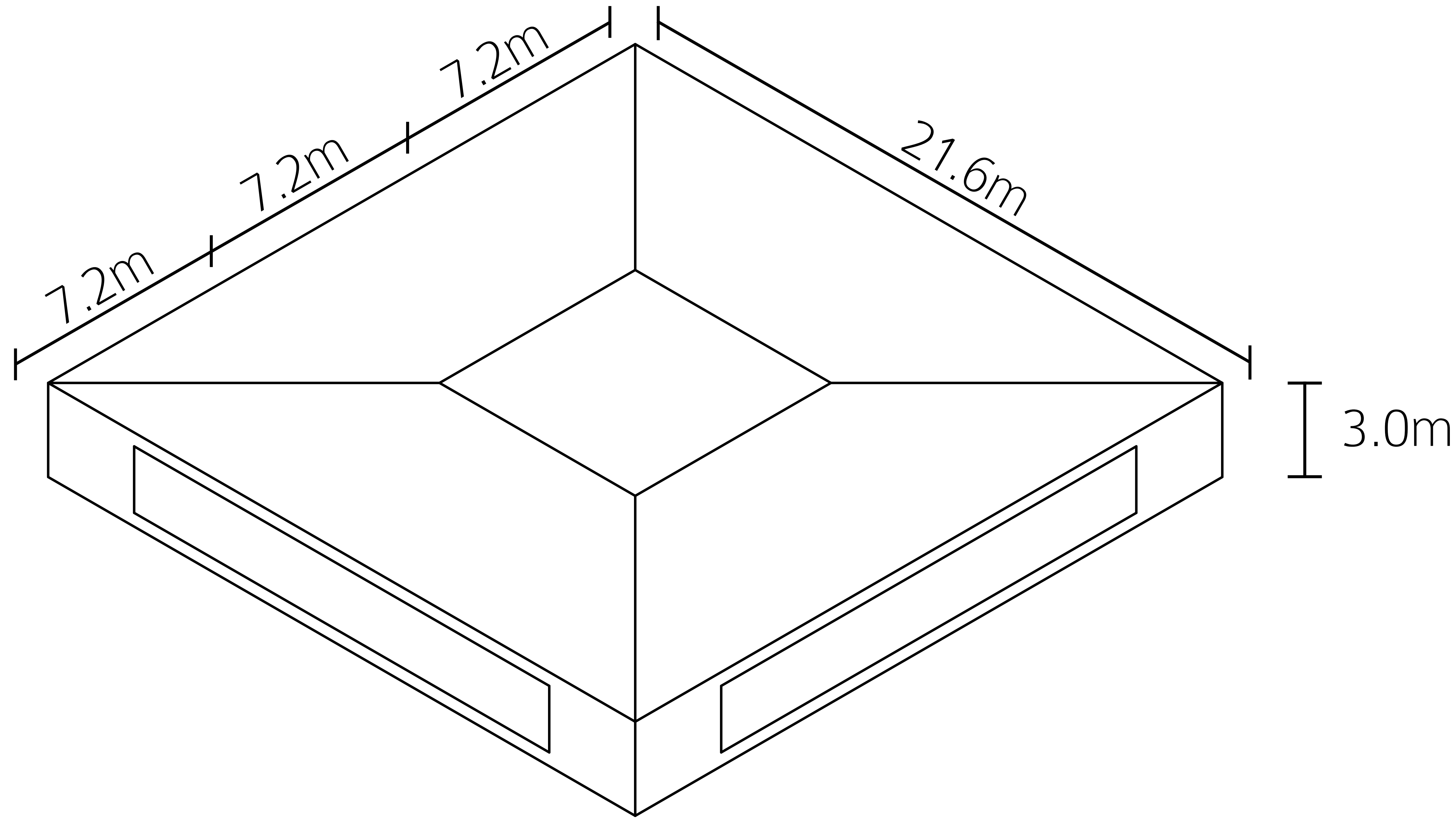


LINEAR THERMAL TRANSMITTANCE / SECOND MOMENT OF AREA



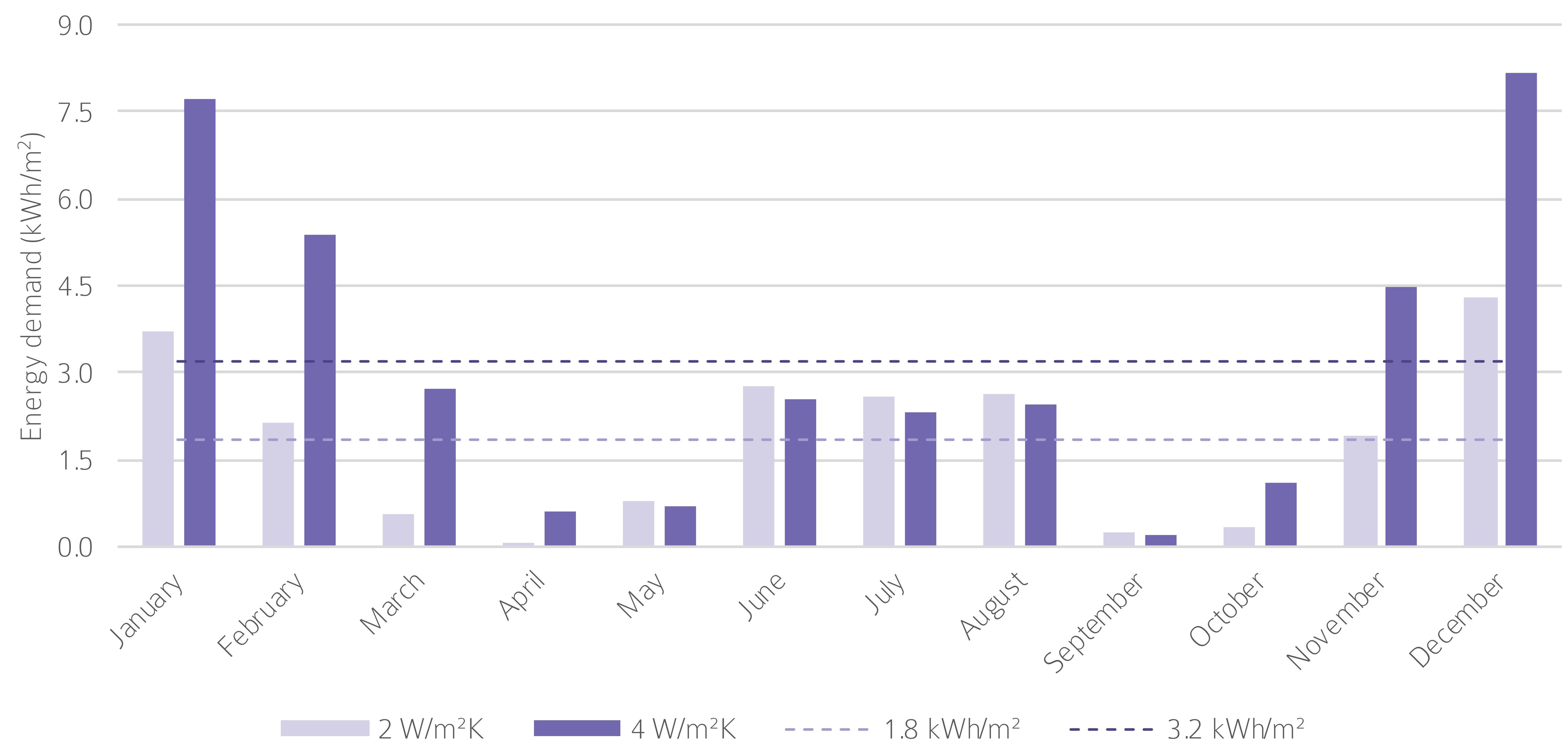
LINEAR THERMAL TRANSMITTANCE / SECOND MOMENT OF AREA

EVALUATION



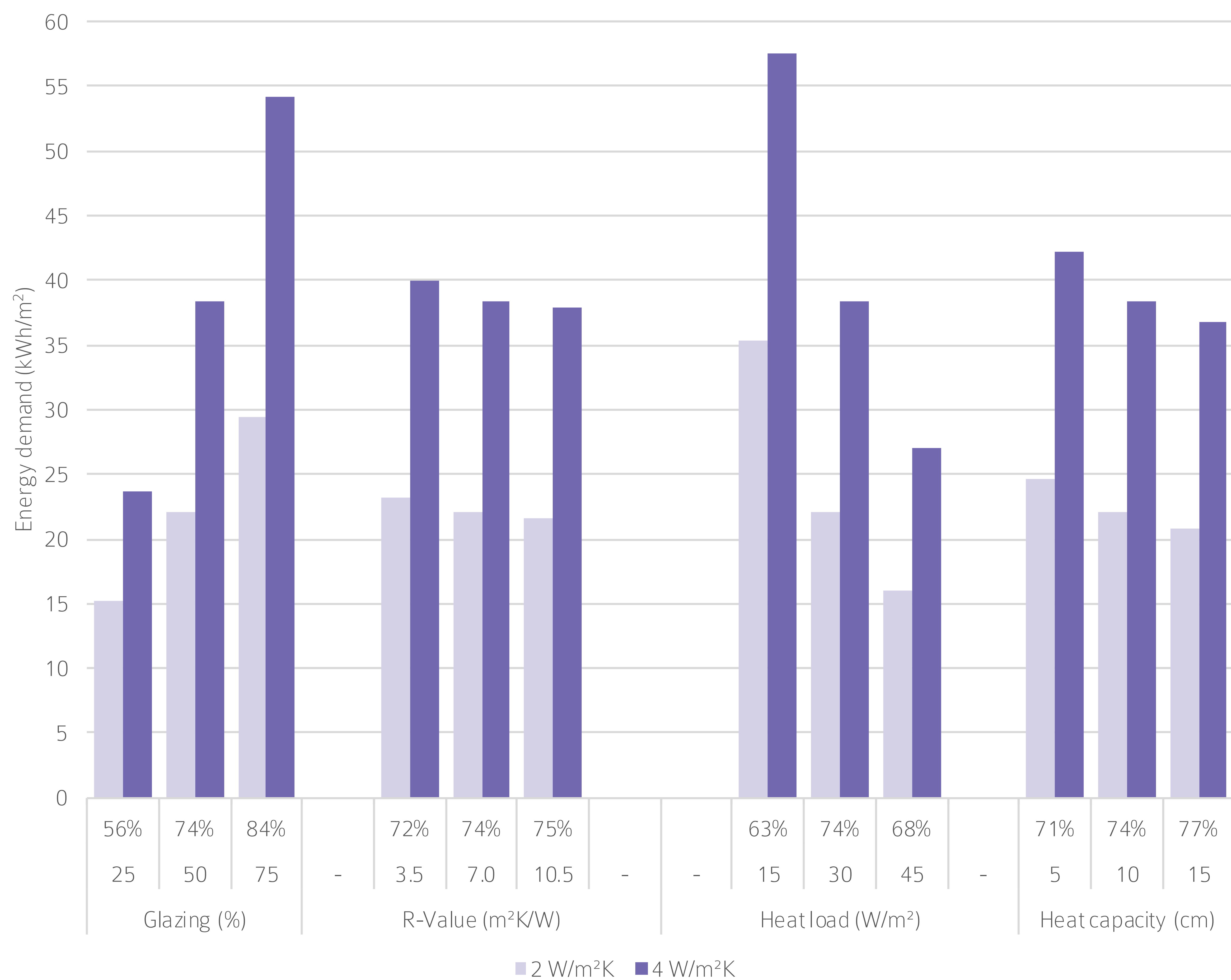
ENERGY MODEL

Glazing // R-Value // Heat load // Heat capacity



MONTHLY ENERGY DEMAND

Glazing 50% // R-value 7.0 m²K/W // Heat capacity 10cm concrete // Heat load 30W/m²



ANNUAL ENERGY DEMAND

IGU
2.756 W/m²K

TGS
2.811 W/m²K

	Insulating Glass Unit	Thin Glass Sandwich
Glass total thickness (mm)	12	1
Glass type density (kg/m³)	2500	2430
Glass type embodied energy (MJ/kg)	10.6	13.9
Window embodied energy (MJ/m²)	318.0	33.8

EMBODIED ENERGY GLASS

per square meter window

IGU
2.756 W/m²K

TGS
2.811 W/m²K

PLA (%)	8.90
PLA (m^3/m^2)	1.14e-3
Embodied energy PLA (MJ/m^2)	98.99
Embodied energy extruding (MJ/m^2)	10.54
Embodied energy sandwich (MJ/m^2)	143.3

Embodied energy IGU (MJ/m^2) 318.0

EMBODIED ENERGY INCLUDING PLA

per square meter window

IGU
2.756 W/m²K

TGS
2.811 W/m²K

Glazing percentage (%)	25	50	75
Glazing area (m^2)	64.8	129.6	194.4
Δ Embodied energy (MJ/m^2)	24.25	48.52	72.78

SAVED EMBODIED ENERGY

per square meter floor

	IGU 1.100 W/m²K	TGS 2.811 W/m²K	
Glazing percentage (%)	25	50	75
Energy demand IGU (kWh/m^2/year)	19.06	26.88	35.85
Energy demand TGS (kWh/m^2/year)	27.59	44.48	62.95
Δ Energy demand (kWh/m^2/year)	8.53	17.60	27.11
Δ Energy demand (MJ/m^2/year)	30.72	63.37	97.58

OPERATIONAL ENERGY

per square meter floor

	IGU 1.100 W/m²K	**TGS** 2.811 W/m²K	
Glazing percentage (%)	25	50	75
Energy demand IGU (kWh/m²/year)	19.06	26.88	35.85
Energy demand TGS (kWh/m²/year)	27.59	44.48	62.95
Δ Energy demand (kWh/m²/year)	8.53	17.60	27.11
Δ Energy demand (MJ/m²/year)	30.72	63.37	97.58

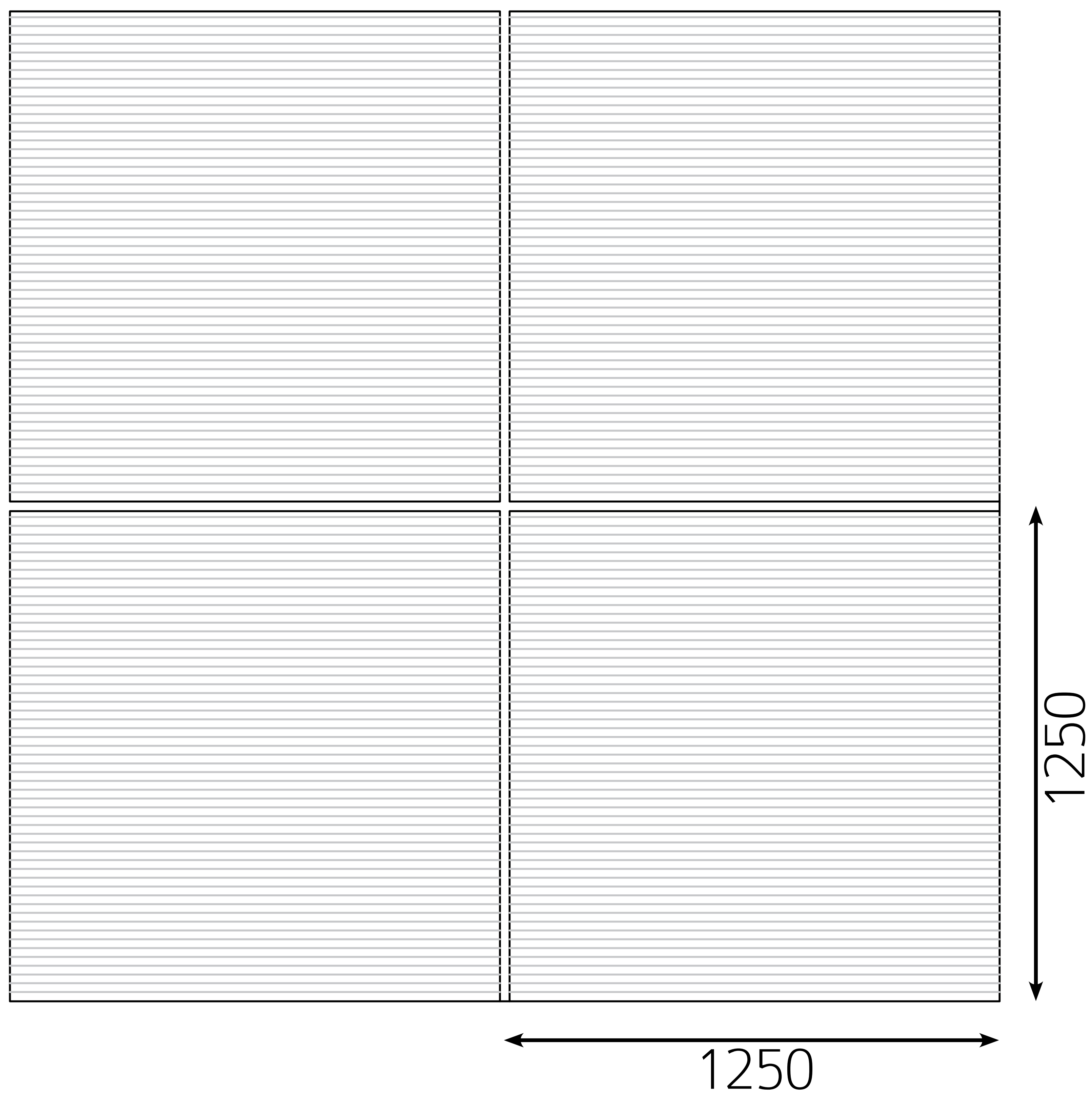
Δ Embodied energy (MJ/m²)	24.25	48.52	72.78

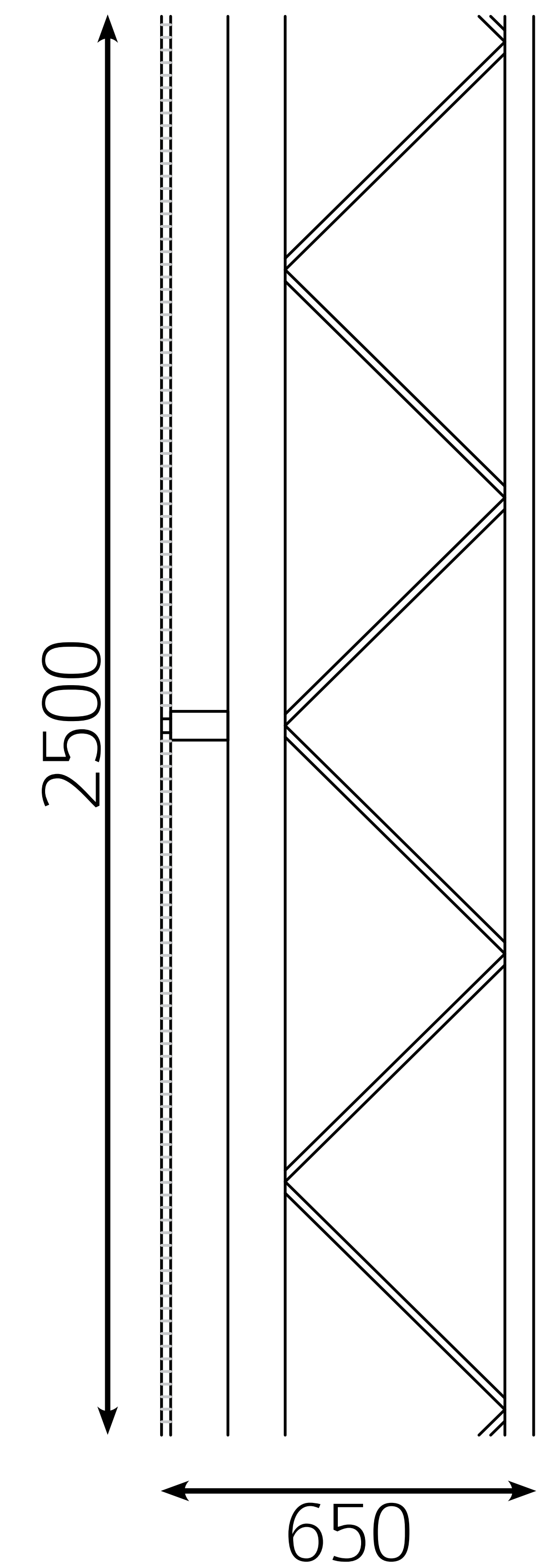
OPERATIONAL ENERGY VERSUS EMBODIED ENERGY

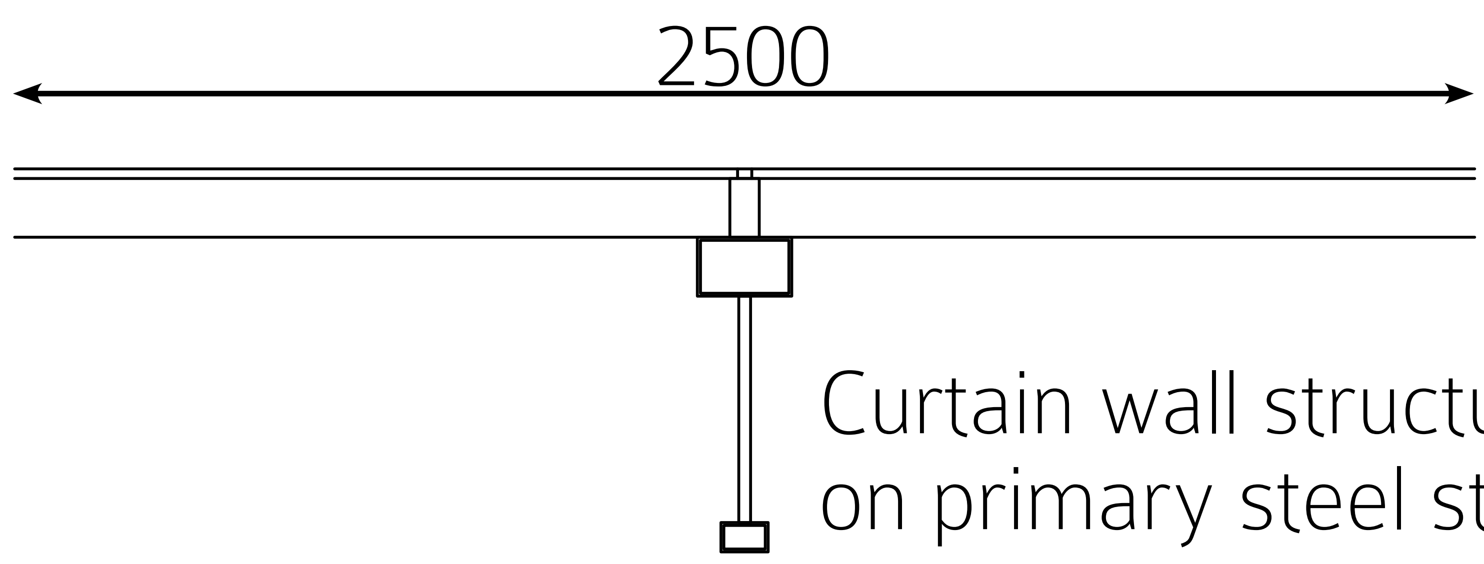
per square meter floor

DIGITAL DESIGN

ORANGE HALL BK-CITY

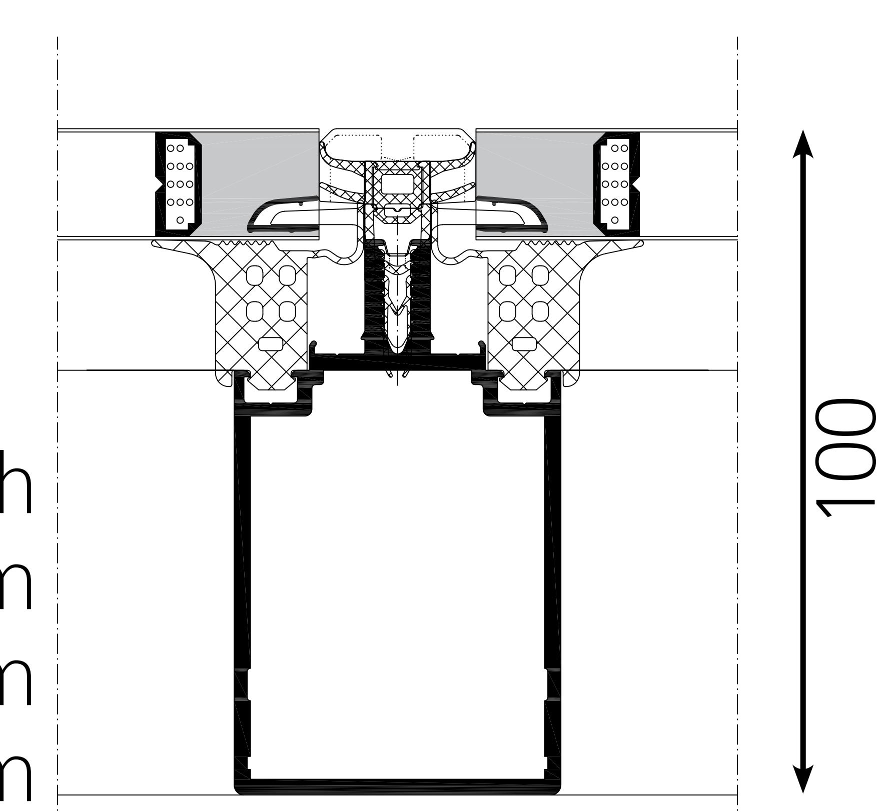






Curtain wall structure mounted
on primary steel structure

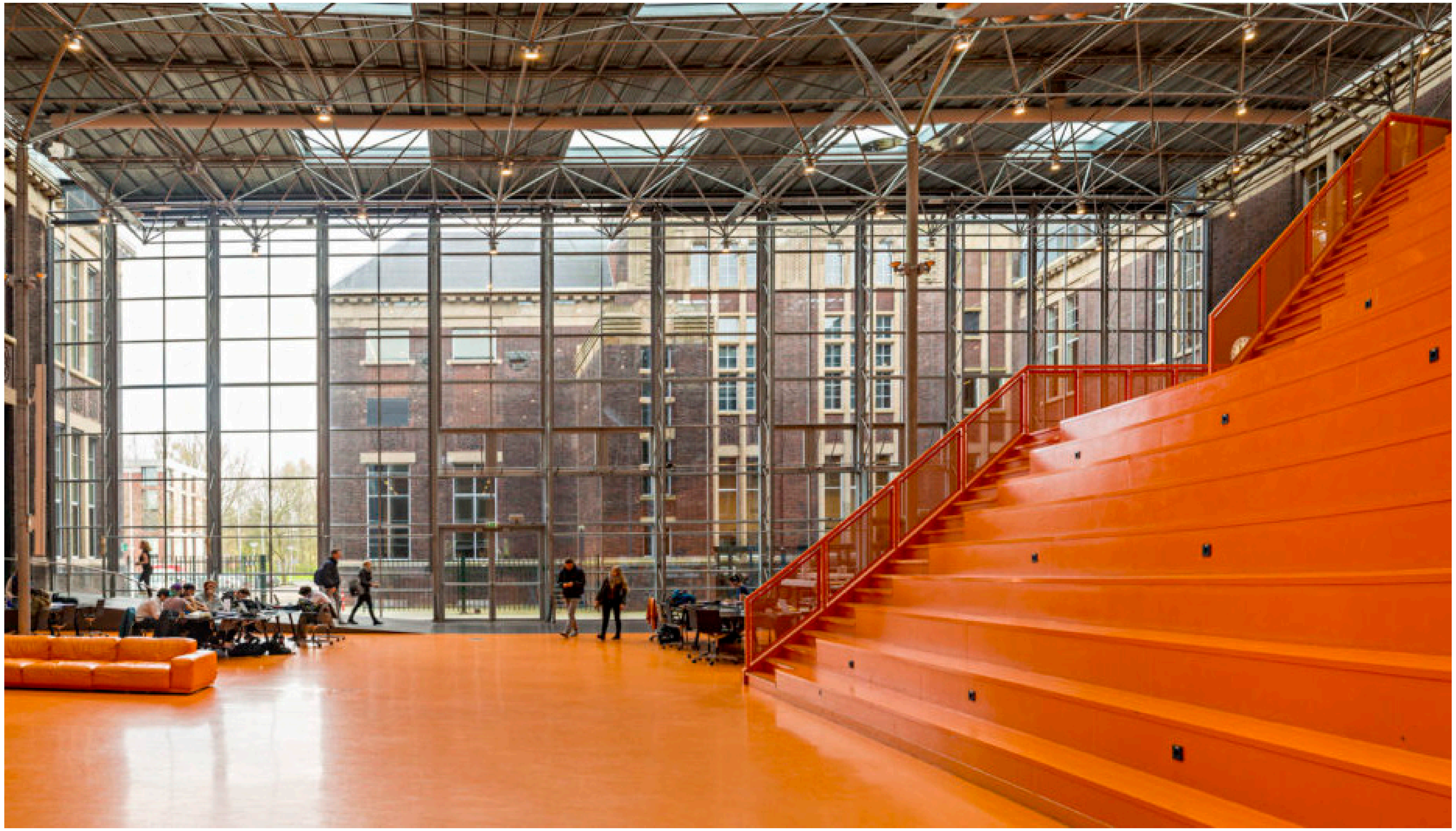
Curtain wall structure



Thin glass sandwich
Aluminosilicate glass 0.5mm
Cavity 16mm filled with PLA ribs 2mm
Aluminosilicate glass 0.5mm

FAÇADE FRAGMENT AND DETAIL

PLA ribs vertical spacing 22mm



CONCLUSIONS

TO WHAT EXTENT CAN A THIN GLASS SANDWICH COUNTERBALANCE ITS DECREASED THERMAL PERFORMANCE BY REDUCING EMBODIED ENERGY DURING PRODUCTION?

Embodied energy is lower compared to IGU

Embodied energy is lower compared to IGU

U-value is higher compared to IGU

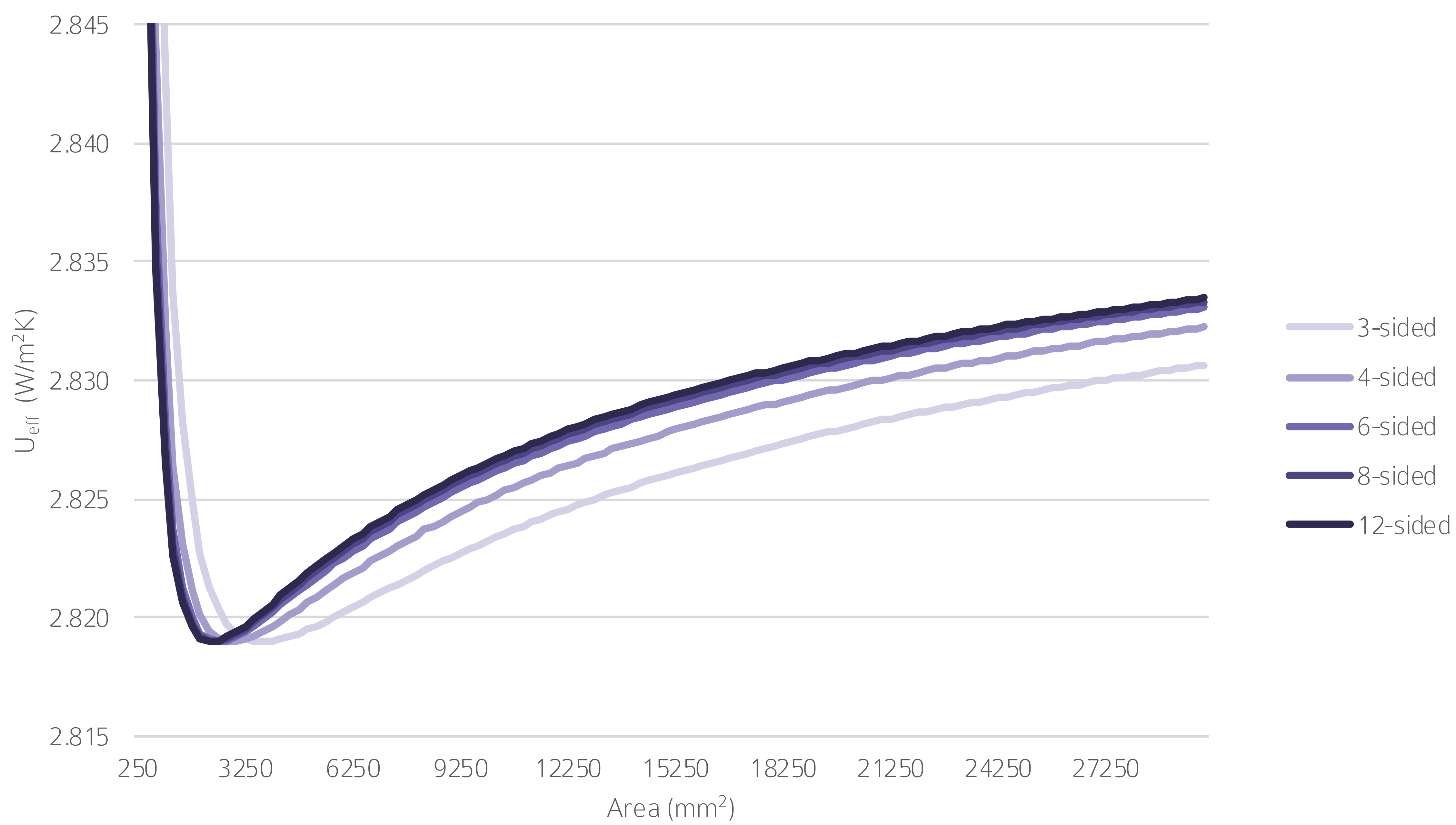
Embodied energy is lower compared to IGU

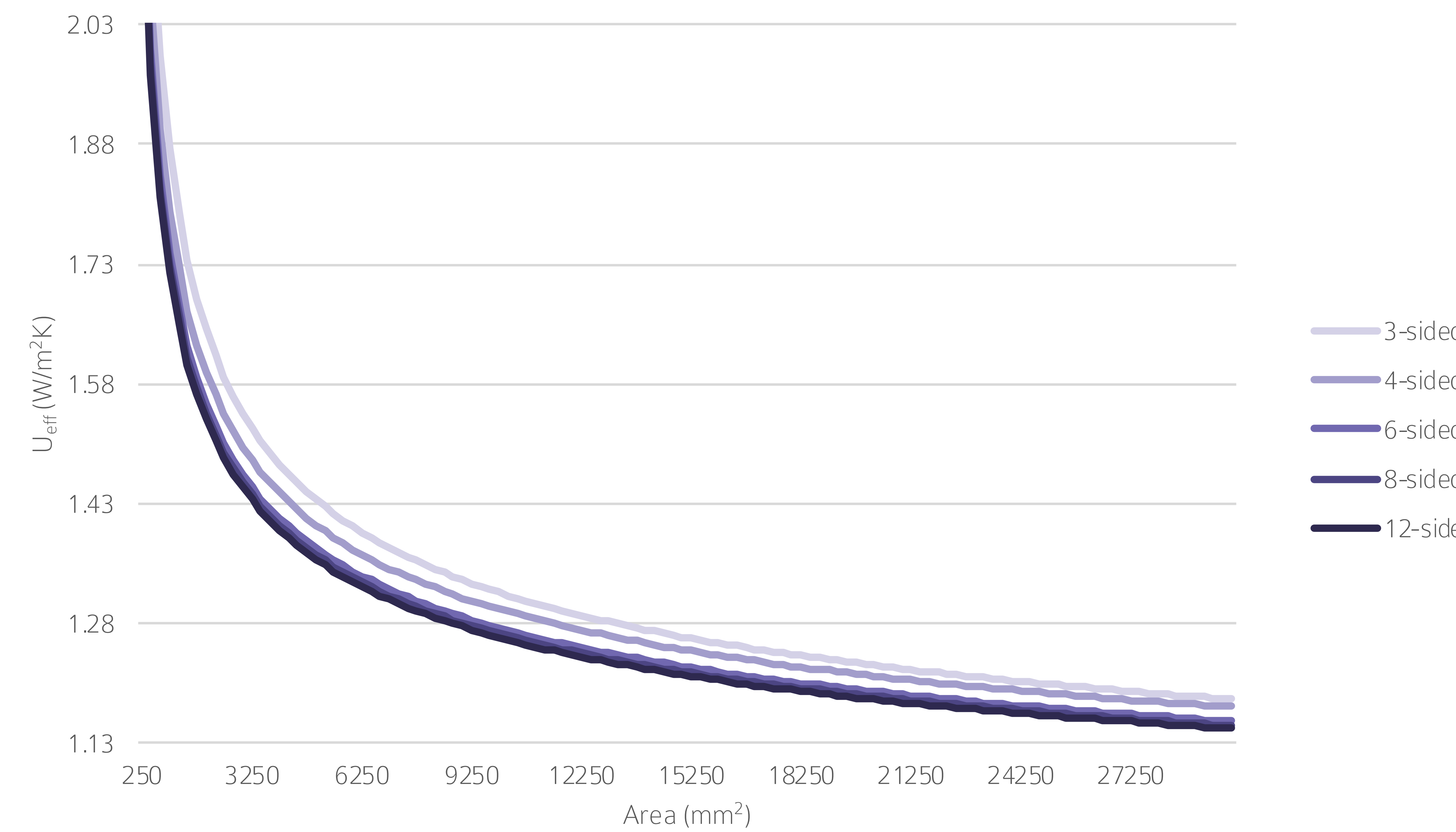
U-value is higher compared to IGU

The thin glass sandwich is lighter compared to IGU

RECOMMENDATIONS

Use of coatings and noble gasses





AIR-FILLED, UNCOATED VERSUS ARGON-FILLED, COATED

Use of coatings and noble gasses

Geometric distribution in elevation for spacers

Use of coatings and noble gasses

Geometric distribution in elevation for spacers

Acoustics when applying in the built environment

THIN GLASS SANDWICH

a thermal study of regular and semiregular tessellations used in bi-directional sandwiches

MARC A.J. DEN HEIJER