$$\Delta q = (\sum \psi \cdot L) \cdot HDH \tag{1}$$

here, Δq is the additional heat transfer caused by the thermal bridge, Ψ and L are the linear thermal transmittance and length of the thermal bridge respectively, HDH represents the heating degree hours.

Derived from the website of EnergyPlus (Anon.), the heating degree days in Shanghai is 1585KD with the baseline of 18℃, and the heating degree hours is 38KKh, so HDH is 38KKh in Shanghai.

The calculation of the Ψ-value is laborious. The theory of heat loss is based on the steady state, 1-dimensional heat transfer, but heat flows at the positions of thermal bridges in the 2- or 3-dimensional form. There is one method introduced by Müller (2009), and the calculation process is based on the numerical computation. Computer simulation makes the calculation easier and more intuitive for architects, THERM is one analysis program for 2-dimensional heat transfer, based on the Finite Element Method (FEM), which models the complicated geometries with meshes of small cells. According to Müller (2009), THERM is one kind of the programs those are able to calculate the heat flow at the positions of thermal bridges. With the help of the program, the thermal transmittance of the thermal bridge and its width are expressed by equation (2).

$$\psi = (U_{TB} - U_0) \cdot w \tag{2}$$

where U_{TB} and U_0 are the thermal transmittance of the thermal bridge and the wall portion without impact of thermal bridge, w is the width of the thermal bridge on the surface.

Consequently, the rate of the heat loss due to the thermal bridges can be calculated with the equation (3):

$$\Delta U = \sum \psi \cdot L / \sum A \tag{3}$$

here, ΔU is the rate of additional thermal transmittance, A is the area of the envelope surface.

The calculations of solar reduction by the balconies are complicated as well, because the shadow created by the sun path changes transiently. By the Chinese standard J134-2010, a simplified method evaluating the shading coefficient (SC) resulted from the fixed shadings is introduced.

$$SC = ax^2 + bx + 1 \quad (4)$$

$$x = d / h \quad (5)$$

where x is the characteristic value of shading depending on the depth of overhang, d, and the distance between the bottoms of the overhang and the window, h. The a and b are the two fitting coefficients referring to the given table.

Table 1. *Fitting coefficients a, b of the south direction*

	Fitting coefficient	South
Horizontal shading	a	0.5
	b	-0.8

Assuming the façade facing south, and thus, the decreased heat load through the glazing in summer is proposed in following equation.

$$r = (1 - SC) \cdot 100\% \quad (6)$$

$$q_r = G_s \cdot r \cdot g \cdot \sum A_g \quad (7)$$

r is the reduction factor, q_r represents the reduced solar radiation, G_s is the global radiation on the south façade, g value is solar heat gain efficiency of glazing, the A_g is the areas of the glazing.

In terms of the climate data of Passive House planning tool, PHPP (Passive House Planning Package), global radiation in Shanghai is shown in the table. Considering the cooling season from May to October, then the G_s in Shanghai is 401 KWh/(m^2·a).

Table 2. *Global radiation of south façade in Shanghai (KWh/(m^2·a)*

Month	1	2	3	4	5	6	7	8	9	10	11	12
South radiation	89	62	68	61	59	53	64	73	68	84	85	92

The energy balance can be expressed by the equation (8).

$$k = \Delta q / q_r \quad (8)$$

k describes the energy efficiency of the balcony, if it is smaller than 1, it means that the extra heat loss in summer is covered by the reduced cooling demand in summer.

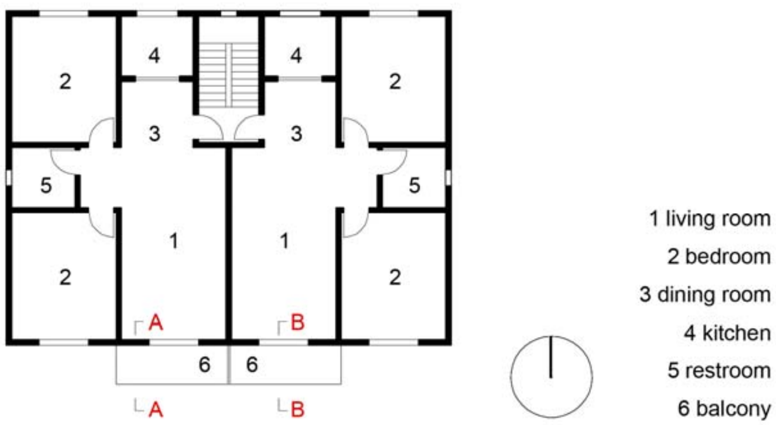

Figure 1. *The layout of the apartment*

The research is based on case study of one prototype of the apartment building. The layout is shown in the figure 1. There are balconies on the 2nd, 3rd and 4th floors, and the two windows in the middle of the 1st, 2nd and 3rd floors are under the shadows. The wall is filled with concrete block and insulated with 50mm thick EPS boards, and U-value of the wall is 0.56W/(m^2·K). Two kinds of the thermal bridges exist at the balcony positions, one with doors and the other without. The windows are composed of double clear glazing units (3+6(air)+3) and fiberglass frames, and average U-value is considered as 3.14 W/(m^2·K). The apartment has four floors and the area of the envelope is 833.8m^2. The composition of the envelope is shown in the table 3.

Table 3. *Envelope composition*

	Area (m^2)	
Roof	197.6	U = 0.67 W/(m^2·K)
Wall	535.4	U = 0.56 W/(m^2·K)
Windows	100.8	U = 3.14 W/(m^2·K)
Glazing under balcony (top floor exclusively)	21.1	g = 0.72

At the positions of the balconies, two kinds of vertical sections exist, one with door and the other without. On the façade of one floor, the length of thermal bridge A is 4.6m and that of B is 3.6m. Figure 2 and figure 3 depict thermal bridge A of the section A-A and thermal bridge B of section B-B, and their insulation conditions.

Table 4. *Lengths of the two kinds of thermal bridges*

	Length (m)
Thermal bridge A	13.8
Thermal bridge B	10.8

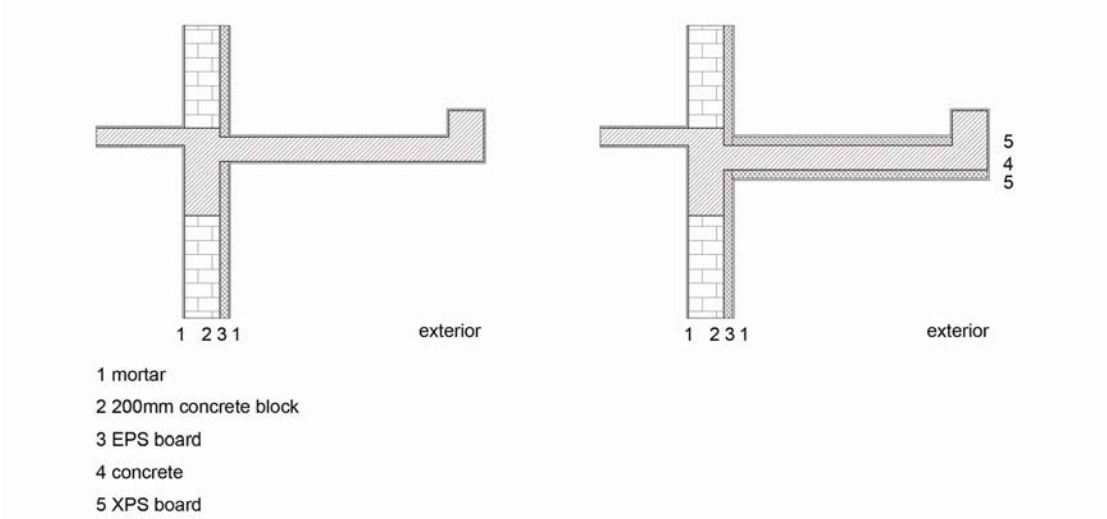

Figure 2. *The vertical section A-A. Right: balcony insulation in Shanghai*

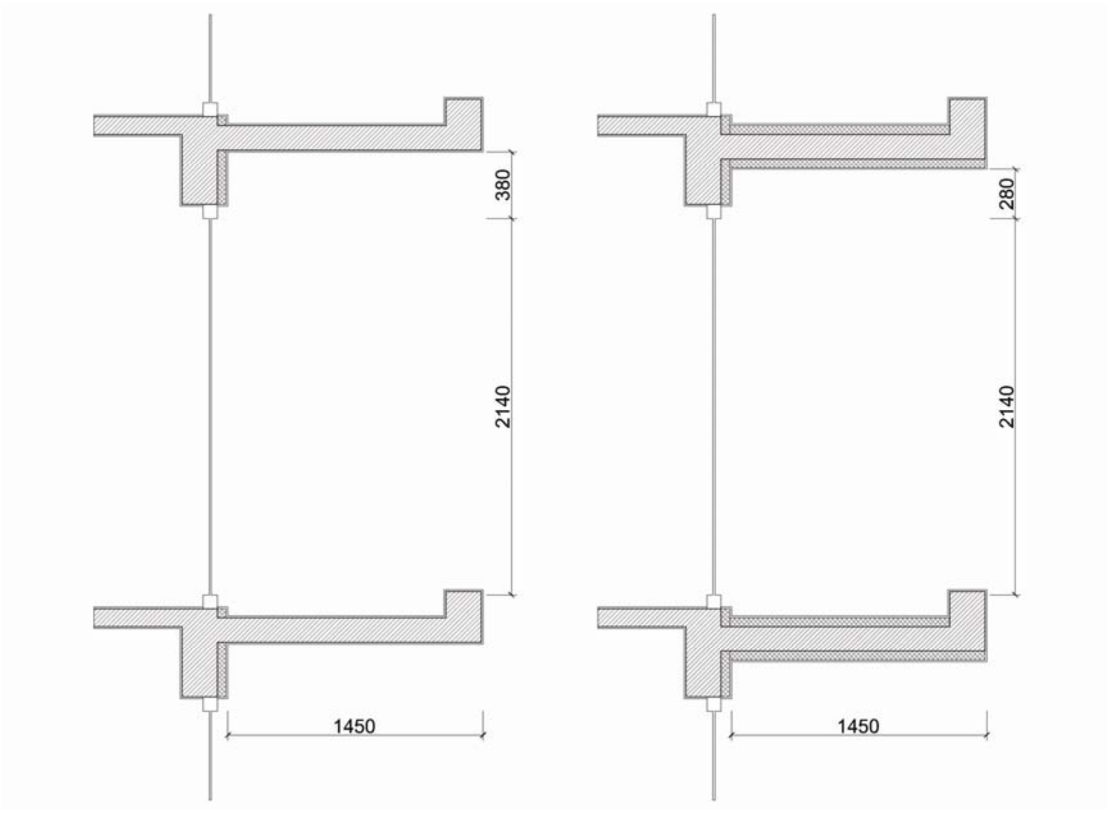

Figure 3. *The vertical section B-B. Right: balcony insulation in Shanghai*

RESEARCH METHODS

It is discussed with two different cases, the balcony not insulated is the case I, and case II is the balcony with insulation. Provided the internal and external air temperatures are 18℃ and -5℃ respectively, the two kinds of thermal bridges with different sections are calculated separately.

1.1. r-value of case I

As is depicted in the figure 3, the depth, d-value and distance between the glazing and the balcony bottoms, h-value are 1.45m and 2.52m respectively. According to equation (4), (5), (6) and table 1, the reduction factor r is 29.5%. Therefore, the reduced solar gain in summer is 85.1 KWh/(m2·a) and the decreased amount of solar energy passing though the glazing, q_r is 1792.2KWh every year.

1.2. Ψ-value of case I

Computed by the program THERM, the U_{TB} is 0.88 W/(m^2·K) and its width on the façade is 2.16m. By the equation (2) the linear thermal transmittance of the section A-A is 0.69W/(m·K), and thus, in terms of the equation (1), the additional heat loss is 361.8KWh.

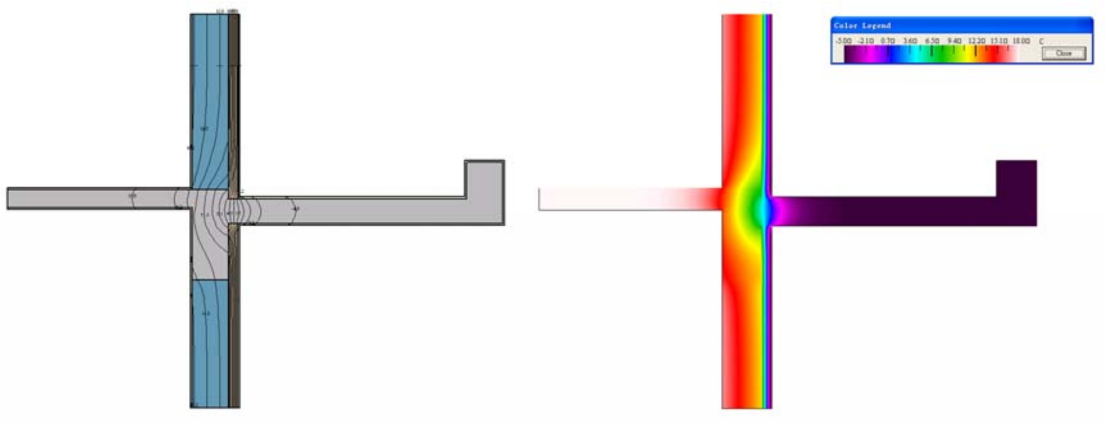

Figure 4. *The results figures with isotherms and color of section A-A*

As for thermal bridge B, the Ψ-value is 0.97W/(m·K), which leads to heat loss of 398.1 KWh. Therefore, the total heat loss resulted from the balconies is 759.9KWh.

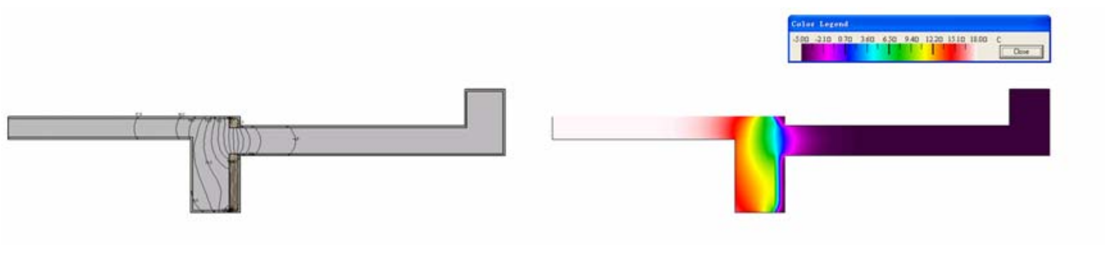

Figure 5.*The results figures with isotherms and color of section B-B*

Thereby, the contribution rate of extra heat loss by the balconies can be calculated with equation (3), and the result is 0.02 W/(m^2·K).

2.1. r-value of case II

As for case II, the depth, d-value and h-value are 1.45m and 2.42m, so the reduction factor r-value is 30.0% in terms of equations and table 1. Therefore, the reduced solar gain in summer is 86.6 KWh/(m^2·a) and the decreased amount of solar energy passing though the glazing, q_r is 1822.9KWh every year.

2.2. Ψ-value of case II

After the balconies are insulated with 50mm thick XPS boards, the U_{TB}-value of the thermal bridge A on the façade is reduced to 0.69W/(m^2·K), and the width is 2.26m. According to equation (2), the Ψ-value of thermal bridge A of case II is 0.29 W/(m·K). Likewise, that of the section B-B is reduced to 0.61 W/(m·K). The two thermal bridges result in the additional heat loss of 152.1KWh and 250.3KWh respectively, in total 402.4KWh, after calculated with equation (1).

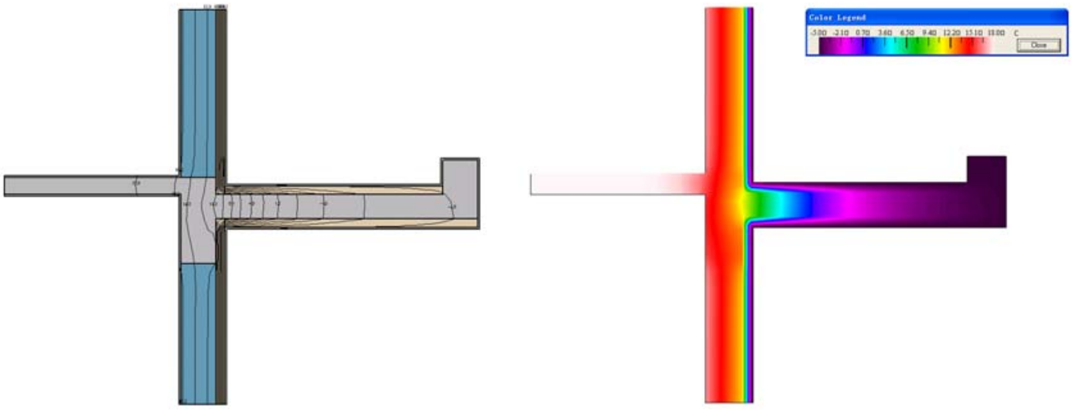

Figure 6.*The results figures with isotherms and color of section A-A*

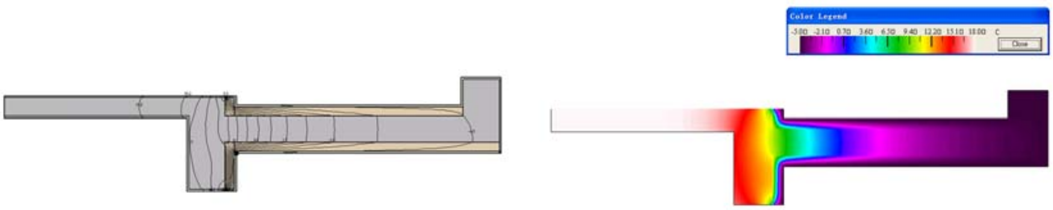

Figure 7.*The results figures with isotherms and color of section B-B*

For case II, the rate of additional heat loss from the balconies is 0.01 W/(m^2·K), as is calculated with equation (3).

RESULTS

Finally, according to equation (8), k_I of the case I is 2.36, k_{II} of the case II is 4.53 that is much better. The extra contributions of heat loss by the balconies of the two cases are 0.02 W/(m^2·K) and 0.01 W/(m^2·K) respectively, which proves that the insulation measure so far works indeed.

DISCUSSION

Therefore, the decreased solar gain in cooling season is much more than the additional heat loss due to the thermal bridges, no matter the balconies are insulated or not. That is to say, between the two influencing factors of the building element, the benefit is the overwhelming one.

During the research process, the calculation of the shading coefficient is done with a simplified method, besides, the cooling season is considered from May to October, which may not be in accordance with the way in reality it is. These factors may lead to the inaccuracy. Although glazing is much more shaded in summer by the overhangs than in winter, they reduce the solar gains in winter more or less, eventually the heating demand in heating season may yet increase even if the thermal bridges are well dealt with. Therefore, the calculation method of exact reduced amount of solar gain during both winter and summer as a result of the shading needs to be developed, rather than the simplified method.

CONCLUSION AND IMPLICATIONS

The overhang is one of the efficient passive cooling measures, because the solar altitude changes from the summer time to the winter time. However, the feature of thermal bridges is one drawback. By the discussion of the research, it is the cooling demand reduction that is much more than the increased heating demand due to thermal bridges.

Even though the Ψ-values of the thermal bridges are reduced a lot after the balconies are insulated, the values are still far over 0.01 W/(m·K), which is a recommended value of Passive House. The thermal break products used in Germany are the specialized in dealing with the thermal performance of the overhang building parts, and they can meet the requirement of the Passive House. Due to some reasons, they are not allowed to be used in China yet, if they are going to be permitted in the future, the joints of thermal bridges can be solved even better.

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