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A Design Chart to Determine the Conductive Heat Transfer Across an Opaque Building Envelope Cross-Section

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Abstract

Conductive heat transfer occurs due to the temperature difference between the inside and the outside of a functional space. Previous research has focused on the different variables affecting that conductive heat transfer concentrating on the role of insulating materials in optimizing energy efficiency in buildings as well as assuring thermal comfort of its users. The research problem can be exemplified by the complex calculations required to determine the amount of heat transfer and energy savings that might result from using different cross-sections with varying insulation properties. The paper's main objective is to create a design chart which could be used to determine the conductive heat transfer across any opaque building envelope cross-section. This conductive heat transfer will occur as heat gain in the overheated zone and as heat loss in the underheated zone. The design chart consists of three graphs, each representing one of the variables that affects the conductive heat transfer across an opaque building envelope cross-section: area, overall coefficient of heat transmission (reciprocal of overall thermal resistance), and temperature difference. That would result in expecting the amount of cooling or heating capacity, needed to confront that amount of conductive heat transfer that in turn would ensure thermal comfort of users, especially when applying the requirements of the building energy codes. There is an additional fourth graph that could be used to determine the energy savings achieved when upgrading the overall thermal resistance of the opaque building envelope cross-section.

Keywords: Building Envelopes, Design Charts, Energy Codes, Heat Transfer, Thermal Properties.

1 Introduction

Conduction is the process of transferring heat across opaque materials from a region of higher temperature to a region of lower temperature [1]. Conductive heat transfer occurs through most opaque components of a building envelope. The amount of this conductive heat transfer depends on several variables: area, overall coefficient of heat transmission, and temperature difference. Conductive heat transfer will occur as heat gain in the overheated zone and as heat loss in the underheated zone. Previous research has focused on the different variables affecting that conductive heat transfer concentrating on the role of insulating materials in optimizing energy efficiency in buildings as well as assuring thermal comfort of its users [2]. The research problem can be exemplified by the complex calculations required to determine the amount of heat transfer and energy savings that might result from using different cross-sections with varying insulation properties. Architects usually prefer utilizing simple quick tools rather than involving such calculations, especially those who are not experts in building science. This, in turn, suggested the necessity of simple quick tools for architects, acting as rule-of thumb, such as design charts. The paper's main objective is to create a design chart which could be used to determine the conductive heat transfer across any opaque building envelope cross-section.

Nomenclature

q	Conductive heat transfer	W
A	Area of a building envelope cross-section	m²
l	Length of a building envelope cross-section	m
w	Width of a building envelope cross-section	m
h	Height of a building envelope cross-section	m
U	Coefficient of heat transmission	W/m² °C
R_T	Overall thermal resistance	m² °C/W
Δt	Temperature difference between outside and inside design temperatures	°C
t_o	Outside temperature	°C
t_i	Inside design temperature	°C
t_1	Higher temperature	°C
t_2	Lower temperature	°C

2 Methodology

A series of simplifications, assumptions and calculations were carried out to create the proposed design chart that determines the conductive heat transfer across an opaque building envelope cross-section as follows.

2.1 Simplifications and Assumptions

The design chart is applicable to determine the conductive heat transfer of any opaque building envelope cross-section in any location whether in the overheated zones (in the lower or mid latitudes), or in the underheated zones (in the upper latitudes). Heat gain would occur in the overheated zone where the outside temperature is higher, while heat loss would occur in the underheated zone where the inside design temperature is higher. The design chart is only applicable for opaque building envelope cross-sections with no direct solar exposure, i.e., shaded by any means of shading, e.g., shading devices, overhangs, self-shading masses, etc., because if there was direct solar exposure, its effect must be considered while calculating the temperature difference between the outside and the inside design temperatures.

2.2 Calculations

The design chart consists of three graphs, each representing one of the variables that affects the conductive heat transfer across an opaque building envelope cross-section: area, overall coefficient of heat transmission (reciprocal of overall thermal resistance), and temperature difference. These graphs are derived based on the following formula [3], i.e., Fourier law [4], that calculates the amount of conductive heat transfer (gain or loss) across an opaque building envelope cross-section (vertical or horizontal) $q\ [W]$ [5] as a function of its area of $A\ [m^2]$, its overall coefficient of heat transmission $U\ [W/m^2\ °C]$, and the temperature difference between outside and inside design temperatures $\Delta t\ [°C]$ [6].

$$q = (A \times U) \times \Delta t\ [W]$$

The first graph finds the area of an opaque building envelope cross-section A by multiplying both given dimensions, whether it is horizontal or vertical.

If the opaque building envelope cross-section is horizontal, e.g., a roof, the formula to calculate its area A is

$$A = l \times w\ [m^2]$$

If the opaque building envelope cross-section is vertical, e.g., a wall, the formula to calculate its area A is

$$A = l \times h\ [m^2] \text{ or } A = w \times h\ [m^2]$$

If the area A is already given, its value could be specified directly on the common vertical axis of the first and second graphs, i.e., skipping the use of the first graph.

The second graph indicates the effect of overall coefficient of heat transmission U (reciprocal of overall thermal resistance R_T) [7] across an opaque building envelope cross-section [8], i.e., $U = 1/R_T$ has a value, and it is calculated as follows [9].

$$U = 1/(R_{so} + R_1 + R_2 + \cdots + R_n + R_{si})\ [W/m^2.°C]$$

The third graph indicates the effect of the temperature difference between the outside t_o and the inside t_i design temperatures, i.e., Δt has a value. It should be noted that heat gain occurs when the outside temperature t_o is higher (overheated zone), while heat loss occurs when the inside design temperature t_i is higher (underheated zone). It is calculated by finding the difference between the higher t_1 and lower t_2 temperatures as follows [10].

$$\Delta t = t_1 - t_2\ [°C]$$

The third graph's right portion of the vertical axis could be used to determine the cooling capacity (overheated zone) or the heating capacity (underheated zone) [11]. It is calculated by dividing the obtained conductive heat transfer $q\ [W]$ on the third graph's left portion of the vertical axis by 745.7 to find the cooling or heating capacities in horsepower $q\ [hp]$ [12].

The additional fourth graph could be used to determine the energy savings achieved when upgrading the overall thermal resistance R_T of the opaque building envelope cross-section.

$$Energy\ Savings = \frac{q_{before\ upgrading} - q_{after\ upgrading}}{q_{before\ upgrading}}\ [\%]$$

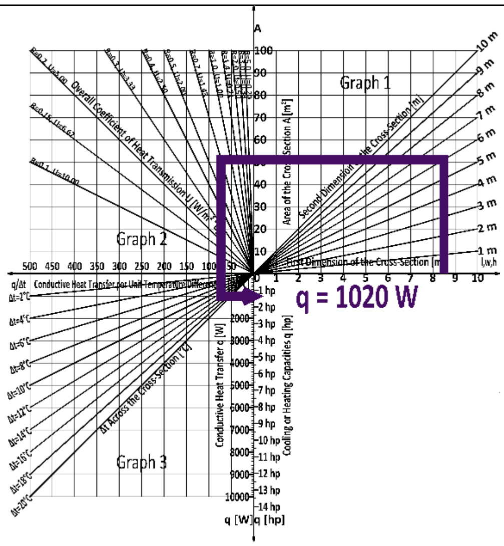
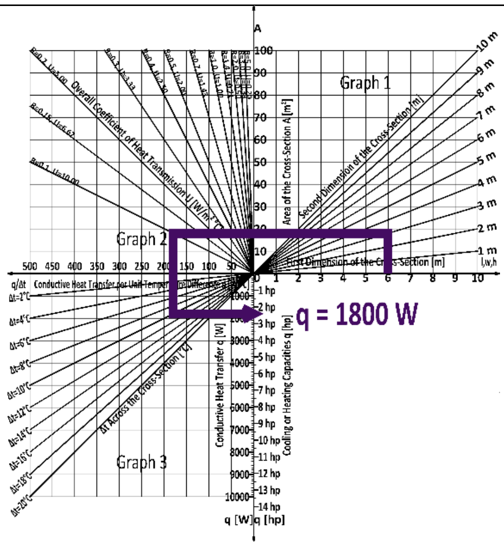
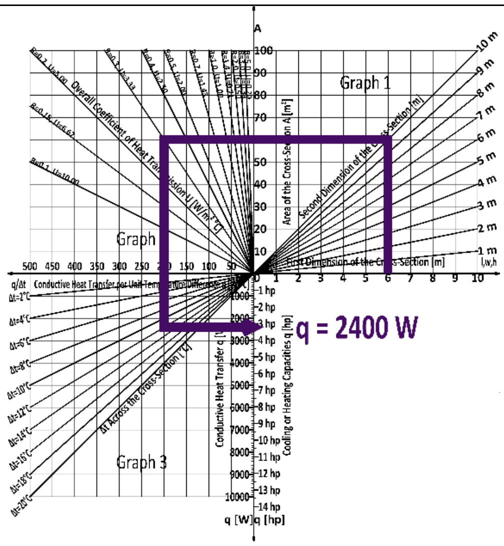
2.3 Verification of the Calculations

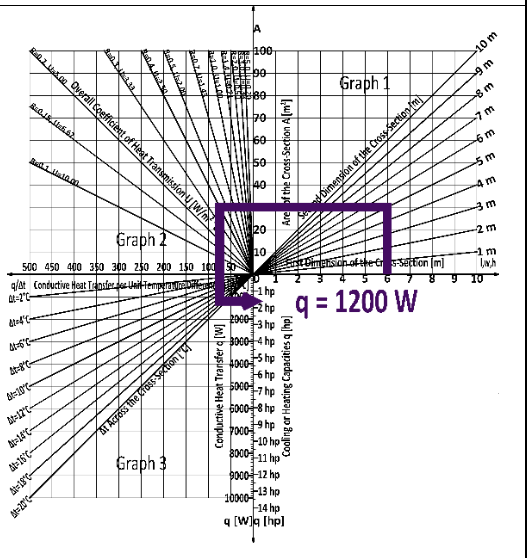
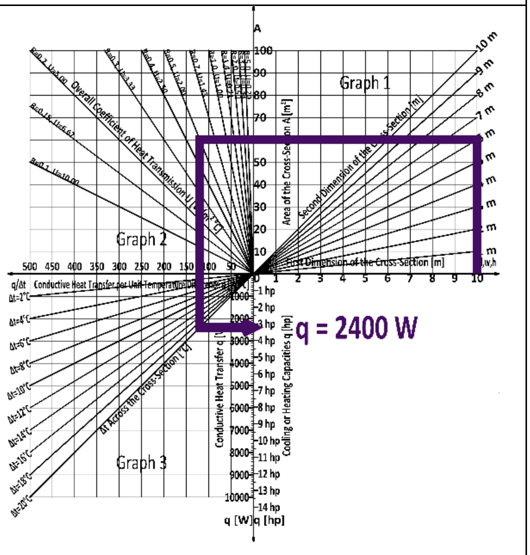
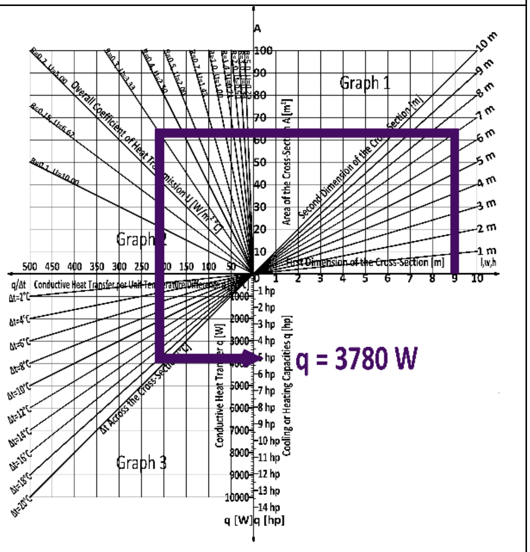
The formulas used in the graphs that constitute the design chart were verified mathematically by matching the $q_{Design\ Chart}$ that was determined by the design chart, up to the values $q_{Calculations}$ that were obtained from the calculations using the following formula.

$$q = (A \times U) \times \Delta t\ [W]$$

The values that were obtained from calculations were discovered to be fully matching those that were obtained from the design chart, which in turn verifies the used formulas within the different graphs of the design chart as shown below in Table 1.

Table 1: The mathematical verification of the design chart graphs.

Building Envelope Cross-Section	$q_{Calculations} = (\boldsymbol{A} \times \boldsymbol{U}) \times \Delta \boldsymbol{t}\ [\boldsymbol{W}]$	$q_{Design\ Chart}$
1. Wall A $l = 8.5\ m$ $h = 6\ m$ $R_T = 0.7\ m^2\ °C/W$ $\Delta t = 14\ °C$	$q = \left((8.5 \times 6) \times (1/0.7)\right) \times 14\ [W]$ $q = (51 \times 1.43) \times 14\ [W]$ $q = 1020$ W	
2. Wall B $l = 6\ m$ $h = 3\ m$ $R_T = 0.1\ m^2\ °C/W$ $\Delta t = 10\ °C$	$q = \left((6 \times 3) \times (1/0.1)\right) \times 10\ [W]$ $q = (18 \times 10) \times 10\ [W]$ $q = 1800$ W	
3. Wall C $l = 6\ m$ $h = 10\ m$ $R_T = 0.3\ m^2\ °C/W$ $\Delta t = 12\ °C$	$q = \left((6 \times 10) \times (1/0.3)\right) \times 12\ [W]$ $q = (60 \times 3.33) \times 12\ [W]$ $q = 2400$ W	

Building Envelope Cross-Section	$q_{Calculations} = (A \times U) \times \Delta t\ [W]$	$q_{Design\ Chart}$
4. <u>Roof A</u> $l = 6\ m$ $w = 5\ m$ $R_T = 0.4\ m^2\ °C/W$ $\Delta t = 16\ °C$	$q = \left((6 \times 5) \times (1/0.4)\right) \times 16\ [W]$ $q = (30 \times 2.5) \times 16\ [W]$ $q = 1200\ \text{W}$	
5. <u>Roof B</u> $l = 10\ m$ $w = 6\ m$ $R_T = 0.5\ m^2\ °C/W$ $\Delta t = 20\ °C$	$q = \left((10 \times 6) \times (1/0.5)\right) \times 20\ [W]$ $q = (60 \times 2) \times 20\ [W]$ $q = 2400\ \text{W}$	
6. <u>Roof C</u> $l = 9\ m$ $w = 7\ m$ $R_T = 0.3\ m^2\ °C/W$ $\Delta t = 18\ °C$	$q = \left((9 \times 7) \times (1/0.3)\right) \times 18\ [W]$ $q = (63 \times 3.33) \times 18\ [W]$ $q = 3780\ \text{W}$	

3 Results

Figure 1 represents the design chart that was created by the author. It consists of three graphs representing the different variables required to determine the conductive heat transfer across any opaque building envelope cross-section.

3.1 Description of the Design Chart

The design chart, shown in Figure 1, comprises three combined graphs utilized in an anticlockwise manner to determine the conductive heat transfer across an opaque building envelope cross-section.

The first graph, at the top right, finds the area of the opaque building envelope cross-section A. It consists of two axes and ten diagonal lines. The horizontal axis represents the first dimension of the cross-section, which ranges from 0 m to 10 m. The diagonal lines represent the second dimension of the cross-section, which ranges from 0 m to 10 m. The vertical axis represents the obtained area of the opaque building envelope cross-section A $[m^2]$, that ranges from 0 m^2 to 100 m^2.

The second graph, at the top left, finds the conductive heat transfer q per unit Δt across the opaque building envelope cross-section $q/\Delta t$. It consists of two axes and twelve diagonal lines. The vertical axis, which is aligned with the vertical axis of the first graph, represents the obtained area of the opaque building envelope cross-section A $[m^2]$, that ranges from 0 m^2 to 100 m^2. The diagonal lines represent the overall coefficient of heat transmission U $[W/m^2\,°C]$, that ranges from 10 $W/m^2\,°C$ to 0.2 $W/m^2\,°C$ (reciprocal of overall thermal resistance R_T, that ranges from 0.1 $m^2\,°C/W$ to 5.0 $m^2\,°C/W$). The horizontal axis represents the obtained conductive heat transfer q per unit temperature difference Δt across the opaque building envelope cross-section $q/\Delta t$ $[W/°C]$ that ranges from 0 $W/°C$ to 500 $W/°C$.

The third graph, at the bottom left, finds the conductive heat transfer q across the opaque building envelope cross-section. It consists of two axes and ten diagonal lines. The horizontal axis, that is aligned with the horizontal axis of the second graph, represents the obtained conductive heat transfer q per unit temperature difference Δt $[°C]$ across the opaque building envelope cross-section $q/\Delta t$ $[W/°C]$ that ranges from 0 $W/°C$ to 500 $W/°C$. The diagonal lines represent the temperature difference between outside and inside design temperatures Δt that ranges from 1 $°C$ to 20 $°C$. The vertical axis represents the obtained conductive heat transfer q $[W]$ that ranges from 0 W to 10000 W as well as the the cooling or heating capacities q $[hp]$ that ranges from 0 $[hp]$ to 14 $[hp]$.

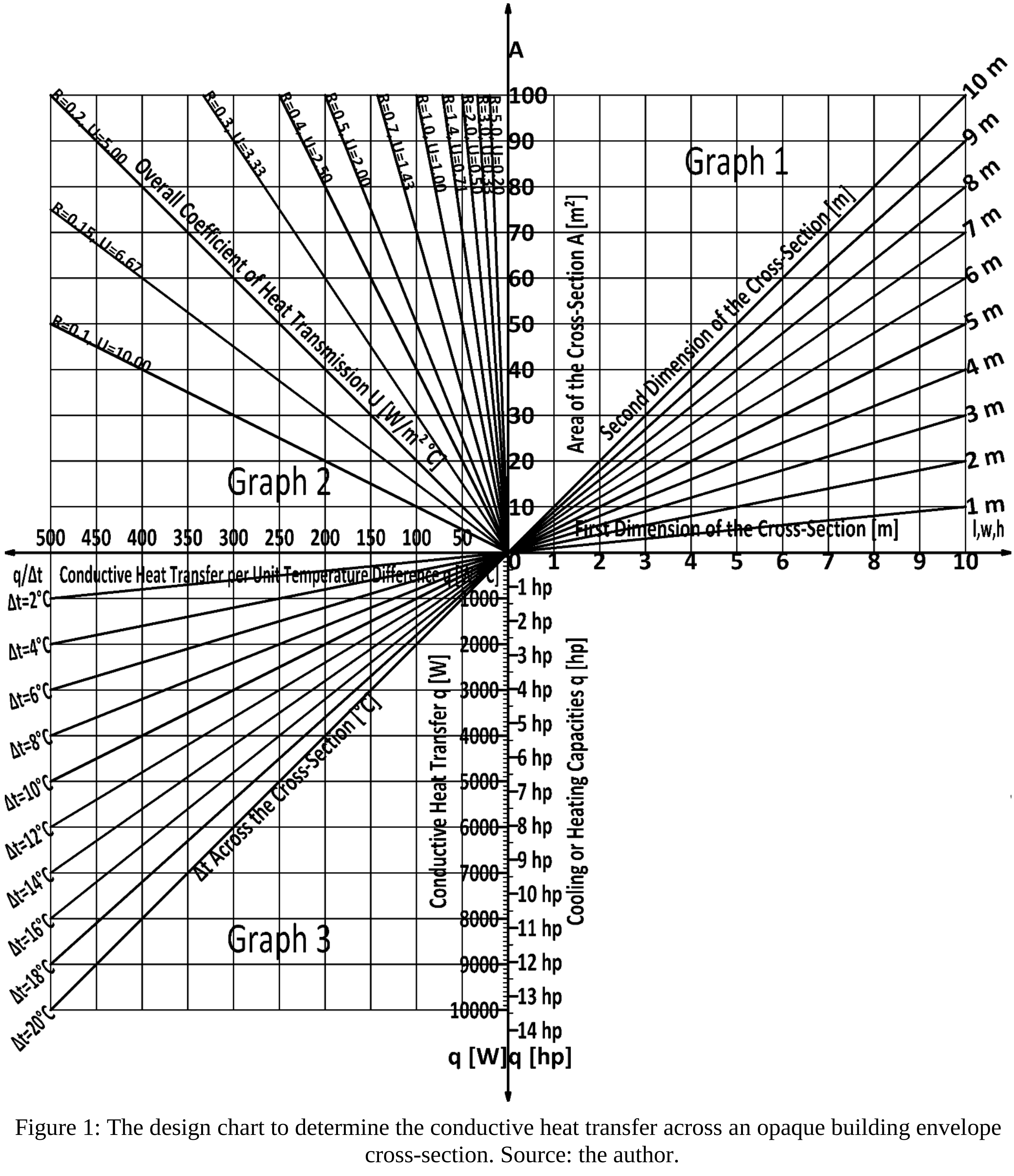


Figure 1: The design chart to determine the conductive heat transfer across an opaque building envelope cross-section. Source: the author.

The additional fourth graph, shown in Figure 2, could be utilized to calculate the percentage of energy savings resulting from upgrading the opaque building envelope cross-section. That cross-section could be upgraded by increasing the overall thermal resistance R_T [13], i.e., decreasing Coefficient of heat transmission U.

It consists of two axes and ten diagonal lines. The horizontal axis represents the conductive heat transfer before upgrading the cross-section $q_{before}[W]$ that ranges from 0 W to 10000 W. The vertical axis represents the conductive heat transfer after upgrading the cross-section $q_{after}[W]$ that ranges from 0 W to 10000 W. The diagonal lines represent the obtained percentage of energy savings, which ranges from 0 % to 90 %.

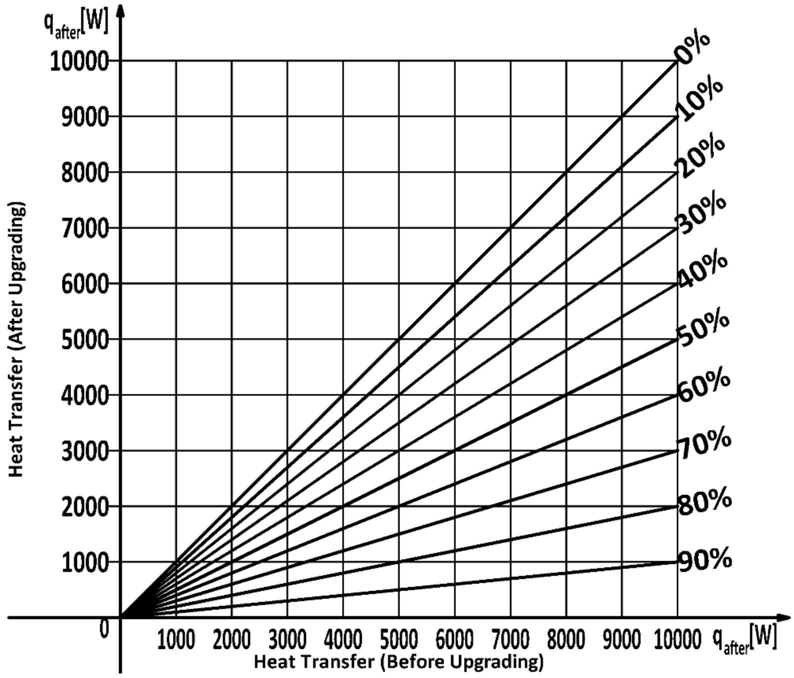


Figure 2: The additional fourth graph to calculate the energy savings resulting from upgrading the opaque building envelope cross-section. Source: the author.

3.2 Utilising of the Design Chart

To determine the conductive heat transfer across an opaque building envelope cross-section, all the three graphs of the design chart are utilized in an anticlockwise manner as follows.

Specify the first dimension of the cross-section on the horizontal axis of the first graph. Extend a vertical line till it intersects one of the diagonal lines that represent the second dimension of the cross-section. From the point of intersection, extend a horizontal line till the area A $[m^2]$ is obtained on the vertical axis. If the area A is already given, its value could be specified directly on the vertical axis of the first graph, i.e., skipping the use of the first graph. From the obtained or specified value of area A, extend a horizontal line till it intersects one of the diagonal lines of the second graph, which represent the overall coefficient of heat transmission U (reciprocal of overall thermal resistance R_T). From the point of intersection, extend a vertical line till it intersects one of the diagonal lines of the third graph, which represent the temperature difference between outside and inside design temperatures Δt. From the point of intersection, extend a horizontal line till the conductive heat transfer q $[W]$ as well as the cooling or heating capacities q $[hp]$ are obtained on the vertical axis of the third graph. The conductive heat transfer q $[W]$ is determined on the third graph's left portion of the vertical axis, while the cooling or heating capacities q $[hp]$, in the overheated or underheated zones respectively, could be determined on the third graph's right portion of the vertical axis.

To calculate the percentage of energy savings resulting from upgrading the opaque building envelope cross-section, the additional fourth graph is utilized as follows.

Specify the conductive heat transfer before upgrading the cross-section $q_{before}[W]$ on the horizontal axis of the additional fourth graph. Draw an extended vertical line. Specify the conductive heat transfer after upgrading the cross-section $q_{after}[W]$ on the vertical axis of the additional fourth graph. Draw an extended horizontal line that would intersect the previously drawn extended vertical line at one of the diagonal lines indicating the percentage of energy savings [%].

Example 1: Utilise the design chart to determine the conductive heat transfer across a wall, whose $l = 6\ m$, $h = 4\ m\ \ R_T = 0.2\ m^2\ °C/W$, and $\Delta t = 10\ °C$.

Solution of Example 1: Specify the first dimension of the wall $l = 6.0\ m$ on the horizontal axis of the first graph. Extend a vertical line till it intersects the diagonal line that represents the second dimension of the wall $h = 4.0\ m$. From the point of intersection, extend a horizontal line till the area $A = 24.0\ m^2$ is obtained on the vertical axis. From the obtained area A, extend a horizontal line till it intersects the diagonal line of the second graph, which represents the reciprocal of overall thermal resistance $R_T = 0.2\ m^2\ °C/W$. From the point of intersection, extend a vertical line till it intersects the diagonal line of the third graph, which represents the temperature difference between outside and inside design temperatures $\Delta t = 10\ °C$. From the point of intersection, extend a horizontal line till the conductive heat transfer $q = 1200\ W$ is determined on the third graph's left portion of the vertical axis, while the cooling capacity (overheated zone) $q = 1.6\ hp$ is determined on the third graph's right portion of the vertical axis (see Figure 3).

Example 2: Utilise the design chart to determine the conductive heat transfer across a wall, whose $l = 9\ m$, $h = 6\ m$, and $\Delta t = 14\ °C$ and this is required for two different cases; before upgrading $R_T = 0.3\ m^2\ °C/W$ and after upgrading $R_T = 1.4\ m^2\ °C/W$, i.e., increasing $R_T\ [m^2\ °C/W]$ by adding insulating materials.

Solution of Example 2: Follow the same steps of example 1 until the step of extending a horizontal line till it intersects the diagonal line of the second graph, that represents the reciprocal of overall thermal resistance for the first and second cases $R_T = 0.3\ m^2\ °C/W$, and $R_T = 1.4\ m^2\ °C/W$ respectively. From the points of intersection, extend two vertical lines for both cases till they intersect the diagonal line of the third graph, which represents the temperature difference between outside and inside design temperatures $\Delta t = 14\ °C$. From the points of intersection, extend two horizontal lines till the conductive heat transfer for both cases $q = 2520\ W$, and $q = 540\ W$ respectively are determined on the third graph's left portion of the vertical axis, while the cooling capacity (overheated zone) for both cases $q = 3.4\ hp$, and $q = 0.7\ hp$ respectively are determined on the third graph's right portion of the vertical axis (see Figure 3).

Example 3: Utilise the additional fourth graph of the design chart to determine the percentage of energy savings resulting from upgrading the wall of example 2.

Solution of Example 3: Specify the conductive heat transfer of the first case in example 2, i.e., before upgrading the wall, $q_{before} = 2520\ W$ on the horizontal axis of the additional fourth graph. Draw an extended vertical line. Specify the conductive heat transfer of the second case in example 2, i.e., after upgrading the wall, $q_{after} = 540\ W$ on the vertical axis of the additional fourth graph. Draw an extended horizontal line that would intersect the previously drawn extended vertical line at one of the diagonal lines indicating the percentage of energy savings, $Energy\ Savings = 79\ \%$ (see Figure 4)

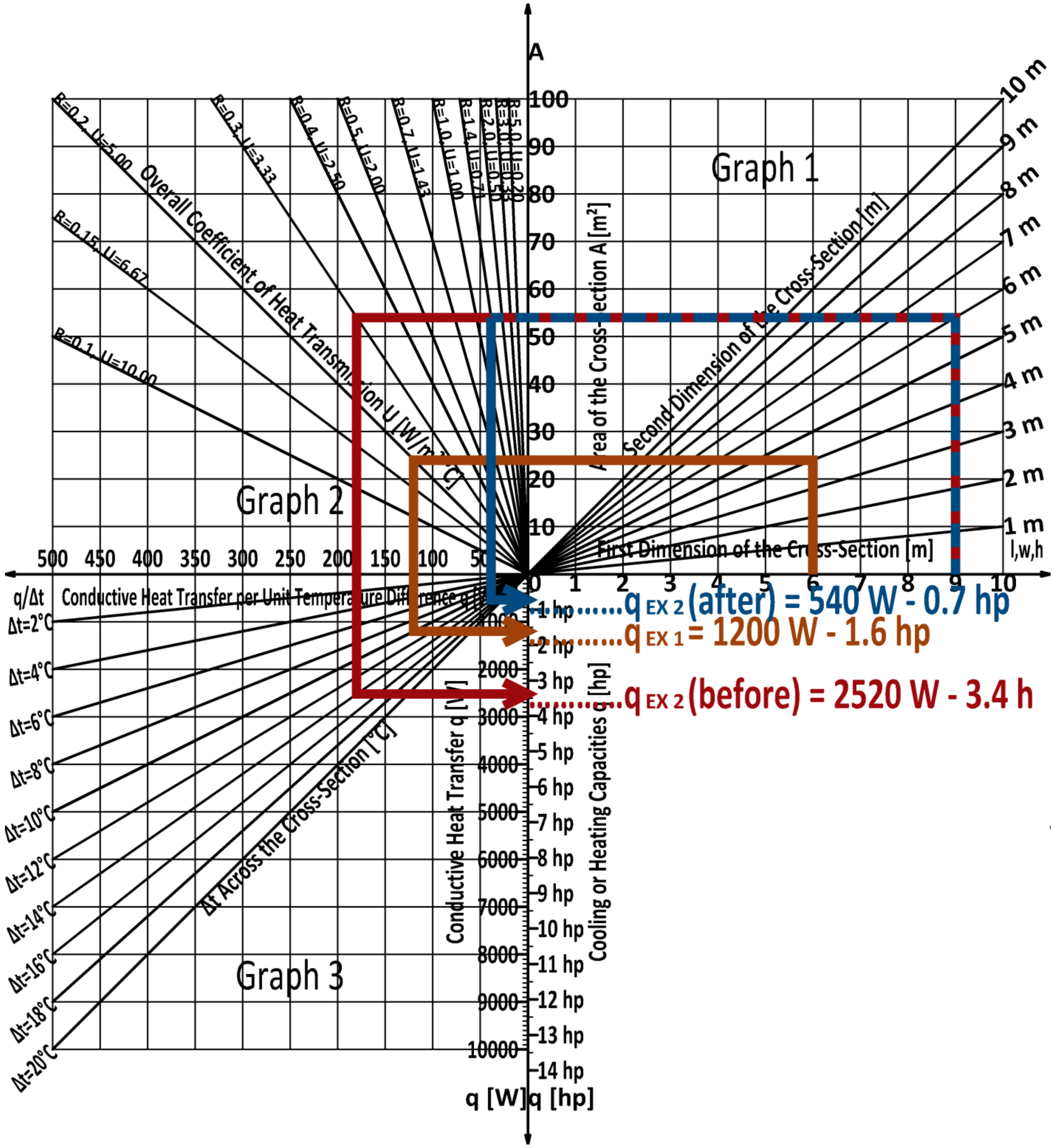


Figure 3: Example of using the design chart to determine the conductive heat transfer across an opaque building envelope cross-section. Source: the author.

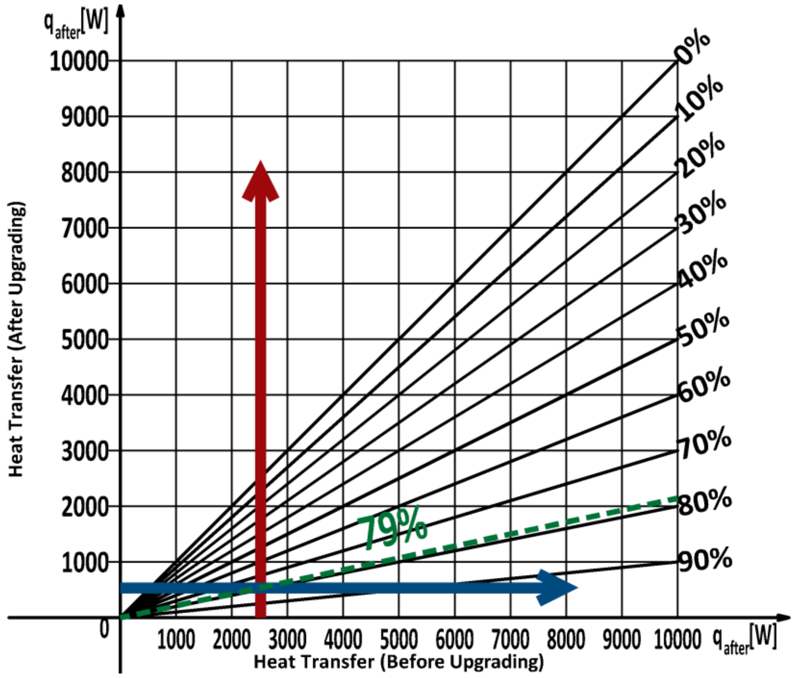


Figure 4: Examples of using the additional fourth graph of the design chart to determine the percentage of energy savings resulting from upgrading the opaque building envelope cross-section. Source: the author.

3.3 Notes on the Design Chart

It is evident from the design chart that the amount of heat transfer is affected by any change in one or more of its variables. It is also obvious from its different graphs that there is a linear relationship between conductive heat transfer and its variables. This relationship is linear with the area, overall coefficient of heat transmission, and temperature difference, on the other hand, it is inverse linear with the overall thermal resistance.

From the additional fourth graph of the design chart, it is obvious that the percentage of energy savings resulting from upgrading the opaque building envelope cross-section is related to upgrading the overall thermal resistance of that cross section by utilizing more insulating materials of higher resistivity. The percentage of these energy savings corresponds to the change in the overall thermal resistance of the opaque building envelope cross-section before and after upgrading.

4 Discussion and Conclusions

The proposed design chart, which was created by the author, could be used by architects to determine the conductive heat transfer across any opaque building envelope cross-section. That would result in expecting the amount of cooling or heating capacity, needed to confront that amount of conductive heat transfer that in turn would ensure the achievement of thermal comfort of users, especially when applying the requirements of the building energy codes. This is helpful especially in the preliminary stages of architectural design and working drawings without involving complex calculations or being an expert in building science. It could also give an estimate of the possible energy savings that might result from using different opaque building envelope cross-sections.

In future research, other design charts could be created in a trial of determining other types of heat transfer in buildings.

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