Chapter 2
Approximating Dynamic Thermal Behaviour of the Building Envelope

Abstract Assessing the building energy performance through the simplified assumptions of the steady-state conditions can prove restrictive. The estimation of heat transfer through the envelope is based on the U-value of the building construction, neglecting the thermal mass effect. Several approaches have, therefore, been developed to approximate the dynamic behaviour of buildings when performing a standard steady-state analysis. According to Barnaby (1982), these methods can be generally divided into those analysing an isolated building element and those considering the context of whole building. The first category introduces some correction values that affect the main parameters of the steady-state heat transmission calculation (i.e. the U-value of the envelope elements and the temperature difference between the indoor and outdoor environments). This chapter investigates a set of correction values that try to represent the dynamic thermal envelope performance in a simplified manner, applying some of them to a set of case-study wall types.

Keywords Heat transfer through building envelope · Thermal inertia · Dynamic heat transfer · Correction values approximating dynamic behaviour

2.1 Heat Transmittance Correction Values

Some of the simplified methods approximating the dynamic behaviour of the building envelope starting from the steady-state approach apply a correction to the U-value of the considered element and are usually referred to the heating season.

2.1.1 Mass Factor

The M factor (or mass factor) is an adjustment value for the heat transmittance of envelope elements developed by Yu (Hankins and Anderson 1976; Yu 1978), which applies to the heating season calculation.

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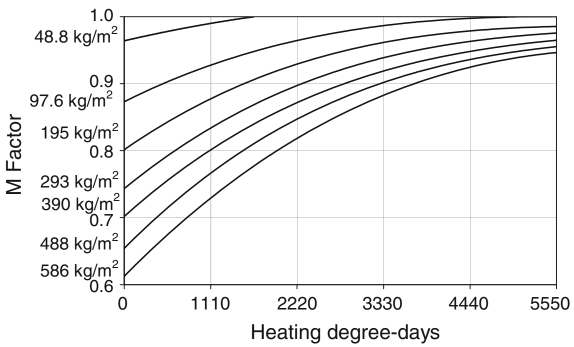


Fig. 2.1 Correlation graph for the M factor, the heating degree-days and the element frontal mass [kg/m^2] in SI units

The correction factor was defined as the ratio of the heat flow for a given wall calculated by the means of a dynamic simulation (assumed as average in January at 8:00 am) and the one calculated by the means of the steady-state method. Several typical envelope constructions were tested and used to develop reference values, which correlate the mass factor both to the element frontal mass and to the heating degree-days of the building location. These values were later translated into a graph in order to enlarge the method's applicability (Fig. 2.1).

This approach did not find large application regarding the heating energy need assessment, since several later studies found it unreliable in this matter because of it extending a value originally calculated for a specific hour to the whole season (Godfrey et al. 1979). In fact, in some cases M factor has been suggested in order to predict the savings due to envelope mass regarding the heating peak load calculation.

2.1.2 *Effective U-Value*

The effective U-value method was developed by Van der Meer (1978). This parameter is defined as the ratio of the seasonal average density of heat flow rate and the seasonal average temperature difference between the indoor and the outdoor environments. By the means of an ad hoc developed software, Van der Meer performed series of dynamic energy simulations for a whole set of construction technologies in relation to the New Mexico climatic conditions, and derived reference values for the most common wall constructions. The aim of this parameter is not to determine a comparison between different constructions, but to make a correction of the traditional U-value and to determine how the element behaviour changes as its orientation or its surface colour are modified. Later on values of this parameter have been calculated for a wider range of construction and they have been implemented in the New Mexico Building Code. As for other simplified methods, the effective U-value is not universally applicable since it is based on a list of reference values that were calculated, by the means of detailed dynamic simulations, for specific kinds of envelope technologies and specific climatic conditions.

2.2 Temperature Difference Correction Values

Some other methods apply a correction value to the temperature difference needed to calculate the heat transfer through the building envelope. They are usually referred to the cooling season.

2.2.1 *Total Equivalent Temperature Differential (TETD)*

Since 1940s, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) started developing a method to calculate the thermal gains for the peak cooling load estimation through the opaque envelope based on an alternative value of the temperature difference, which could take into account the combined effects of solar radiation and envelope thermal inertia. Starting from experimental data and calculation using the periodic analysis (see Chap. 1), some default data regarding specific envelope technologies were derived as the ratio of the calculated heat flow and the nominal U-value and were collected into reference tables. In ASHRAE (1972) the total equivalent temperature differential (TETD) was introduced to determine the cooling peak load. The method can be applied both choosing pre-calculated values from the reference tables, which were calculated for specific constructions and for mild climates, and calculating directly the specific value by the means of a general equation that depends mostly on the decrement factor and on the time lag of the analysed building envelope (Eq. 2.1).

$$TETD_t = T_{as,e,t} - T_{a,i,t} + f\left(T_{as,e,t-\delta} - T_{as,e,t}\right) \quad (2.1)$$

where

$T_{as,e}$ outdoor sun-air temperature [K]
$T_{a,i}$ indoor air temperature [K]
f decrement factor
δ time lag [h]

Because of this last option, this method can be considered simple and at the same time accurate in calculating the cooling load. In fact it can still be found in current researches, even if with more sophisticate calculations of the time lag and decrement factor values (Yumrutaş et al. 2007; Kaşka and Yumrutaş 2009).

2.2.2 Cooling Load Temperature Difference (CLTD)

Another method, which is still suggested by ASHRAE (2001) as a simplified assessment method for residential buildings cooling load calculation, is the Cooling Load Temperature Difference (CLTD).

Also in this case, standard reference values for typical envelope constructions (the basic ones considered by ASHRAE and classified in different categories), with specific U-values and frontal mass, were derived by the ratio of the dynamic heat flow, calculated by the means of the conduction transfer function (CTF) method, and the nominal U-value. The boundary conditions for the dynamic calculation were:

- 40° north latitude (which influences the solar radiation effect);
- July as the standard month for the cooling load evaluation;
- 29.4 °C of outdoor design temperature;
- 25.5 °C of indoor design temperature;
- a dark coloured outside surface.

As for most of these simplified methods, the accuracy of the provided values strongly depends on the similarities between the actual building and the simulation conducted by ASHRAE: in order to address this problem, in ASHRAE (1989) Eq. 2.2 was proposed to adjust the table data for boundary parameters different from the previously mentioned ones and for the presence of additional insulation.

$$CLTD_{corr} = (CLTD + LM)K + \left(25.5 - T_{set,i}\right) + \left(T_{a,e,prj} - 29.4\right) \tag{2.2}$$

where

$CLTD$	is the standard CLTD for typical boundary conditions [K]
LM	is the adjustment factor for latitude, reference month and orientation [°C]
K	is the adjustment factor for surface finishing [%]
$T_{set,i}$	is the internal set-point temperature [°C]
$T_{a,e,prj}$	is the outside air design temperature [°C]

Later researches still proposed the adoption of this method, trying to develop data for a wider range of boundary conditions. Bansal et al. (2008), in particular, calculated reference CLTD values for typical constructions and climate of India, solving the Fourier's equation by the means of the finite difference method.

2.2.3 Overall Thermal Transfer Value (OTTV)

As a representation of the energy consumption due to the building envelope, always in summer, ASHRAE developed the overall thermal transfer value (OTTV), which tries to combine the effect of the envelope elements exposed to different orientations and of both the opaque and transparent parts of these elements.

$$OTTV = \frac{(A_{op} \cdot U \cdot \alpha \cdot TD_{EQ}) + (A_{win} \cdot SC \cdot ESM \cdot SF)}{A} \tag{2.3}$$

where

A	envelope surface [m^2]
A_{op}	surface of the opaque part of the envelope [m^2]
U	thermal transmittance of the opaque part of the envelope [W/(m^2 K)]
α	absorbtance of the opaque part of the envelope
TD_{EQ}	equivalent temperature difference for the opaque part of the envelope [K]
A_{win}	surface of the glazed part of the envelope [m^2]
SC	shading coefficient of the surface
ESM	external shading multiplier (depending on the orientation)
SF	solar factor of the glazed surface [W/m^2]

Considering a single opaque element, the characteristics taken into account by this index are the U-value, the thermal absorptance and an adjusted value of temperature difference. The reference values of equivalent temperature difference were listed according to the surface orientation and to the element weight, after being calculated by the means of dynamic simulations. Even if since 1989 this index is not part of the ASHRAE Standard 90.1 anymore, the building codes in some eastern countries (i.e. Hong Kong 1995) still use it to evaluate the summer thermal gains for commercial buildings.

2.2.4 Fictitious Ambient Temperature

Nilsson (1994, 1997) developed a simplified analysis tool for the evaluation of a whole building behaviour, based on the preparation of duration diagrams describing the different variables in the thermal zone heat balance equation. However, the principle and the equations are here described since within this tool the dynamic behaviour is introduced by an adjusted reference outdoor temperature for the steady-state calculation of the heat transfer through the building envelope. The principle underneath this approach is that massive constructions are more influenced by the outdoor temperature history than by its instantaneous value.

Equation 2.4 was therefore analytically developed in order to calculate the alternative outdoor temperature, which was called fictitious ambient temperature (FAT). In order to allow easier evaluations when outdoor air temperature values are known at defined time intervals (e.g. hourly steps), Eq. 2.5 was also provided.

$$T^*_{a,t} = T_{a,t} - \left[\left(T_{a,t} - T_{a,0}\right)\mathrm{e}^{-\frac{t}{\tau^*}}\right] \tag{2.4}$$

$$T^*_{a,N} = T_{a,N} - \left[\left(T_{a,N} - T^*_{a,N-1}\right)\mathrm{e}^{-\frac{\Delta t}{\tau^*}}\right] \tag{2.5}$$

where

T_a^* is the fictitious ambient temperature [K]
T_a is the outdoor air temperature [K]
τ^* is the time coefficient [s]
Δt is the time interval [s]
t,N represents the current time
0 represents the initial time

Within the above equations, time coefficient is the characteristic describing the dynamic thermal behaviour of the envelope. Differently from the time constant used in other applications (see also the CEN method in the Chap. 3), this time coefficient is adopted in case of hourly changing outdoor temperature and is calculated considering only the envelope elements (instead of the entire building internal mass) and in their whole thickness.

The envelope heat capacity is described as a lumped mass, meaning that no temperature gradient throughout the mass is taken into account and so the insulation position in the structure cross-section has no effect on the heat transfer: adjustment standard values (ξ) were therefore developed to distinguish between specific layers layouts with the same lumped mass value (Eq. 2.6).

$$\tau^* = \frac{\xi \sum cm}{\sum UA} \tag{2.6}$$

where

ξ is the correction coefficient due to the layers layout
c is the specific heat [J/(kg K)]
m is the mass [kg]
U is the heat transmittance [W/(m^2 K)]
A is the surface [m^2]

Reference values of the correction coefficient were derived and listed in tables for basic layouts (such as massive layers both on the inside and on the outside, only on the inside, only on the outside, and insulation layers both on the inside and on the outside) on the basis of the difference between the fictitious ambient temperature method results and corresponding dynamic simulation results.

2.3 Applications

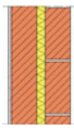
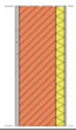
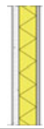
A larger research carried out in Politecnico di Milano surveyed some of these international simplified methods, for which useful data are available (Ferrari and Zanotto 2010a), and applied them to four different wall solutions, having different aeric mass but the same U-value (and therefore the same steady-state performance), in order to understand their effectiveness (Ferrari and Zanotto 2010b). The results of this research are reported in the present section.

The chosen wall samples are the same considered in the comparison between the finite element calculations and the climatic chamber tests (Chap. 1), and their characteristics are described in Table 2.1:

- a heavyweight masonry wall (“Heavy”), made by one layer of high density hollow bricks;
- a medium/heavyweight wall (“Mid-Ins”), made by outdoor face bricks and a hollow brick layer with insulation within;
- a medium/heavyweight wall (“Ext-Ins”) with hollow bricks and exterior insulation;
- a lightweight wall (“Light”) composed by an insulation sandwich panel.

The outside boundary condition was set as the heat flow resulting from the standard outdoor surface heat transfer coefficient (EN ISO 6946 2007) and the hourly sol-air temperature for a wall facing South in the city of Rome, calculated according to the Test Reference Year (TRY) climatic data. Similarly, as inside boundary condition the heat flow resulting from the standard indoor surface heat transfer coefficient and a constant temperature (20 °C for the heating season and 26 °C for the cooling season) was used.

Table 2.1 Chosen wall types and related main thermal characteristics

	Heavy	Mid-Ins	Ext-Ins	Light
				
Thickness [m]	0.480	0.365	0.400	0.125
U-value [W/(m^2 K)]	0.298	0.299	0.306	0.312
Aeric mass [kg/m^2]	431	343	301	35
Heat capacity [kJ/(m^2 K)]	368	291	259	28

2.3.1 M Factor

Starting from Fig. 2.1, the M factor values were derived for the four wall types and for the city of Rome, which is characterised by 1415 heating degree-days. According to these adjustment factors, the corrected U-value were calculates, as shown in Table 2.2.

As design outside temperature for the heating peak load calculation, the lowest value from the Rome TRY data (−0.8 °C) is used. In case of the finite element analysis, the peak load has been derived as the maximum heat flow density rate effect due to the minimum sol-air temperature solicitation. In this way the positive heating effect of the daily solar radiation on the element surface is taken into account.

As shown by Fig. 2.2, the winter peak load prediction according to the M factor and the one according to the finite element analysis method are very different, except for the lightweight construction, which in both cases shows a behaviour consistent with the steady-state approach. According to both methods, the maximum difference can be seen between the lightweight and the heavyweight constructions: this difference is 23 % in case of the M factor method and 46 % in case of the finite element analysis. This discrepancy could be explained, in large extent, by the fact that the M factor was developed in the 1970s, when the envelope average U-values were much higher than the 0.30 W/(m^2 K) of the chosen wall types.

Furthermore, the simplified model is based on a lumped heat capacity approach, bringing to deceiving results when dealing with walls with similar frontal mass but different layouts, for instance in case of the two medium-weight constructions.

2.3.2 CLTD

In order to implement the CLTD method, four wall types were selected from the reference tables provided by ASHRAE (1989), as the most similar constructions (in terms of U-value, frontal mass and layout) to the chosen samples described in Table 2.1. Since, again, the CLTD data were derived for walls with higher average U-values than the studied ones, the correction method for additional insulation was

Table 2.2 Corrected U-values determination according to the nominal U-values and the M factor for the four wall types

	Heavy	Mid-Ins	Ext-Ins	Light
U-value, nominal [W/(m^2 K)]	0.298	0.299	0.306	0.312
M factor	0.81	0.84	0.85	1.00
U-value, corrected [W/(m^2 K)]	0.241	0.251	0.260	0.312

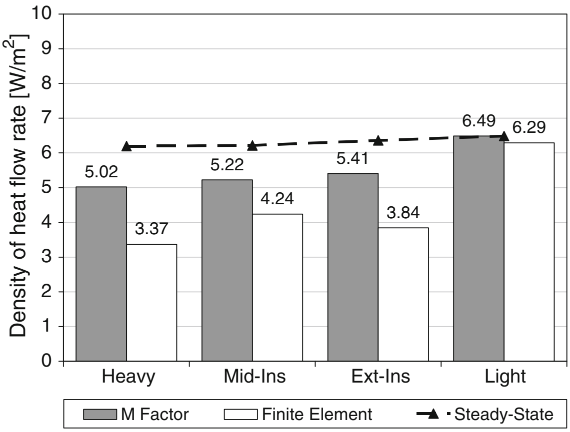


Fig. 2.2 Comparison of the winter peak loads calculated by the means of the M factor, the finite element analysis and the steady-state methods

applied. According to this method, the wall category needs to be upgraded for every 1.23 (m^2 K)/W increase in the thermal resistance value: the first subsequent category has to be adopted unless the insulation is outward, in which case the second subsequent one should be used. If, after this upgrade, the wall is above category A, a temperature difference value is applied for a further category (A^+).

Table 2.3 shows the corrected CLTD values, determined according to the previous consideration and the correction factors in Eq. 2.2. In this study, in particular, an orientation adjustment of 0.5 °C and a surface finishing correction factor of 0.83 (for medium-coloured surfaces) were adopted.

As design outside air temperature for the cooling peak load calculation, the value connected to the highest sol-air temperature from the TRY data (34 °C) is selected, while the design inside air temperature is set to 26 °C, consistently with the Italian common practice.

Figure 2.3 shows the peak density of heat flow rate results for the summer season according to CLTD and finite element analysis. They are quite different, and it can be explained considering the particularly high amount of adjustments necessary to adapt the ASHRAE reference wall types to our four samples. In fact, it was difficult to point out categories matching to our four types, since the selection is based both on the layout descriptions and on the thermal characteristics, and the Italian and U.S. construction traditions are very different.

Table 2.3 Corrected CLTD determination according to the wall types category, increased insulation and the adjustment factors the four wall-types

	Heavy	Mid-Ins	Ext-Ins	Light
Starting category	D	C	B	G
Insulation corrected category	A^+	B	A^+	F
Base CLTD	9.40	11.00	9.40	26.00
Corrected CLTD	12.32	13.65	12.32	26.10

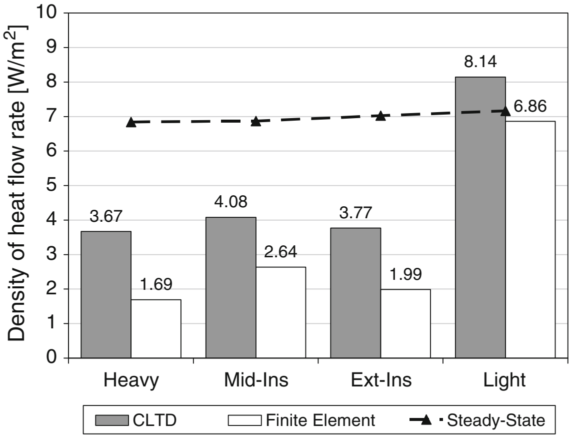


Fig. 2.3 Comparison of the summer peak loads calculated by the means of the CLTD, the finite element analysis and the steady-state methods

It has to be noted that in this method the layers configuration, taken into account together with the lumped heat capacity, affects the results: the advantage of this approach can be seen in the values regarding the two medium-weight walls, which show the same trend of the finite element analysis ones.

As for the winter peak load, the maximum difference according to both methods is between the lightweight and the heavyweight walls, for 54 % in case of the CLTD method and 75 % in case of the finite element analysis method.

2.3.3 FAT

As explained in Sect. 2.2.4, although this method was originally developed in the framework of a whole building behaviour evaluation, the principle and the equations are here applied to isolated element analysis in first approximation.

According to Eq. 2.6 and to the data provided by Nilsson (1997), the characteristic time coefficients for the selected wall types have been derived (Table 2.4).

Later on, the hourly fictitious ambient temperatures for the winter and summer seasons have been calculated according to Eqs. 2.4 and 2.5, and used in the steady-state equation to find the transmission heat exchange. The resulting seasonal heat exchange values have been afterwards compared to the ones from the finite element analysis.

The heating season (November 1st–April 15th) and the cooling season (July 1st–September 15th) have been set according to the Italian praxis.

Figure 2.4 shows the seasonal balance of winter and summer heat exchanges through the selected walls according to the steady-state approach, the FAT method and the finite element analysis.

The values from the simplified method are similar to the ones from the exact solution of the heat conduction equation, as well as to the steady-state results. The

Table 2.4 Time coefficient determination according to the wall types category for the four wall-types

	Heavy	Mid-Ins	Ext-Ins	Light
Category (outwards-inwards)	Massive-massive	Massive-massive	Light-massive	Light-light
Correction factor (ξ)	0.11	0.11	0.08	0.38
Time coefficient [h]	37.84	29.70	18.77	9.54

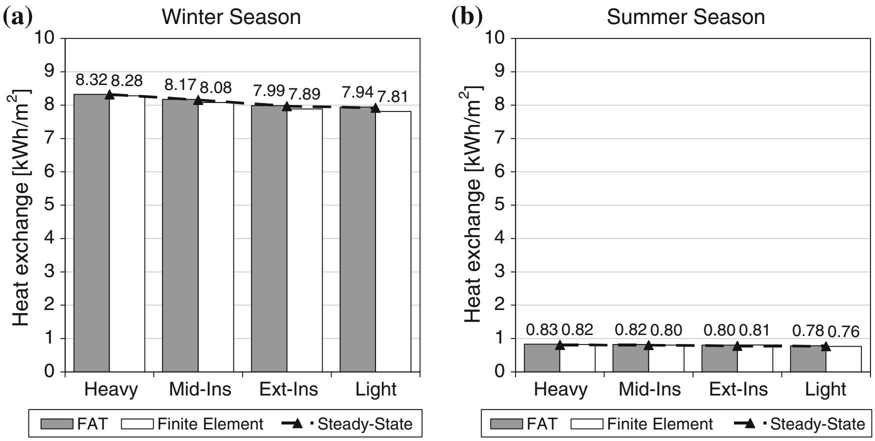


Fig. 2.4 Comparison of the winter and summer seasonal heat exchanges calculated by the means of the fictitious ambient temperature (FAT), the finite element analysis and the steady-state methods

energy balance in the long period, in fact, is similar independently from the magnitude of the heat flow oscillations, which occur around the same average value because of the same environmental conditions. Actually, only considering the whole building performances (including the effects of heat gains and ventilation inside the building), as foreseen by the conventional application of the FAT method, it is possible to appreciate differences even in terms of seasonal balance.

2.3.4 Lessons Learned

Regarding the simplified methods to adjust the steady-state heat exchange calculation, the analysed ones aiming at the peak load calculation showed a very small applicability, due to the way they were developed. A possible extension of their use could be foreseen only in case of the development of a wider reference data range (regarding CLTD this has already been done by international studies, e.g. Bansal et al. 2008).

Considering the climatization seasonal need, the study demonstrates that the effect of the thermal mass in different constructions is negligible in the long term (i.e. monthly or seasonal) evaluation of the mere heat exchange through the envelope. In fact it does not consider the local maxima and their interaction with the other unsteady parameters that strongly affects the zone energy balance (i.e. the internal heat sources, the ventilation heat losses, and mass effect due to every other construction element, as described also in Chap. 3). Therefore the adoption of parameters approximating the dynamic behaviour by the means of simplified parameters adopted in the single element analysis will always give inconsistent results.

References

ASHRAE, *Handbook of Fundamentals* (American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, 1972)

ASHRAE, *Handbook of Fundamentals* (American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, 1989)

ASHRAE, *Handbook of Fundamentals* (American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, 2001)

K. Bansal, S. Chowdhury, M.R. Gopal, Development of CLTD values for buildings located in Kolkata. India. Appl. Therm. Eng. **28**(10), 1127–1137 (2008)

C.S. Barnaby, A survey of simplified techniques for calculating energy effects of building mass, in *Proceedings of the Building Thermal Mass Seminar*, Knoxville TN, 2–3 June 1982

EN ISO 6946, *Building components and building elements—Thermal resistance and thermal transmittance—Calculation method* (European Committee of Standardization, Brussels, 2007)

S. Ferrari, V. Zanotto, Simplified indices assessing building envelope's dynamic thermal performance: a survey, in *Proceedings of the CIB World Congress 2010—Building a Better World*, Salford, 10–13 May 2010a

S. Ferrari, V. Zanotto, Assessing building envelope's dynamic thermal performance through simplified parameters, in *Proceedings of PALENC 2010—Cooling the Cities—The absolute priority*, Rhodes, 29 September-1 October 2010b

R.D. Godfrey, K.E. Wilkes, A.G. Lavine, A technical review of the M factor concept, in *Proceedings of the Conference on the Thermal Performance of the Exterior Envelopes of Buildings*, Kissimmee FL, 3–5 December 1979

Hankins and Anderson, *Report on the effect of wall mass on the storage of thermal energy* (Masonry Industry Committee, Boston, 1976)

Hong Kong Building Authority, Code of practice for Overall Thermal Transfer Values in buildings (1995), http://www.bd.gov.hk/english/documents/code/e_ottv.htm. Accessed 21 Dec 2009

Ö. Kaşka, R. Yumrutaş, Experimental investigation for total equivalent temperature difference (TETD) values of building walls and roofs. Energ. Convers. Manag. **50**(11), 2818–2825 (2009)

P.E. Nilsson, *Heating and cooling requirements in commercial buildings—a duration curve model including building dynamics*, Ph.D. Thesis, Chalmers University of Technology, 1994

P.E. Nilsson, Short-term heat transmission calculations by introducing a fictitious ambient temperature. Energ. Build. **25**, 31–39 (1997)

W.J. Van der Meer, Effective U values: a method for calculating the average thermal performance of building components. (New Mexico Energy Institute—University of New Mexico, Albuquerque, 1978)

H.C. Yu, The M-Factor: a new concept in heat transfer calculations. Consult. Eng. **51**(1), 96–98 (1978)

R. Yumrutaş, Ö. Kaşka, E. Yıldırım, Estimation of total equivalent temperature values for multilayer walls and flat roofs by using periodic solution. Build. Environ. **42**(5), 1878–1885 (2007)

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