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RESEARCH ARTICLE

Thermal Imaging for Detection of Defects in Envelopes of Buildings in Use: Qualitative and Quantitative Analysis of Building Energy Performance

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Abstract
The proposed interdisciplinary method of identifying defects in the building envelope insulation enables the user to quickly assess the scale of heat loss problems in occupied buildings. The method rests upon the quantitative analysis of macroscopic infrared images of the buildings. The method was applied in practice to assess effects of thermal upgrade project in Dźbów housing estate in Częstochowa, a city located in southern Poland. The results confirmed the applicability of the method to monitoring energy performance of buildings in use without intervention into the building's fabric and without disturbing the occupants.

Keywords
multifamily housing stock, periodic inspection of buildings, envelope, insulation defects, thermal imaging

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1 Introduction

Thermal retrofit of the nineteen-sixties' multifamily housing stock in Poland is a necessary though difficult task. The buildings, typically of brickwork structure, were originally of low energy performance. This fact, combined with effects of wear and tear of the buildings' fabric and obsolescence of systems and equipment, makes them being far from contemporary building code requirements and user expectations. However, typically good location and sound structure justify investment in their upgrade. Thermal retrofit projects in these assets are expected to offer quick return in terms of reduced CO_2 emissions, improved quality of life, and increased value of property.

The market offers an abundance of materials and methods for improving thermal properties of building envelopes. However, mistakes in the design of details, bad workmanship, or even the way the buildings are used, seriously limit the scale of benefits from improvements. The ownership structure (private ownership of flats) adds to the problem as, firstly, all owners need to agree on the scope and cost of works and, secondly, they need to grant access to privately owned spaces.

As observed in practice, the building envelope retrofit measures taken so far consisted mostly in applying thermal insulation to the walls, whereas roofs and basement ceilings were left uninsulated. Quite often, the problem of thermal bridging was not properly solved, and basement walls, window reveals, cornices, balconies or chimneys were not sufficiently (or not at all) protected against heat loss [1]. Typically, insulation joints did not get enough attention from the designers and/or builders. The quality of windows and external doors was often questionable even if they were replaced recently; this was confirmed, among others, by Bobrska-Narożny et al. [2]. Another problem was the actual effect of insulating particular elements on the building's energy balance [2].

Therefore, the actual effects of thermal retrofit projects are worth monitoring. Direct measurements could be difficult: in the course of projects the buildings were typically not equipped with measurement systems. To enter the buildings, not to mention particular flats, with test instruments, the researcher would have to get consent of flat owners. For this reason, infrared imaging is considered a useful tool of inspection [3, 4].

Wróbel and Wróbel [4] experimentally confirmed that the heat flux density can be reliably estimated on the basis of thermal images. The authors tested the same buildings by means of heat flux sensors and by analyzing infrared shoots. The heat flux sensor, though useful in laboratory conditions, proved difficult to apply to measurements in the existing buildings as it requires access to both sides of the outer wall, and the results concern a particular point on the surface. In contrast, thermal imaging provides the user with immediate information on non-uniformity of thermal properties of the whole surface of the outer wall [4].

To provide results usable for quantitative analysis of the building envelope's thermal properties, the infrared images need be taken in favorable atmospheric conditions (such as an overcast sky, not too strong wind, with an adequate difference between indoor and outdoor temperatures). The analysis should account for a different emissivity of building components, conditions at the moment of the measurement, and the instrument sensitivity [5, 6, 7]. The requirements on exposition time of thermal images are difficult to adhere to on site in winter time, and the presence of nearby objects such as other buildings or trees inevitably affects the results. In spite of these limitations, thermal imaging is a standard tool in qualitative assessment of buildings [8], and researchers agree that it is the best non-destructive method for testing buildings in the operation phase [9, 10, 11, 12, 13]. Efficiency of thermal imaging in Polish conditions was confirmed in long-term research of Nowak [12], Adamczewski [14], Wróbel et al. [11, 15, 16], Kisielewicz [17] and Ostańska [18].

The analyses are often integrated with a numerical simulation of heat transfer [7, 19, 20]. Wróbel and Kisielewicz [21] used infrared images in their tests on structural thermal bridges. Benko [22] observed that quantitative analysis of the energy dispersion via thermal bridges can be based solely on thermal images of an outer surface of a building wall. The research of Wróbel [16] confirmed that the accuracy of infrared cameras in capturing temperature differences is adequate to provide input for the quantitative assessment. Knowing the value of the theoretical heat transfer coefficient of the wall (calculated for e.g. the energy audit of the building), as well as the indoor and outdoor air temperatures, the thermograms provide enough input for estimating the actual heat transfer coefficient of the wall [4].

A different approach was proposed by Asdrubali et al. [23] extending their previous research based on the standard [24]. The authors defined a parameter that describes the effect of a thermal bridge on the overall performance of the outer wall. Readings from the thermal images were used to calculate the incidence factor of the thermal bridge. The authors proposed a method of image analysis to assess the heat flux perpendicular to the wall surface. The ideas of Asdrubali et al. were developed by Barreneche et al. [25] and Pisello et al. [26] who investigated into the overall effect of thermal bridges on heat losses through the building envelope. The object of testing was a purpose-built one-room building. The building's performance was monitored in terms of the indoor air quality and energy consumption in dynamically changing natural environment in winter time. The building was not inhabited, but entered only by the research team attending sensors, therefore the findings cannot be directly transferred to normally occupied premises. A common problem in the thermal imaging of inhabited buildings is to meet the condition of perpendicular measurement, which requires collision-free access from each side of the building..

The literature on thermal imaging presents applications of dynamic infrared analysis: changes in the thermal image of a surface in the process of controlled heating allow the researchers to detect hidden details or damages [27]. The method was used, among others, to detect wall paintings covered by layers of plaster in heritage buildings with no interference in the building's fabric, or to map defects like plaster delamination or moisture infiltration areas. However, as the tested component of the building has to be directly accessed to be heated, the method would not be convenient in the analysis of the whole envelope of an inhabited housing block.

As observed in practice, the energy audits of buildings contain calculations for external wall with no consideration of thermal bridging (the Polish standard allows omitting thermal bridges if a correct insulation is assumed). This means that the auditors assumed a perfectly tight insulation layer, with no allowance for "bad workmanship". However, thermal insulation is rarely completed with enough care for detail. As comes from the literature review, there exists no widely accepted method of monitoring actual effects of thermal retrofit of buildings. Therefore, the research question is: is it possible to reliably estimate the actual thermal properties of the recently insulated elements of the building's envelope on the basis of thermal images? If so, the results could be used to plan and design further improvement measures. The aim of research is to develop a simple non-invasive method of identification and quantification of deficiencies in the shell of occupied buildings.

The proposed method combines input from on-site macroscopic observations (among others, thermal images) with the analysis of building records (among others, the energy performance parameters calculated according to the standards and present in the building's original plans or audits) to assess the actual effect of retrofit measures taken so far, and to define the scope and urgency of further improvement or repair actions.

2 The method

The idea of the proposed method of analysis of building energy performance (MA-ST-AN) is presented in Fig. 1.

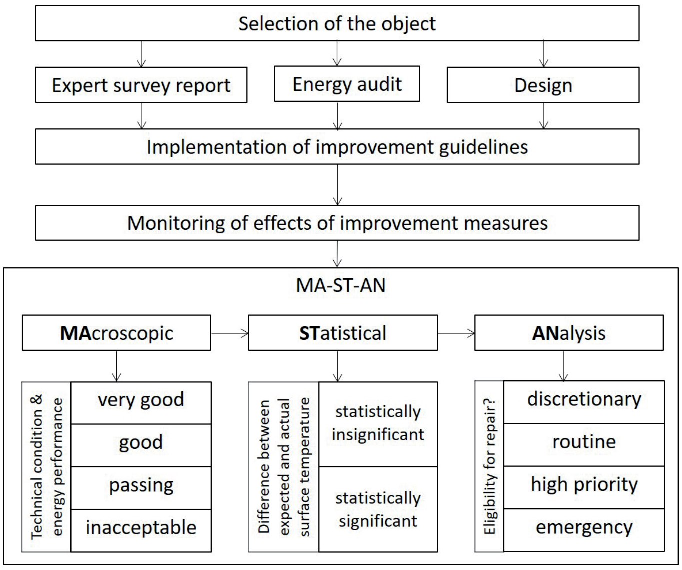

Fig. 1 MA-ST-AN method of analysis building energy performance

After the object of analysis is selected, its archival records are searched for any details on current energy performance. The records include: the original design, energy audits, and survey reports. The next step is to check whether any modifications or improvement measures (recommended by audits/surveys or not) were actually implemented. Then the building is to be surveyed element by element, and thermal images of the envelope are to be taken. This way, a complete set of input related to the current state of the building is prepared, with a list of new or remaining thermal bridges.

The next step consists in a three-stage assessment of the building on the basis of the above mentioned input. The first stage is the macroscopic analysis (MA-) of thermal images and linear profiles of characteristic sections of the envelope. It is aimed at assessing quality of the thermal insulation of the building shell. This quality was classified in four categories: very good, good, passing, inacceptable. Then a statistical analysis (-ST-) is to be conducted to determine whether the differences between the actual and the expected temperature of the considered element are statistically significant or insignificant, that is to say whether they should be classified as a thermal bridge. The last step, so the final analysis (-AN), involves classifying the object into one of the four categories of recommended corrective actions: discretionary, routine, high priority or emergency (Fig. 1).

The calculations of the actual heat transmittance coefficient were assumed to follow a modified method described by Wróbel [4] and Miczka [28] that is based on a simplified formula of Fourier's law. The approach was applied to the assessment of selected energy retrofit measures and found reliable by Kulka [29]. On this basis, a simplified and non-intrusive method of assessing actual heat transmittance coefficient of the shell of an insulated building was proposed. The actual heat transmittance coefficient of a wall (U1) was estimated according to Eq. (1):

$$\frac{U_1}{U_2} = \frac{T_1 - T_e}{T_2 - T_e}, \tag{1}$$

where: U_1 is the actual heat transmittance coefficient, W/m^{2}K, U_2 – the as-designed heat transmittance coefficient (as calculated in the design or as determined in the energy audit), W/m^{2}K, T_1 – the actual temperature of the object, read from the thermal image (cold side), °C, T_2 – the expected temperature of the object, calculated according to the standard or read from the thermal image in the part of the properly insulted envelope (cold side), °C, and T_e – the ambient temperature at the moment of measurement (on the cold side of the envelope), °C.

In the proposed approach, the actual surface temperature was derived from the thermal images of the cold side of the envelope, read in 10 points on the line along the element considered as a thermal bridge and along the line on the properly installed insulation.

Having identified the envelope deficiencies, the user of the method may proceed to defining the current status of the building envelope elements as acceptable or eligible for repair/improvement (Fig. 1). If intervention in the building fabric is required, its urgency can be defined as one of the following: discretionary (no required completion date stated), routine (to be completed within up to 5 years), high priority (to be completed within one year), and emergency (requiring immediate action). On the basis of the above described analysis, the actual condition of the building elements can be precisely assessed. This, after initial statistical and analytical verification, directs further modifications of the building, or provides grounds for accepting the current state of the building as satisfactory.

3 Application of the method

3.1 The case

The case to follow serves as an illustration of the method's application. The object of the analysis was an estate of multifamily housing blocks located in Dźbów housing area of Częstochowa (N50°49'04", E19°08'18"). The blocks were subject to an energy retrofit project aimed at reducing CO_2 emissions of the municipal housing stock. Figure 2 presents a typical building of the estate.

Fig. 2 The object of analysis. Photo: Nowak S. [1].

The project involved modernization of 39 blocks with 610 flats, and a municipal kindergarten [1]. The buildings, erected in nineteen-fifties, were heated by means of individual tile stoves or coal boilers serving a whole building. The energy retrofit project [30] included insulation of external walls, basement ceilings and attic floors as well as replacement of windows and external doors. In addition, the gas network of the housing estate was completed and the buildings were equipped with central gas heating systems [1].

3.2 The methods

The on-site survey to assess the effects of energy retrofit was conducted in February 2012, so two years after the completion of works. Thermograms of all 39 buildings of the estate (over 500 images) were taken by means of FLIR B350 from the ground level. The images were taken in the early morning before sunrise (between 4 and 5:50 a.m.) so that the assumption on constant indoor temperature [4] could be considered true. As there was no access to the flats, the author assumed that the indoor temperature was 20°C (in Poland, this temperature is preferred for indoor settings), and that the heater settings were unchanged for at least 4 hours prior to the test. The temperature outside the building dropped from -5 to -10°C during last eight hours before the test, and stabilized at -10°C during the time of the test [14]. The wind was weak (below 2m/s).

A detailed qualitative analysis concerned the most typical (repeatable) cases of thermal bridges of highest heat radiation. They were selected on the basis of thermal images if their temperature differed by no less them 3K from the temperature of nearby components. The images of building facades were analyzed by means of FLIR Reporter 8.5. All 39 buildings were analyzed, but the results presented in the tables and on the figures concern a particular area of a particular building – though, by comparison with similar locations in other buildings, they are considered representative.

Readings were taken from the points along the measurement line of the properly installed insulation of external walls and along the objects assumed to be thermal bridges. The mean temperature was calculated for the properly insulated envelope (as the expected temperature) and for each object assumed as a thermal bridge (as the actual temperature). The statistical significance of the differences between these temperatures was established using the T-test. If the difference between the expected and the actual temperature of a an area considered a colder spot was statistically significant, the area was qualified as a thermal bridge and selected for further analysis. The actual heat transfer coefficient was calculated from Eq. (1) for each measurement point, and results are given as the mean values with standard deviation. The percentage difference between the actual heat transfer coefficient and that given by the audit (U_2 = 0.236 W/m^{2}K) [31] was also calculated.

Table 1 The state of the element's insulation

No.	Element	Insulation as designed in 2009	Actual insulation	Comments
1.	Basement wall, insulation with identified thermal bridge	7 cm of EPS boards	7cm of EPS with unintended cavity*	Conduct statistical analysis
2.	Basement wall, correct insulation		7 cm of EPS boards without cavity*	Conduct statistical analysis
3.	Balcony	2 cm of EPS boards	None**	Conduct statistical analysis
4.	Upper surface of window opening	14 cm of EPS boards in two layers (2×7) or 16 cm	None**	Conduct statistical analysis
5.	Cornice		None**	Conduct statistical analysis

* according to the construction reports,

** according to the *in situ* studies and thermal images

Table 2 Selected deficiencies in the insulation

No.	Element*	Identified deficiencies*	p-level of statistical significance test**	Conclusion**
1.	Basement wall, insulation with identified thermal bridge	Discontinuous insulation between the basement wall and the superstructure wall	$p<0,05$	Statistically significant
2.	Correctly insulated basement wall	none	$p>0,05$	Not statistically significant
3.	Balcony	No insulation	$p<0,001$	Statistically significant
4.	Lintel	No insulation	$p<0,001$	Statistically significant
5.	Cornice between floors	No insulation	$p<0,001$	Statistically significant

* the phase of the macroscopic analysis (MA-);

** the phase of the statistical analysis (-ST-)

3.3 Results

As some deficiencies in the thermal insulation of the building had been identified, their reasons were analyzed. Table 1 contains information on the state of the actual thickness of the insulation determined in the course of the "in situ" investigations (2012), as compared to the as-designed thermal insulation [30]. The detailed thermographic analysis of the areas of considerable heat losses enables the user to identify thermal bridges, then to conduct a statistical analysis (Table 2), and to quantitatively assess the actual heat loss coefficient (Table 3). As a result, a database of elements most obvious as thermal bridges was compiled, containing basement walls, lintels, balconies and cornices.

Let us consider the basement wall (Fig. 3, Fig. 4). Measurements in four selected areas and their statistical analysis confirmed that only the area no. 1 was insulated correctly: the temperature measured on site was not statistically different ($p>0.05$)

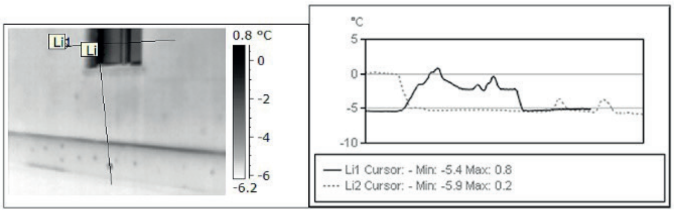

Fig. 3 Thermal image of a fragment of elevation of the insulated building and the analysis of a window and basement wall – description in the text

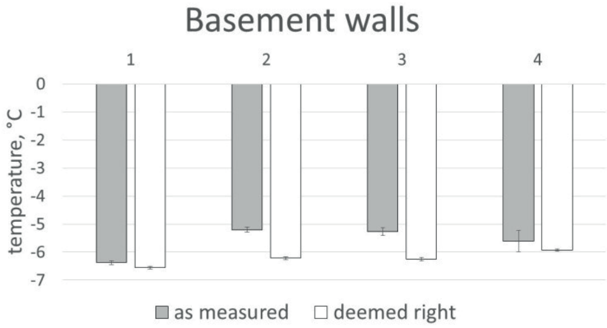

Fig. 4 Mean differences in temperature between the selected areas of basement walls and correctly insulated wall; "deemed right" means the temperature of a properly insulated surface

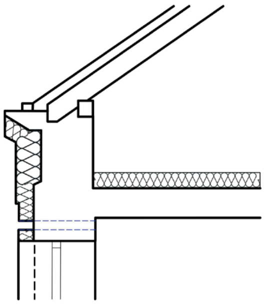

Fig. 5 Fragment of the section of the building as in the original design [30]

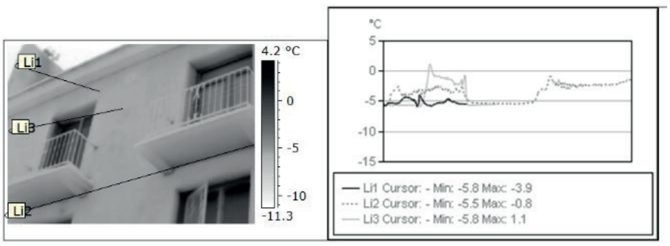

Fig. 6 Thermal image of a fragment of elevation of the insulated building and the analysis of a fragment of the external wall with balconies – description in the text

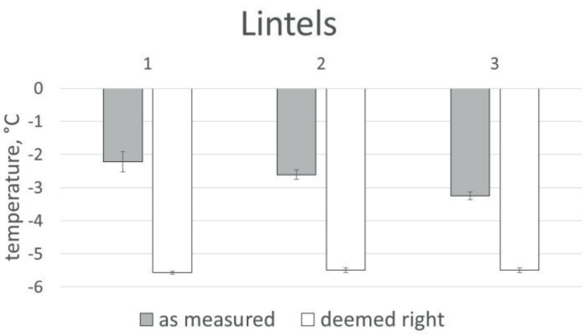

Fig. 7 Mean differences in temperature between selected areas of a lintel and correctly insulated wall; "deemed right" means the temperature of a properly insulated surface

from the temperature deemed correct, as expected on the outer surface of the properly insulated wall. In the case of the remaining areas (2–4), the difference between the measured temperature and the temperature deemed correct were statistically significant ($p < 0.05$).

As for the lintels (Fig. 5, Fig. 6, Fig. 7), measurements were taken in three selected areas and their statistical analysis indicated that the lintels were not correctly insulated. The temperature measured on site was statistically different ($p < 0.001$) from the temperature deemed correct, so expected from a properly insulated element.

Balconies (Fig. 8, Fig. 9) were checked in a similar manner and proved to be inadequately insulated. The temperature measured on site was statistically different ($p < 0.001$) from the expected temperature. The measurements were taken on the outer surface of the corner between the balcony slab and the wall.

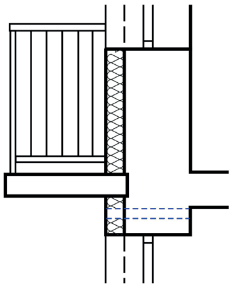

Fig. 8 Fragment of the section of the building as in the original design [30]

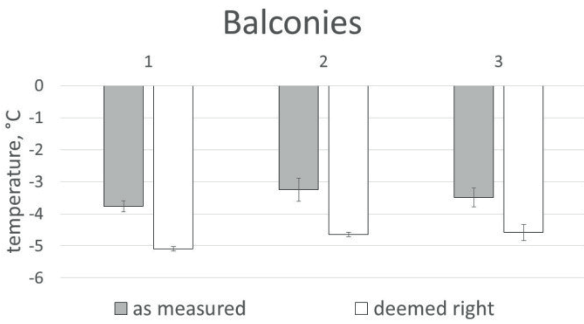

Fig. 9 Mean differences in temperature between selected areas of balconies and a correctly insulated wall; "deemed right" means the temperature of a properly insulated surface

Fig. 10 Mean differences in temperature between selected areas of a cornice between floors and a correctly insulated wall; "deemed right" means the temperature of a properly insulated surface

Cornices between floors (Fig. 10) occurred to be uninsulated. Measurements were taken in four selected areas on their surface. The measured temperature was statistically different ($p < 0.001$) from the temperature considered correct.

As a result of the research and analysis it was found that the most intense thermal bridging effect was that of lintels (Table 3, item 4), for which the calculated actual heat transfer coefficient was 0.50 ± 0.17W/m^{2}K (Table 1) and was more than twice as high as the one found in the audit [31]. It should be noted that the *in situ* study confirmed that the lintels had not been insulated (Table 1–2), in spite of recommendations of the specification [30]. This qualifies the lintels as urgently in need for insulating (high priority), despite the wall insulation was installed in 2009.

Another important thermal bridges were cornices between floors (Table 3, item 5), whose calculated actual heat transfer coefficient was 0.49 ± 0.09 W/m^{2}K, so more than twice as high as the number given by the audit. The *in-situ* studies have confirmed the absence of insulation of the cornice (Tables 1–2), though the specification [30] clearly indicated that it was required. As in the case of the lintels, this gives the cornices a high priority status (the insulation should be completed within one year).

The cause of thermal bridging at the basement walls was the unsealed joint between the insulation of the ground floor wall and the basement wall. As a result (Table 3, item 1), there was a local reduction in thermal quality of the envelope – over 45% in comparison with the properly insulated basement wall. This joint was recommended for insulation in the routine mode (the insulation should be completed within five years). The thermal effect of a correct insulation of the basement wall with a 7 cm polystyrene boards without a thermal bridge in the joint, is shown in Table 3, item 2. It was confirmed that it is possible to tighten the insulation and to avoid thermal bridging on the basement wall, and the cause of increased heat efflux at the contact of the insulation boards was the result of careless fitting of insulation elements. A properly installed basement wall insulation, consistent with the design, would not require any improvements.

The analysis confirmed the presence of linear thermal bridges at the balconies (Table 3, item 3), whose actual heat transfer coefficient was 0.36 ± 0.04 W/m^{2}K and was slightly over 50% higher than assumed in the audit [31]. In the case of this element, a thermal bridge on the contact of the balcony with the basement wall has been found and this item was recommended for repair in the routine mode (within 5 years).

The cause of the thermal bridge in the outer reveal surfaces was the lack of planned insulation in the design [30]. The effect of the thermal bridge on lintels (Table 3, item 4) was local reduction of thermal quality; its actual heat transfer coefficient was 0.50 ± 0.17 W/m^{2}K, so over 110% higher than that of the correctly insulated envelope. The lack of insulation on the reveal calls for a high priority repair (up to 1 year).

To summarize the findings, the energy retrofit measures taken in the analyzed housing estate had a positive effect on the user comfort as well as on market value of the built assets. According to the energy audits, the overall energy demand of the estate was expected to drop by 72% [1]. An inspection with use of thermal imaging, conducted some time after completion of the works, confirmed that the quality of insulation was satisfactory, though not without reservations.

4 Conclusions and further research

The proposed approach to identify insulation deficiencies, MA-ST-AN, that consists of a macroscopic assessment of heat losses through elements pointed to by means of thermal imaging (MA-), a determination of the statistical significance of differences between the mean temperature of the thermal bridge and the properly insulated wall based on thermal

Table 3 Relative difference between the heat transfer coefficient on the basis of the thermograms (U_{mean}) and given in the audit, and recommendations for improvement

No.	Element tested	Tmean the base of thermogram, °C *	The mean difference in the temperature of the test element and properly insulated wall, read from the thermogram**	U_{mean} W/(m^{2}K)	Standard deviation of U_{mean} W/(m^{2}K) **	(U_{mean} /U_{audit}) 100 %	Conclusions: repair recommendation and the mode of implementation ***
1.	Basement wall, insulation with identified thermal bridge	-5,36	0,77	0,40	0,09	170,7	Routine
2.	Correctly insulated basement wall	-6,38	0,18	0,30	0,03	125,0	Repair not necessary
3.	Balcony	-3,50	1,27	0,36	0,04	151,3	Routine
4.	Lintel	-2,69	2,83	0,50	0,17	210,5	High priority
5.	Cornice between floors	-4,74	1,32	0,49	0,09	206,5	High priority

* the phase of MAcroscopic analysis (MA-);

** the phase of STatistical analysis (-ST-);

*** the phase of the ANalysis (-AN).

images (-ST-), and an estimation of actual heat transfer coefficient using Eq. (1) with further analysis and recommendations for repair action (-AN), has been successfully used to evaluate the quality of the thermal insulation of many buildings. The method, based on the query of the building design documents and the audit data, and on the analysis of thermal images, may become a tool facilitating a non-invasive assessment of the effects of thermal upgrade of inhabited buildings. The method allows the user to identify deficiencies and formulate recommendations for further repair of the elements which are not adequately insulated, and can contribute to increased energy savings in the analyzed buildings. The author's experience with practical applications prompts that, with the current state-of-the-art in the repair technologies, the proposed repairs are possible to be conducted even to a recently insulated building, and they are almost non-invasive. Examples of non-destructive technical solutions for the elimination of thermal bridges in insulated can be found e.g. in [32] on methods of sealing insulation joints between the new plastered insulation of the walls and the lintels. The costs of the repair is small compared to the costs caused by the heat losses in long-term operation of the built facility. In addition, the abandonment of corrective actions may have an impact on the durability of the insulation. Ideally, all recommended repairs would be done at the same time. However, the main goal of the research is to select the most urgent interventions.

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References

[1] Taracha, K., Ostańska, A., Nowak S. "Propozycje poprawy jakości życia w budynkach prefabrykowanych". *Przegląd Budowlany*. 83(9), pp. 36–41. 2012.

[2] Bobrska-Narożny, M., Stevenson, F., Grudzińska, M. "Overheating in retrofitted flats: occupant, learning and interventions". *Building Research& Information*, 45(1–2), pp. 40–59. 2016. https://doi.org/10.1080/09613218.2016.1226671

[3] Vavilov, V. P. "A pessimistic view of the energy auditing of building structures with the use of infrared thermography". *Russian Journal of Nondestructive Testing*, 46(12), pp. 906–910. 2010. https://doi.org/10.1134/S1061830910120065

[4] Wróbel, A., Wróbel, A. "Kontrola termograficzna izolacyjności cieplnej nowo wzniesionych budynków mieszkalnych cz. I.". *Inżynier Budownictwa*, 2(3), pp. 55–60. 2011.

[5] Avdelidis, N. P., Moropoulou, A. "Emissivity considerations in building thermography". *Energy and Buildings*, 35(7), pp. 663–667. 2003. https://doi.org/10.1016/S0378-7788(02)00210-4

[6] Barreira, E., de Freitas, V. P. "Evaluation of building materials using infrared thermography". *Construction and Building Materials*, 21(1), pp. 218–224. 2007. https://doi.org/10.1016/j.conbuildmat.2005.06.049

[7] Datcu, S., Ibos, L., Candau, Y., Matteï, S. "Improvement of building wall surface temperature measurements by infrared thermography". *Infrared Physics & Technology*, 46(6), pp. 451–457. 2005. https://doi.org/10.1016/j.infrared.2005.01.001

[8] PN-EN 13187 "Właściwości cieplne budynków – Jakościowa detekcja wad cieplnych w obudowie budynku – Metoda podczerwieni". 2001.

[9] Balaras, C. A., Argiriou, A. A. "Infrared thermography for building diagnostics". *Energy and Buildings*, 34(2), pp. 171–183. 2002. https://doi.org/10.1016/S0378-7788(01)00105-0

[10] Lo, Y. T., Choi, K. T. W., "Building Defects Diagnosis by Infrared Thermography". *Structural Survey*, 22(5), pp. 259–263. 2004. https://doi.org/10.1108/02630800410571571

[11] Nowak, H. „Ochrona cieplna obiektów budowlanych w aspekcie oszczędności energii w budownictwie na świecie – nowe możliwości pomiarów za pomocą urządzenia termowizyjnego". In: *Optymalizacja systemów budownictwa uprzemysłowionego. IV Toruńska Konferencja Problemowa, Toruń*, pp. 205–217. 1979.

[12] Nowak, H. "*Zastosowanie badań termowizyjnych w budownictwie*". Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2012.

[13] Snell, J., Spring, R. "*Nondestructive Testing of Building Envelope Systems Using Infrared Thermography*". Snell Infrared Montpelier, Vermont, 800-636–920, 2002.

[14] Adamczewski, W. "Zastosowania termowizji w budownictwie". In: *Pomiary termowizyjne w praktyce. Agenda Wydawnicza Pomiary Automatyka Kontrola*, Warszawa 2004.

[15] Kisielewicz, T., Wróbel, Al., Wróbel, A. "*Inwentaryzacja rzeczywistych strat ciepła przez przegrody budynków z wykorzystaniem termografii*". Archiwum Fotogrametrii, Kartografii i Teledetekcji, 18, pp. 231–240. 2008. http://ptfit.sgp.geodezja.org.pl/wydawnictwa/miedzyzdroje/AFKIT_vol18a_Kisielewicz.pdf

[16] Wróbel, A. "Termografia w pomiarach inwentaryzacyjnych obiektów budowlanych". In: *Rozprawy Monografie nr 209, Wydawnictwa AGH*, Kraków. pp. 1–135. 2010.

[17] Kisielewicz, T. "*Wpływ izolacyjnych, dynamicznych i spektralnych właściwości przegród na bilans cieplny budynków energooszczędnych*". Wydawnictwo Politechniki Krakowskiej. Kraków 2008.

[18] Ostańska, A. "*Podstawy metodologii tworzenia programów rewitalizacji dużych osiedli mieszkaniowych wzniesionych w technologii uprzemysłowionej na przykładzie osiedla im. St. Moniuszki w Lublinie*". Politechnika Lubelska, Monografie Wydziału Inżynierii Budowlanej i Sanitarnej vol. 1, Wydawnictwa Uczelniane Lublin, 2009.

[19] Déqué, F., Ollivier, F., Roux, J. J. "Effect of 2D modelling of thermal Bridges on the Energy performance of buildings – numerical application on the Matisse apartment". *Energy and Buildings*, 33(6), pp. 583–587. 2001. https://doi.org/10.1016/S0378-7788(00)00128-6

[20] Zalewski, L., Lassue, S., Rousse, D., Boukhalfa, K. "Experimental and numerical characterization of thermal bridges in prefabricated building walls". *Energy Conversion and Management*, 51(12), pp. 2869–2877. 2010. https://doi.org/10.1016/j.enconman.2010.06.026

[21] Wróbel, A., Kisielewicz, T. "Detection of thermal Bridges – aims, possibilities and conditions". In: *9. International Conference on Quantitative Infrared Thermography*, Jul. 2–5, 2008, Cracow, Poland.

[22] Benko, I. "*Quantitative analysis of thermal Bridges of structures through infrared thermograms*". Qirt 2002. Dubrovnik, Croatia, September 24–27; 2002. http://dx.doi.org/10.21611/qirt.2002.027

[23] Asdrubali, F., Baldinelli, G., Binanchi, F.A. "A quantitative methodology to evaluate thermal Bridges in buildings". *Applied Energy*, 97, pp. 365–373. 2012. https://doi.org/10.1016/j.apenergy.2011.12.054

[24] Asdrubali, F., Baldinelli, G. "Thermal transmittance measurements with the hot box method: calibration, experimental procedures, and uncertainty analyses of three different approaches". *Energy and Buildings*, 43(7), pp. 1618–26. 2011.
https://doi.org/10.1016/j.enbuild.2011.03.005

[25] Barreneche, C., de Gracia, A., Serrano, S., Navarro, M. E. E., Borreguero, A. M., Fernández, A. I., Carmona, M, Rodriguez, J. F., Cabeza, L. F. "Comparison of the different devices available in Spain to test thermal properties of building materials including phase change materials" *Applied Energy*, 109, pp. 421–427. 2013.
https://doi.org/10.1016/j.apenergy.2013.02.061

[26] Pisello, A. L., Cotana, F., Nicolini, A., Buratti, C. "Effect of dynamic characteristics of building envelope on thermal-energy performance in winter conditions: In field experiment". *Energy and Buildings*, 80, pp. 218–230. 2014.
https://doi.org/10.1016/j.enbuild.2014.05.017

[27] Grinzato, E., Vavilov, V., Kauppinen, T. "Quantitative infrared thermography in buildings". *Energy and Buildings*, 29(1), pp. 1–9. 1998.
https://doi.org/10.1016/S0378-7788(97)00039-X

[28] Miczka, G. "Rola pomiarów w certyfikacji i auditingu energetycznym budynków. Termografia – trzecie oko audytora energetycznego". *Doradca Energetyczny*, 2, pp. 25–27. 2012.

[29] Kulka, K. "Zastosowanie kamery termowizyjnej do „identyfikacji wad izolacji termicznej budynków". pp. 18–20. www.termo-control.pl

[30] Kędzierski, P., Jabłońska, M., Materak, I., Mesjasz, M., Walczyk, M. "Projekt Budowlany". In: *Termorenowacja budynku mieszkalnego wielorodzinnego oraz remont przewodów spalinowych i wentylacyjnych*. Pracownia Projektowa "ATTYKA" Piotr Kędzierski Częstochowa, październik 2009 r.

[31] Kukla, P. "Audyt energetyczny budynku mieszkalnego przy ul. Wopistów 1. Fundacja na rzecz Efektywnego Wykorzystania Energii". Katowice, aktualizacja maj 2009.

[32] Ostańska, A. "*WIELKA PŁYTA. Analiza skuteczności podwyższania efektywności energetycznej*". Termodernizacja, termografia, wytycznenaprawcze."Wydawnictwo PWN 2016.