Assessment of the energy performance of buildings

V V Khan¹, N P Dekanova² and P V Khan³

¹Irkutsk National Research Technical University, Lermontov str. 83, Irkutsk, Russia
²Department of information systems and information security, Irkutsk State Transport University, Chernyshevkogo str., bld. 15, Irkutsk, Russia
³Melentiev Energy System Institute, Lermontov str. 130, Irkutsk, Russia

E-mail: khan@istu.edu

Abstract. The problems of the heat engineering condition of buildings during operation diagnos
are considered. A significant problem is the difficulty of obtaining measurement and other
information for complete decision making. As a result of this, it is often necessary to make
technical decisions regarding the long-term operation of facilities in conditions of
incompleteness and fuzzy information about their functioning and their condition The use the
methods of the theory of fuzzy sets. is proposed when making technical decisions to increase the
energy efficiency of objects.

Currently, the energy efficiency survey of a large number of buildings and structures is being carried
out as part of the energy audit of organizations in accordance with Federal Law No. 261 “On Energy
Saving and Energy Efficiency Improvement and Amending Certain Legislative Acts of the Russian
Federation”, as well as Programs to promote housing and communal services reform after major re
pairs or reconstruction of residential buildings.

An important component of the energy inspection of buildings is the diagnosis of their energy
performance, which consists of the condition of the building envelope, the condition of the internal
heating pipes, ventilation and hot water supply, the availability and quality of work of regulation systems
[1, 2]. Operational diagnostics of the energy performance of buildings and structures is also necessary
for the organization of their high-quality operation, which is especially important for areas with a long
heating period and high tariffs for electricity and thermal energy [3-8].

In the ideal case, for a full-fledged diagnosis, it is necessary to have, along with technical
documentation, the ability to take air temperature measurements in all rooms of the building while
simultaneously recording the outside temperature; thermograms of all internal and external surfaces
obtained simultaneously; heat carrier temperatures in all sections of the internal heating p
pipes. It is
important to obtain the results of such measurements at different outdoor temperatures. Obviously,
taking measurements in such a volume requires significant costs and is advisable in exceptional cases
[8-11]. In most cases, when examining buildings and structures, a very limited scope of measurements is
available. At the same time, it is important to maximize the use of additional information obtained
from surveys of operating personnel and users of the premises. Information of this kind usually falls
into the category of fuzzy information and is presented in the form of intuitive or expert judgments. For
example, “hot”, “warm”, “cool”, “cold” - if this relates to indoor air temperature. Regarding the quality
of regulation of indoor microclimate parameters, one can obtain estimates of this kind: “good”,
“normal”, “satisfactory”, “unsatisfactory”. In terms of assessing the condition of building envelopes,
one can also obtain judgments of the type: “normal”, “satisfactory”, “unsatisfactory”. Some of the information is fuzzy in nature. For example, heat carrier flow in open heat supply networks depends on many factors, while constantly changing over time. The imbalance of heating networks often leads to the fact that in peripheral objects the available pressure drop between the supply and return pipelines is insufficient to ensure normal circulation of the heat carrier. In such cases, users often resort to draining the coolant into the sewer [4,6]. This, in turn, affects the distribution of flows in the heating networks and the hydraulic modes of their operation. Obviously, user behavior can only be described on the basis of fuzzy set theory approaches. Usually, qualitative indicators of the thermal conductivity characteristics of building envelopes obtained as a result of surveys are taken into account on an intuitive level, or based on expert judgment [1-3]. At the same time, modern methods of the theory of fuzzy sets are widely and effectively used for decision-making in a wide variety of fields. [2-5].

Given the above factors, it is advisable to use an integrated approach based on the combined use of measurement results, analysis of balance relations of objects of different hierarchical levels and methods of the theory of fuzzy sets [1, 6] to diagnose the state of engineering systems of buildings. At the same time, it seems important to develop a formalized decision-making algorithm taking into account fuzzy information. The aim of the present work is to develop an algorithm for diagnosing the heat engineering state of a residential building based on the approaches of the theory of fuzzy sets [12-15].

Usually, when examining heat consumption objects, their design characteristics and contractual loads are known, the results of flow measurements and the parameters of the heat carrier at the entrance to the building are available, the results of measurements of the temperature of the heat carrier along the risers are known. However, the available information is insufficient to determine the actual thermal and hydraulic modes of the heating system, to assess the energy performance of the building envelope and the actual loss of thermal energy. Additional sources of information may be the results of thermography of the building, as well as conclusions obtained on the basis of a rule base based on fuzzy information [12,13].

Based on the results of a survey of experts, qualitative scales are formed for three characteristics: the indoor air temperature, the deviation of the indoor climate parameters from the normative and the deviation of the state of the building envelope from the design. The indoor air temperature is evaluated according to the following quality scale: “very cold”, “cold”, “cool”, “normal”, “warm”, “hot”. Membership functions are formed for each indicator according to the experts judgments. The membership functions are linear for the extreme indicators “very cold” and “hot”:

- “very cold”
  \[
  \mu^l(x) = \alpha(x) \cdot \frac{x_{max}^l - x}{x_{max}^l - x_{min}^l}, \text{ где } \alpha(x) = \begin{cases} 1, & x_{min}^l \leq x \leq x_{max}^l \\ 0, & \text{иначе} \end{cases}
  \]

- “hot”
  \[
  \mu^p(x) = \alpha(x) \cdot \frac{x - x_{min}^p}{x_{max}^p - x_{min}^p}, \text{ где } \alpha(x) = \begin{cases} 1, & x_{min}^p \leq x \leq x_{max}^p \\ 0, & \text{иначе} \end{cases}
  \]

For intermediate indicators “cold”, “cool”, “normal”, “warm” the membership functions are non-linear and are determined by the following relation:

\[
\mu^k(x) = e^{-\frac{(x - \alpha(x))^2}{2(x_{max}^k - x_{min}^k)^2}}, \text{ где } \alpha(x) = \frac{x_k - x_{min}^k}{x_{max}^k - x_{min}^k}, \quad k = 1, ..., 4.
\]

In relations (1)-(3) \(X\) - current value of the characteristic; \(x_{min}^{l,p,k}\) and \(x_{max}^{l,p,k}\) - limit values of relevant indicators.

Graphs of membership functions of indicators of internal air temperature are given in the figure. 1.
The control of the indoor climate parameters according to the results of a survey of residents is evaluated on a scale of "good", "normal", "satisfactory", "unsatisfactory". When forming membership functions for the indicators "good" and "unsatisfactory", formulas (1) and (2) are used, respectively, and for the indicators "normal" and "satisfactory", the formula (3) is used. Membership functions corresponding to such judgments are shown in the figure.

The condition of the building envelope is estimated by the deviation of the value of the overall heat transfer coefficient of the building from the normative indicator in three gradations: "normal", "satisfactory", "unsatisfactory". Membership functions formed in accordance with relations (1) - (3) are shown in Figure 3.
To diagnose the energy performance of buildings, we define the following rule base:

1. Poor quality of service by the operating organization if
   - the indoor temperature is rated as very cold, cold or hot;
   - regulation of the water temperature in the heat network is rated as very good or normal;
   - building heat transfer coefficient is rated as satisfactory or unsatisfactory.

2. Unsatisfactory quality of heat carrier supply by heating network company if:
   - the indoor temperature is rated as very cold, cold or hot;
   - regulation of the water temperature in the heat network is rated as satisfactory or unsatisfactory;
   - building heat transfer coefficient is rated as good, normal or satisfactory.

3. Good quality of service by the operating organization if
   - the indoor temperature is rated as normal or warm;
   - regulation of the water temperature in the heat network is rated as satisfactory or unsatisfactory;
   - building heat transfer coefficient is rated as normal or satisfactory.

4. All services work fine
   - the indoor temperature is rated as normal or warm;
   - regulation of the water temperature in the heat network is rated as very good or normal;
   - building heat transfer coefficient is rated as normal.

The algorithm for obtaining a conclusion about the energy performance of buildings and the quality of service, based on the results of the observation and the rule base, is as follows.

At the current time, the indicators of the indoor temperature, the characteristics of regulating the temperature of the network water and the actual heat transfer coefficient are estimated. We call such a set of parameters "a situation". Further, for each situation, the following steps of the algorithm are performed.

1. For each rule i, the value of the membership function of each characteristic j is determined in accordance with the union operation based on the s-norm (algebraic sum):
   \[ \mu_i(x_j) = \bigvee_{k \in K_j^i} \mu_k(x_j), \quad i = 1, \ldots, 4; \quad j = 1, \ldots, 3. \]

For each rule i, the value of the generalized membership function is determined in accordance with the intersection operation on the basis of the t-norm (average):

\[ \mu_i(x_1, x_2, x_3) = \mu_i(x_1) \bigwedge \mu_i(x_2) \bigwedge \mu_i(x_3), \quad i = 1, \ldots, 4. \]
2. To determine the resulting value of the membership function and select the output corresponding to the situation in question, the accumulation operation is used:

\[ D = \max_{i=1,4} \mu^i(x_1, x_2, x_3). \]

We illustrate the operation of the algorithm in the following example. Suppose that during monitoring of heat consumption objects 10 different situations are recorded (table 1, figure 4).

| Situation number | Air temperature, °C | Network water temperature deviation, % | Building heat transfer coefficient deviation, % |
|------------------|---------------------|----------------------------------------|-----------------------------------------------|
| 1                | 12                  | 1                                      | 12                                            |
| 2                | 16                  | 3                                      | 20                                            |
| 3                | 27                  | 2                                      | 10                                            |
| 4                | 12                  | 4                                      | 5                                             |
| 5                | 16                  | 6                                      | 8                                             |
| 6                | 27                  | 5                                      | 11                                            |
| 7                | 23                  | 4                                      | 3                                             |
| 8                | 25                  | 7                                      | 10                                            |
| 9                | 23                  | 1                                      | 2                                             |
| 10               | 25                  | 2                                      | 5                                             |

Figure 4. Observation data.
Based on the membership functions, qualitative estimates of the observed situations were obtained (table 2).

**Table 2. Qualitative assessment of the observed situations.**

| Situation number | Air temperature | Network water temperature deviation | Building heat transfer coefficient deviation |
|------------------|-----------------|---------------------------------------|---------------------------------------------|
| 1                | very cold       | very good                             | satisfactory                                |
| 2                | cold            | satisfactory                           | unsatisfactory                             |
| 3                | hot             | normal                                | satisfactory                                |
| 4                | very cold       | satisfactory                           | normal                                     |
| 5                | cold            | unsatisfactory                        | satisfactory                                |
| 6                | hot             | satisfactory                           | satisfactory                                |
| 7                | normal          | satisfactory                           | normal                                     |
| 8                | warm            | unsatisfactory                        | satisfactory                                |
| 9                | normal          | very good                             | normal                                     |
| 10               | warm            | normal                                | normal                                     |

A graphical representation of the values of the membership function for each rule is given in Figure 5. Based on the graph, for each situation, not only the value of the membership function of the dominant rule, but also the ratio of the values of the membership functions of each rule to each other can be evaluated.
The result of the algorithm execution is the conclusion based on the rule base on the quality of the heating network company and the quality of servicing heat consumption objects from the operating organization and the values of the resulting membership function for the situations under consideration (table 3).

The results obtained make it possible to take into account the oral information obtained by interviewing operating personnel and/or residents when making decisions. Further development of the proposed approach is associated with the development of a model that takes into account the full range of information obtained during measurements and during surveys.

**Table 3.** Qualitative and quantitative assessment of the situations under consideration, obtained on the basis of membership functions and formulated rules.

| Situation | Diagnos                                      | Value   |
|-----------|----------------------------------------------|---------|
| 1         | Unsatisfactory performance of the operating organization | 0.649   |
| 2         | Unsatisfactory performance of the operating organization | 0.297   |

![Figure 5. Values of membership functions of each of the four rules for the situations under consideration.](image)
Acknowledgements

This work was carried out as part of work on the topic of research No. 30/19 of IRTU with partial financial support from Melentyev Energy Systems Institute of SB RAS in the framework of the scientific project III.17.1.3 of the program of basic research of the SB RAS, reg. No.AAAA-A17-117030310443-5

We thank all contributors for their cooperation.

References

[1] Khan V V, Dekanova N P and Khan P V 2017 Comparative analysis of heat supply options for small and middle-sized settlements of Eastern Siberia by using uncertain and fuzzy information Journal of Physics: IOP Conference Series Materials Sc. and Engineering. 262 (1) ID: 012081. DOI: 10.1088/1757-899X/262/1/012081.

[2] Khan V V, Dekanova N P, Romanova T A and Sharaeva S A 2017 Complex analyses of efficiency of energy effectiveness measures for the objects of social sphere in the Eastern Siberia on the basis of system approach. Izvestiya vuzov. Investitsii. Stroitel'stvo. Nedvizhimost Proceedings of Universities. Investment. Construction. Real estate 7(1) pp. 84–93. (In Russian)

[3] Dekanova N P Khan V V 2011 Approaches of the theory of fuzzy sets in the problems of diagnostics of heat networks and heat consumption objects Modern technologies. System analysis. Modeling 4(32) pp. 96-102

[4] Chupin RV and Pham N M 2019 Optimization of the structure and parameters of developing systems of group water supply Water supply and sanitary equipment p.30-36

[5] Shcherbakov V, Akulshin A, Chizhik K and Tolstoy M 2018 Design of interacting wells for optimization of investments and operating costs while constructing water-diverting structures 6-th International Scientific Conference on Integration, Partnership and Innovation in Construction Science and Education, IPCICE Moscow, Russian Federation; 14-16 November Код 143421. DOI: 10.1051/matecconf/201825103037 MATEC Web of Conferences 251 03037

[6] Chupin V R, Pham N M and Chupin R V 2019 Optimization of the sewerage systems scheme of cities and populated areas IOP Conference Series: Materials Science and Engineering 667 012017. doi: 10.1088/1757 899X/667/1/012017/

[7] Lavygina O L and Grebneva O A. 2019 Environmental technologies in the housing and communal service system of the Baikal natural territory Izvestiya vuzov. Investitsii. Stroitel'stvo. Nedvizhimost Proceedings of Universities. Investment. Construction. Real estate 9(4) pp 726-33. https://doi.org/10.21285/2227-2917-2019-4-726-733
[8] Lavygina O, Grebneva O and Maizel I 2019 Environmental aspects for the reconstruction of housing and communal services in the village Listvyanka of Irkutsk region. *IOP Conf. Series: Materials Science and Engineering* [880](2020) 012045 doi: 10.1088/1757-899X/880/1/012045

[9] Chupin V R, Pham N M and Chupin R V 2019 Optimization of developing district water supply systems taking into account variability of perspective water consumption *IOP Conf. Series: Materials Science and Engineering* [667](2018) 012018 doi: 10.1088/1757-899X/667/1/012018

[10] Skibo D, Sudnikovich V and Tolstoy M 2018 Technical innovations as a means of increasing the efficiency of technological equipment in modern production conditions *Int. Scientific Conf. Investment, Construction, Real Estate: New Technologies and Special-Purpose Development Priorities" ICRE Irkutsk; Russian Federation; 26-27 april* Код 142654 212 010142018

[11] Tunik A A, Tolstoy M Y and Kalashnikov M P 2020 The complex mobile independent power station for the recreational areas *IOP Conf. Series: Earth and Env. Science* [408](1) 012012

[12] Kobersi I S, Finaev V I 2013 Control of the Heating System with Fuzzy Logic. *World Appl. Sc. J.* 23 (11): 1441-47.

[13] Piegat A 2001 *Fuzzy Modelling and Control* Physica-Verlag Heidlberg p 798

[14] Rutkovska D Pilinski M and Rutkovski L 2008 Neural networks, genetic algorithms and fuzzy systems (Moscow: TeleCom) p 462

[15] Taha H 1985 Introduction to operation research. In 2 books (Moscow: Mir) book I p 476, book II p 496

[16] Kulkov V N, Solopanov E Yu and Kamalov R T 2019 Using immobilised sludge for wastewater treatment and its air regeneration *Proceedings of Universities. Investment. Construction. Real estate* [9](3) pp 522–529

[17] Pupyrev E I and Chupin V R 2019 Features of regional development of water disposal systems in the central ecological zone of the Baikal natural territory *Proceedings of Universities. Investment. Construction. Real estate* [9] pp 354–363

[18] Chupin V R and Dushin A S 2019 Assessment of the reliability of water supply to consumers: water supply reliability indicators *Proceedings of Universities. Investment. Construction. Real estate* [9](3) pp 578–593