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THE APPLICATION OF THE ANALYTIC HIERARCHY PROCESS APPROACH TO THE SELECTION OF GAS RADIANT HEATING SYSTEM IN AN INDUSTRIAL BUILDING

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Abstract. *Those involved in the heating industry of large-scale facilities have different expectations of them. It is expected that heating systems will be characterized, among other things, by rational investment and operating costs, enable maintenance of internal conditions suitable for workers or related to the technological process. Identification of selected factors influencing the selection of infrared gas heaters for heating the industrial hall is the purpose of the article. The identified factors form a base of criteria for their evaluation using the Analytic Hierarchy Process (AHP) multi-criteria method. Using an industrial building as an example, a hierarchical model is presented to determine which variant meets the requirements to the highest degree and which decision can be considered optimal. The presented algorithm allows a thorough analysis and evaluation of the factors affecting the selection of infrared gas radiant heaters as a heating solution for industrial halls. In the case of the analyzed hall, the solution with ceramic heaters and standard radiation efficiency proved to be the solution with the highest decision-making index.*

Key words: ***MCDA, luminous local space heater, tube local space heater, radiation efficiency of the heater***

Introduction. Changing environmental requirements, laws and regulations in the heating industry mean that investors of hall buildings must constantly face new challenges, rising costs of building heating installations, and high operating costs. At the same time, it is expected that the heating system will provide appropriate internal conditions, such as temperature, humidity and air movement, in accordance with the requirements of employees and technological processes. In addition, the system should also be reliable and enable integration with modern technologies, such as automatic process control, hybrid heating systems, cogeneration or heat recovery, and should not have a negative impact on the natural environment.

The heating system with infrared gas heaters has been known for many years and is common in large-space buildings. However, the design and quality of the heater can vary greatly, which affects the cost and efficiency of the entire solution, gas consumption and building operating costs. Choosing the type of device requires taking into account many aspects and factors. Their identification in the case of a specific investment facilitates the selection of infrared gas heaters for hall heating. The identified factors, creating a database of criteria for their assessment, facilitate decision-making using the multi-criteria Analytic Hierarchy Process (AHP) method. The application of the AHP decision method for the selection of infrared gas heaters is the aim of this article.

Types and application of gas infrared heaters. Heating with gas infrared heaters began to be developed in the United States in the early 1970s, when the first heater with straight tubes and a screen was patented. Subsequent models of heaters and radiating tapes were more and more advanced, and with the development of new designs that were patented in various countries, nomenclature for various types of heaters was introduced. The main division of gas radiant heaters is the result of their construction and the combustion method of the air-gas mixture, which leads to the distinction of two main types [1]:

- high-intensity heaters, the so-called ceramic or luminous, in which combustion takes place on the surface of the ceramic plate;
- low-intensity heaters, the so-called tube or dark, in which combustion takes place inside the pipe.

Infrared gas heaters are installed primarily to heat the entire interior of large buildings, separate zones, or additional heating of workstations. Ceramic heaters can be additionally used outside buildings, for heating sports stands, railway station platforms or for defrosting ramps. Gas heaters also have other applications, such as drying thin layers of bulk materials and paint coatings, in the brick and ceramic industries. The devices are particularly effective in warehouses, logistics centres and production halls and in other buildings with periodic use, poor thermal insulation or large dimensions. They are also used in aircraft hangars, performance halls and sports facilities, indoor swimming pools, commercial pavilions, livestock buildings and livestock farms, greenhouses, churches and public transport depots. Wide application results from low investment and operating costs compared to other heating systems [2, 3].

The use of gas radiant heaters to heat residential and office spaces is unacceptable due to safety hazards. They should not be installed in rooms where flammable materials are stored, substances produced or stored that may form explosive mixtures, flammable gases or dusts and vapours.

From the heat balance of a gas heater, the total amount of heat from the heater can be calculated using the following equation:

$$Q_c = Q_R + Q_{SK} + Q_{SR} + Q_{SP} \quad (1)$$

where: Q_c – total power of the heater; Q_R – radiation power sent in the desired direction; Q_{SK} – heat loss as a result of convection from the structural elements of the heater to the environment; Q_{SR} – heat loss due to radiation from structural elements in an undesirable direction; Q_{SP} – heat loss in flue gases.

In buildings, the heat transferred by Q_R radiation is used to heat the occupied zone, while the heat given off as a result of Q_{SK} convection, the heat given off as a result of radiation in the undesirable Q_{SR} direction and the heat in the Q_{SP} flue gases in the context of heating the building are heat lost. The efficiency of radiant heat transfer to the environment is determined by the radiation efficiency of the heater, also called the directional efficiency, and determined by the formula:

$$\eta_R = \frac{Q_R}{Q_c} \cdot 100\%, \quad (2)$$

where η_R is the radiation efficiency of the heater (in other words: directional efficiency), %.

The radiation efficiency of ceramic heaters is in the range of 60,6 to 80,9% and of tube heaters in the range of 55 to 83%. Higher efficiency is achieved, e.g. thanks to the insulation of the radiating screen. There is no official division of heaters due to efficiency.

Generally, in the case of gas radiant heaters available on the market, due to their efficiency, devices are divided into:

- high-efficiency radiation > 70%.
- standard with efficiency in the range 65–70 %,
- with low efficiency, i.e. below efficiency 65%.

As part of its drive to improve energy efficiency and reduce the negative environmental impact of energy-related products, the European Union has developed a number of EcoDesign Directives and Regulations. These documents provide the legal basis for EU policy to control and regulate the placement on the market of products that consume or affect energy consumption. The implementation of Regulation 2015/1188 [4] is one of the EU legal acts that refers to the requirements that should be met by ecodesign in the field of local space heaters. According to the regulations, ceramic and tube infrared heaters for gaseous or liquid fuel are considered commercial heaters. Their basic parameters according to Regulation 2015/1188 are: seasonal energy efficiency ηS, % and nitrogen oxide emissions, mg/kWhinput. Table 1, in accordance with Annex II of the Regulation [4], provides specific ecodesign requirements for seasonal energy efficiency and NOx emissions for commercial local space heaters [1].

1. Ecodesign requirements for gas heaters [4]

Seasonal space heating energy efficiency with an infrared heater η_S, %		Nitrogen oxide emissions by ceramic and tube heaters, mg/kWh_{input}
ceramic	tube	200
85	74	

Another classification of gas heaters includes the way they regulate their power. There are models with burner modulation in various power ranges from 50% to 70%. They are equipped with automatic regulation of the burner or the power can be set manually using a potentiometric regulator.

Analytical hierarchical process (AHP) – methodology. The Analytic Hierarchy Process (AHP) is one of the most known and popular methods in the world in the field of

Multiple-Criteria Decision Analysis (MCDA) used in the field of environmental engineering [5, 6]. In the decision-making model, a hierarchical structure is built, which makes it possible to gather all the factors affecting the decision-making goal in one place. The AHP method is distinguished by the fact that it allows to include both tangible (measurable) and intangible (immeasurable) elements in one hierarchical multi-criteria model. This is particularly important because most other multi-criteria methods only focus on measurable issues. Due to this, AHP allows for a more comprehensive analysis and decision making based on many different criteria, regardless of their nature.

2. Significance indicators in the AHP analysis [7]

Significance indicators	Definition	Explanation
1	equal validity	the influence of both factors is the same
2	intermediate value	variation between the two ratings
3	slight advantage	one factor slightly outweighs the other
4	intermediate value	variation between the two ratings
5	a major advantage	significant advantage of one factor over the other
6	intermediate value	variation between the two ratings
7	very strong advantage	clear dominance of one factor over the other
8	intermediate value	variation between the two ratings
9	absolute advantage	the dominance of one factor over the other is absolute

The AHP methodology consists of two phases: hierarchy and assessment, which consists of seven steps. The first step is to identify and define the purpose of the decision support. Then, possible solutions should be given and criteria affecting the analysis and selection of solutions should be defined. In the next step, individual solutions are evaluated, establishing relative relationships between them by comparing them in pairs using bipolar scaling of the nine-point scale shown in Table 2. Square comparison matrices are built for each level of the model structure, scale vectors are determined, their compliance is checked and final scale vector. Then, the decision variants are ranked and the obtained results are interpreted. After selecting the best solution, implementation and impact assessment follow to check whether the problem has been solved satisfactorily.

AHP model for choice of heaters. As part of the application of the AHP method to solve the decision problem regarding the choice of a heating system in a large-space facility, an own hierarchical decision model was proposed, and shown on the diagram in Fig. 1. This proposal can be adapted to the decision-maker's preferences, and these changes can significantly affect the final result. This is due to the fact that the preferences of decision makers depend on many factors, such as the financial situation or the current needs of the investor or company. The assumption of the weight and importance of individual factors is made individually in each decision-making situation. Depending on the purpose of decision making for a given building, the selection of criteria will be made after a thorough identification and definition of the decision-making problem and after taking into account the available solution variants.

The main criteria (Fig. 1) have been divided into 3 categories:

1) K1 – economic;
2) K2 – technical, taking into account design aspects;
3) K3 – socio-environmental, taking into account operational and environmental aspects related to the internal conditions of the room.

Each of the above categories is a set of subcriteria:

1) Economic criterion includes:
   - K1.1. Investment costs.
   - K1.2. Operating costs.
   - K1.3. Return on investment.

2) The technical criterion is a set of sub-criteria affecting the design and construction of the heating system, such as:
   - K2.1. Radiation efficiency of gas heaters is understood as a division into high-efficiency, standard, and low-efficiency heaters.
   - K2.2. Burner modulation is understood as the possibility and method of regulating their power.

- K2.3. WHR - Waste heat recovery systems understood as the possibility of connecting a heat exchanger to recover heat from flue gases [8].
- K2.4. Expansion of the system understood as the need to make additional openings in building partitions, access to free space in the hall for maintenance of the heating system is also taken into account.
- K2.5. Reliability and reputation understood as a choice of proven systems that work reliably and without failures, are easily serviceable and repairable, made by companies with an appropriate level of specialization, high brand credibility and certificates.
- K2.6. The lead time is understood as the period from placing the order to installing and starting the system in the building.

3) The socio-environmental criterion takes into account the operation of the heating system (so-called operational factors) and its environmental impact, therefore:

- K3.1. CO2 emission.
- K3.2. Certification is understood as the possibility of obtaining a certificate of sustainable construction, e.g. in the case of high-efficiency ceramic radiant heaters.
- K3.3. Technical support understood as a social aspect related to technical support at the design, construction or operation stage.
- K3.4. Thermal comfort is related to avoiding an asymmetric field of thermal radiation.
- K3.5. Aesthetics/smell/safety understood as factors important for people staying in the hall, also taking into account the health aspect.

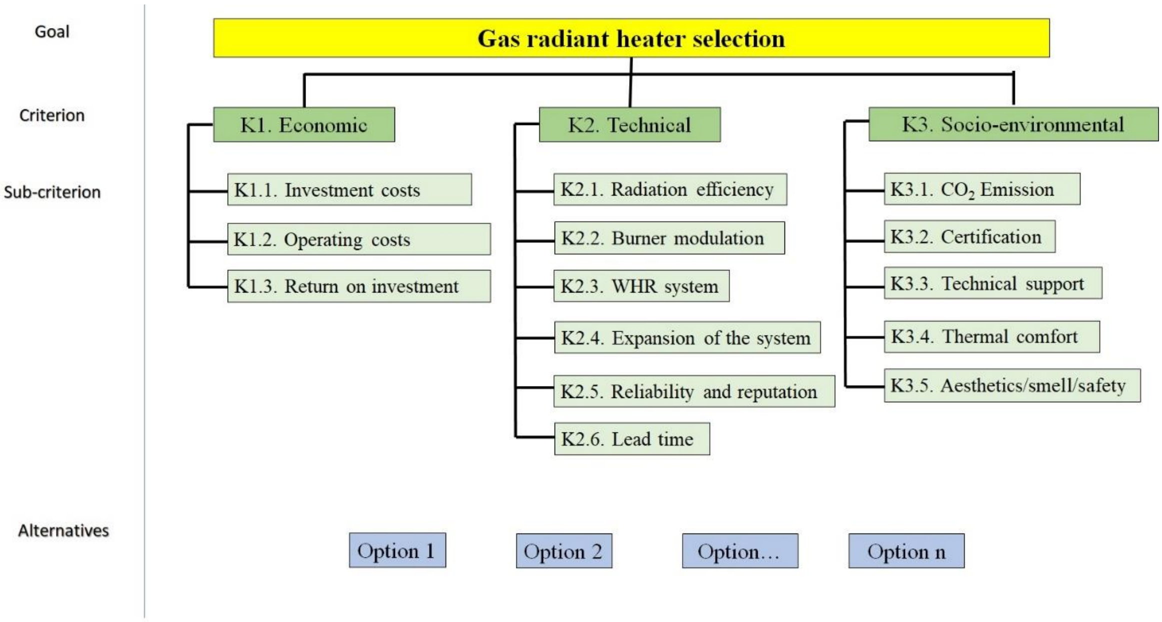

Figure 1. An example of a hierarchical decision model enabling the selection of gas heaters in a hall building

Case study. The purpose of the analysis is to demonstrate the usefulness of the AHP method the possibility of using gas heaters in an example industrial hall, the distinguishing parameter of which is the radiation efficiency. Analysis using this method at the early stage of developing a heating system design allows you to create a ranking of factors influencing the choice of a solution and identify potential risks resulting from its implementation in large halls.

According to the algorithm of the AHP method, the factors given in Fig. 1 become criteria, and step 1 consists in finding the scale vector (GW) for the 3 main criteria compared in pairs according to Table 2. Then, in step 2, in each group of main criteria a vector is determined scale (RW) of individual factors in relation to the criterion. After that, individual comparison matrices should be synthesized by multiplying the scores obtained for the individual alternatives (SCORE -1/0/+1) by their respective relative importance (RW) and by aggregating (GW) the results obtained to calculate overall preferences. Tables 3-10 show pairwise comparisons of individual factors, normalized matrices, and designated scale vectors. The CR coefficient reflects the reliability and competence of the experts. According to the recommendations contained in the literature on the AHP method, the results are considered consistent when the value of the CR coefficient does not exceed 0.10 (10%).

The final multi-criteria evaluation matrix is shown in Table 11.

3. Pairwise comparison of the main criteria

Criterion	K1	K2	K3
K1 Economical	1.00	1.00	5.00
K2 Technical	1.00	1.00	5.00
K3 Socio-environmental	0.20	0.20	1.00
s_j	2.20	2.20	11.00

4. Normalized matrix and scale vector for main criteria

Criterion	K1	K2	K3	Scale vector
K1 Economical	0.444	0.444	0.556	0.481
K2 Technical	0.444	0.444	0.556	0.481
K3 Socio-environmental	0.089	0.089	0.111	0.096
CR=0.07				

5. Pairwise comparison of economic criteria

Criterion	K1.1	K1.2	K1.3
K1.1	1.00	1.00	4.00
K1.2	1.00	1.00	4.00
K1.3	0.25	0.25	1.00
s_j	2.25	2.25	9.00

6. Normalized matrix and scale vector for economic criteria

Criterion	K1.1	K1.2	K1.3	Scale vector
K1.1	0.444	0.444	0.444	0.444
K1.2	0.444	0.444	0.444	0.444
K1.3	0.111	0.111	0.111	0.111
CR=0.08				

7. Pairwise comparison of technical criteria

Criterion	K2.1	K2.2	K2.3	K2.4	K2.5	K2.6
K2.1	1.00	1.00	5.00	6.00	0.33	0.50
K2.2	1.00	1.00	5.00	2.00	1.00	1.00
K2.3	0.20	0.20	1.00	0.20	0.20	0.14
K2.4	0.17	0.50	5.00	1.00	2.00	3.00
K2.5	3.00	1.00	5.00	0.50	1.00	1.00
K2.6	2.00	1.00	1.00	0.33	1.00	1.00
s_j	7.37	4.70	22.00	10.03	5.53	6.64

8. Normalized matrix and scale vector for technical criteria

Criterion	K2.1	K2.2	K2.3	K2.4	K2.5	K2.6	Scale vector
K2.1	0.136	0.213	0.227	0.598	0.060	0.075	0.218
K2.2	0.136	0.213	0.227	0.199	0.181	0.151	0.184
K2.3	0.027	0.043	0.045	0.020	0.036	0.022	0.032
K2.4	0.023	0.106	0.227	0.100	0.361	0.452	0.212
K2.5	0.407	0.213	0.227	0.050	0.181	0.151	0.205
K2.6	0.271	0.213	0.045	0.033	0.181	0.151	0.149
CR=0.08							

9. Pairwise comparison of socio-environmental criteria

Criterion	K3.1	K3.2	K3.3	K3.4	K3.5
K3.1	1.00	1.00	5.00	6.00	0.33
K3.2	1.00	1.00	5.00	2.00	1.00
K3.3	0.20	0.20	1.00	0.20	0.20
K3.4	0.17	0.50	5.00	1.00	2.00
K3.5	3.00	1.00	5.00	0.50	1.00
s_i	5.37	3.70	21.00	9.70	4.53

10. Normalized matrix and scale vector for socio-environmental criteria

Criterion	K3.1	K3.2	K3.3	K3.4	K3.5	Scale vector
K3.1	0.186	0.270	0.238	0.619	0.074	**0.277**
K3.2	0.186	0.270	0.238	0.206	0.221	**0.224**
K3.3	0.037	0.054	0.048	0.021	0.044	**0.041**
K3.4	0.031	0.135	0.238	0.103	0.441	**0.190**
K3.5	0.559	0.270	0.238	0.052	0.221	**0.268**
CR=0.09						

Discussion and conclusion. The radiation efficiency of gas heaters is one of the factors affecting investment and operating costs. The higher the efficiency, the lower the operating costs, because the heater uses less gas to reach the required temperature. It is possible to compare operating costs. Table 12 presents the expected costs of annual electricity and gas consumption for heaters of various efficiency, installed in the production hall with the required temperature of 17°C.

11. Final multi-criteria evaluation matrix

Criterion	GW	Sub-criterion	RW	ceramic heater high efficiency		ceramic heater standard efficiency		ceramic heater low efficiency		tube heater high efficiency		tube heater standard efficiency		tube heater low efficiency	
				Score		Score		Score		Score		Score		Score	
K1	0,481	K1.1.	0.44	-1	-0.213	1	0.213	1	0.213	-1	-0.213	1	0.213	1	0.213
		K1.2.	0.44	1	0.213	0	0	-1	-0.213	1	0.213	0	0	-1	-0.213
		K1.3.	0.11	1	0.053	1	0.053	1	0.053	1	0.053	1	0.053	1	0.053
K2	0,481	K2.1.	0.22	1	0.105	0	0	-1	-0.105	1	0.105	0	0	-1	-0.105
		K2.2.	0.18	1	0.088	1	0.088	-1	-0.088	1	0.088	1	0.088	-1	-0.088
		K2.3.	0.03	-1	-0.015	-1	-0.015	-1	-0.015	0	0	1	0.015	1	0.015
		K2.4.	0.21	1	0.101	1	0.101	1	0.101	-1	-0.101	-1	-0.101	-1	-0.101
		K2.5.	0.20	1	0.098	1	0.098	-1	-0.098	1	0.098	1	0.098	-1	-0.098
		K2.6.	0.15	1	0.071	1	0.071	1	0.071	0	0	0	0	0	0
K3	0,096	K3.1.	0.28	1	0.026	0	0	-1	-0.026	1	0.026	0	0	-1	-0.026
		K3.2.	0.22	1	0.021	0	0	0	0	1	0.021	0	0	0	0
		K3.3	0.04	1	0.004	1	0.004	0	0	1	0.004	1	0.004	0	0
		K3.4	0.19	0	0	0	0	-1	-0.018	1	0.018	1	0.018	0	0
		K3.5	0.27	-1	-0.025	-1	-0.025	-1	-0.025	1	0.025	1	0.025	1	0.025
Total score					**0.53**		**0.59**		**-0.15**		**0.34**		**0.42**		**-0.33**

Investment costs are always determined individually for each investment, as they require consideration of many factors, such as:

- purpose of a large-volume room;
- time of use of the facility during the day;
- type of technology used in the facility;
- layout of workstations and method of storing products;
- dimensions of the room and construction features - coefficient of penetration of building partitions (insulation of walls, especially flat roof), degree of glazing, size of entrance gates;
- spacing between structural columns and crane runway heights or other obstructions, e.g. sprinkler systems;
- method of room ventilation;
- type of heating fuel available;
- the need to ensure the same temperature throughout the room or comfort temperature in the zones occupied by people or the appropriate temperature due to the technology used;
- the desired temperature inside the facility and the standby temperature.

Catalogue prices, given in different currencies, serve only as a suggestion, and the final price is determined on the basis of an individual valuation. Discounts are applied based on order size and other factors, which can make it difficult to accurately compare investment costs. The conducted analysis of cumulative costs made it possible to determine the assessment of economic criteria for individual alternatives (SCORE -1/0/+1). Due to the highest price, high efficiency heaters have a value of -1 (Table 11).

In addition, Table 12 contains information on CO_2 emissions, which is important from the point of view of environmental protection and is one of the environmental criteria (K3.1.) and has been appropriately adopted in -1 for low-efficiency heaters and +1 for high-efficiency heaters (Table 11).

12.Comparison of operating costs of heating devices with different efficiency [1]

Heating device	Installed power, kW	The amount of gas used, kWh/year	The amount of electricity used, kWh/year	Consumption cost gas, PLN	The cost of electricity consumption, PLN	Emission CO_2, t/year
Low efficiency heater	129.8	165 672	919	34 792	425	35
Standard heater	126.3	157 138	511	32 999	235	33
High efficiency heater	108.1	138 052	715	28 992	332	29

Modulation of the burners (K2.2.) is possible in the case of heaters with better efficiency, the cheapest devices usually do not have this option, hence the score for them is -1.

Recently, modern technological solutions have appeared that enable the effective recovery of waste heat from gas radiant heaters. It is possible to recover heat from the hot air that is concentrated around the heaters, as well as from the mixture of hot exhaust gases and air created during the operation of the heater. The publications present an overview of possible heat recovery systems [1]. Unfortunately, heat recovery systems for gas radiant heaters are offered by only a few companies and are used sporadically. There are no market solutions available in the case of ceramic heaters (score -1), whereas in the case of high-efficiency tube heaters, their profitability is negligible.

Gas tube heaters require additional openings in building partitions, and furthermore due to the dimensions of a larger space on the floor for maintenance of them, hence the rating -1. Installation of ceramic heaters on poles or vertical partitions allows easier access during annual maintenance. Due to the fact that the flue gases are discharged into the room, chimneys are not necessary. It also speeds up the execution time, and hence sub criterion K2.6. has a positive value. However, an important element in the use of a hall heated with ceramic heaters is the specific smell that persists in the room as a result of gas combustion products rising to the roof of the hall despite the operation of the ventilation system, which is why subcategory K3.5. was negatively rated for these devices.

Low-efficiency heaters have been withdrawn from production due to eco-design requirements. High brand credibility and technical support cannot be expected here, which was included in the score -1 in the sub criterion K2.5. and K3.3. Increasingly, hall buildings such as warehouses and industrial facilities are applying for a "green building" certificate. Under the current certification methodology, the use of high-efficiency gas heaters allows you to obtain 1 to 2 points. This results in a positive grade in K3.2. for these devices.

Properly designed heating with infrared gas heaters allows you to achieve the desired temperature in the room. The radiation intensity should not exceed 300 W/m^2 at a height of 1,8 m above the floor, while the permissible value is 200 W/m^2 at a height of 1,5 m above the floor. The intensity of the radiation and the height of the installation of the heaters is the decisive criterion for their selection, as an excessive increase in the temperature felt at the height of the human head cannot be allowed. The less insulated the hall, the greater the power demand per 1 m^2 of the floor. In the analysis of the internal environmental conditions of a room heated by radiation, parameters such as radiation temperature and radiation temperature asymmetry are important, which affect the thermal comfort of a person working in such a room. It has also been shown that the type of clothing worn by employees is important. The use of heater systems improves the thermal conditions in the hall, especially in the case of individual workstations.

In the final multi-criteria evaluation matrix supporting the decision-making process (Table 11) the local weights of the sub-criteria (RW) were combined with the weights of the relevant main criteria (GW) and the total weights were obtained, which were used to rank the decision variants. The highest value, that is, 0.59, was obtained by the standard efficiency ceramic heater system, which was overtaken by highly efficient ceramic heaters due to lower investment costs. Next in the ranking are standard and high-efficiency tube heaters. Low-efficiency heaters, despite the lowest investment costs, have many features that make their total result negative. The commonly used system of standard heaters made it possible to determine the largest number of their advantages and achieve the highest result in the group of heaters.

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ЗАСТОСУВАННЯ ПРОЦЕСНОГО ПІДХОДУ АНАЛІТИЧНОЇ ІЄАРХІЇ ДО ВИБОРУ СИСТЕМИ ГАЗОВОГО ПРОМЕНЕВОГО ОПАЛЕННЯ ПРОМИСЛОВОЇ БУДІВЛІ

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Анотація. *Ті, хто займається опаленням великомасштабних об'єктів, мають різні очікування від них. Очікується, що системи опалення характеризуватимуться, серед іншого, раціональними інвестиціями та експлуатаційними витратами, які дозволять підтримувати внутрішні умови, зручні для працівників або пов'язані з технологічним процесом. Метою дослідження є виявлення окремих факторів, що впливають на вибір інфрачервоних газових обігрівачів для опалення виробничих приміщень. Виявлені фактори формують базу критеріїв для їх оцінки за допомогою багатокритеріального методу аналітичного ієрархічного процесу (AHP). На прикладі промислової будівлі представлена ієрархічна модель, яка визначає, який* *варіант найбільше відповідає вимогам і яке рішення можна вважати оптимальним. Представлений алгоритм дозволяє провести ретельний аналіз і оцінку факторів, що впливають на вибір інфрачервоних газових обігрівачів як рішення для опалення промислових приміщень. У випадку аналізованого залу рішення з керамічними нагрівачами та стандартною ефективністю випромінювання виявилося рішенням з найвищим індексом прийняття рішень.*

Ключові слова: ***MCDA, світловий локальний обігрівач, трубчастий локальний обігрівач, радіаційна ефективність обігрівача***