

Article

Aspects of Heat Supply Security Management Using Elements of Decision Theory

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Abstract: Security in heat supply systems plays an important role in social, technical and political terms. It includes three main components: energy security, security of heat supply, security of people. The differences concern the subject, area, scope, as well as the degree and purpose of the analyses. The article is a continuation of research conducted by the author, presenting the concept of security of heat supply as a necessary “umbrella” supported by reliability and system resilience to threats, constituting a set of actions aimed at minimizing the risk. The subject of the analysis of this article is the security of heat supply, analysed in the context of heat supply management to recipients and risk analysis related to the lack of heat supply. The elements of decision theory were used as adequate for this purpose. Different configurations of heat distribution in the system have been taken into account when determining the expected values of risk related to the occurrence of power limitation for various degrees of restrictions and various network configurations. The author’s use of elements of decision theory in heat supply systems illustrated at the work gives the opportunity to assess and manage the security of heat supply to the recipient. It takes into account the possibility of different heat distribution configurations in the system at the operational stage, as well as may be the basis for optimizing changes in the distribution of power supply areas and selecting the most advantageous network configuration at the design stage.

Keywords: heat supply; district heating system; security management; decision theory

1. Introduction

The supply of heat implemented through related elements of the heat supply system is one of the areas being subject to the analysis of urban logistics. The delivery and distribution of heat are tasks of heating companies. The rules for the delivery and distribution of heat are set out in legal regulations. One of the key challenges of the heating industry is to ensure the security of heat supply to customers. Hence the concept of security of heat supply as a necessary “umbrella” supported by the reliability and resilience of the system to threats, constituting a set of actions aimed at minimizing the risk. Heating infrastructure plays an important role in ensuring energy security but its management in the aspect of security is important as well.

The aim of the article is to present the aspects of managing the security of heat supply in urban agglomerations. Elements of decision theory were used as adequate for risk assessment and heat safety management for customers. In order to understand the purpose of the considerations being the subject of this work, an explanation of the basic concepts in this field is provided.

Security is defined as a state of non-hazard, certainty, peace, it means no risk to people and to the environment in which they live. Unfortunately, the state of security is not a stable state—just as happiness is not good given to the entity (man, company, etc.) forever. There are constant security threats in today’s world, both from the forces of nature and from human activities (terrorist attacks, cyber attacks). There is a constant need to ensure the stability of the state, which is safety, that is

why a person, a social group, an organization, a state, a heating company, and so forth affect their external environment and the internal sphere to remove or at least distance threats. They can do this by eliminating their own anxiety, fear, anxiety and uncertainty, minimizing the risk at the same time.

Security is a concept against risk, it is a feature of a system or facility that describes its adoption to avoid hazards and exposures. It is also described as the ability to effectively protect against the effects of external threats [1]. Safety is a property that characterizes resistance to dangerous situations.

Ensuring continuity and reliability of heat supply system operation according to Energy Law [2] and Regulation of the Minister of Energy [3] must meet the requirements to ensure:

- energy security—as a condition of the economy which enables full coverage of the customers' ongoing and prospective demand for fuels and energy in a technically and economically justified manner, meeting the environment protection requirements;
- security of energy supply, forming an ability of the system to ensure the security of the operating network and balancing energy supply with demanding for this energy;
- safety of people, as users or operators of a system.

Energy security is the subject of many discussions and agreements at various levels of state management. It is defined as a state enabling coverage of the current and prospective demand of customers for fuels and energy in a technically and economically justified manner, while meeting environmental protection requirements. Security of energy supply ensures network security and balancing energy supply with the demand for energy and is associated with the reliability of systems [4]. The relationship between reliability, security and risk in district heating system (DHS) is illustrated by the concept of heat supply analysis to recipients (Figure 1).

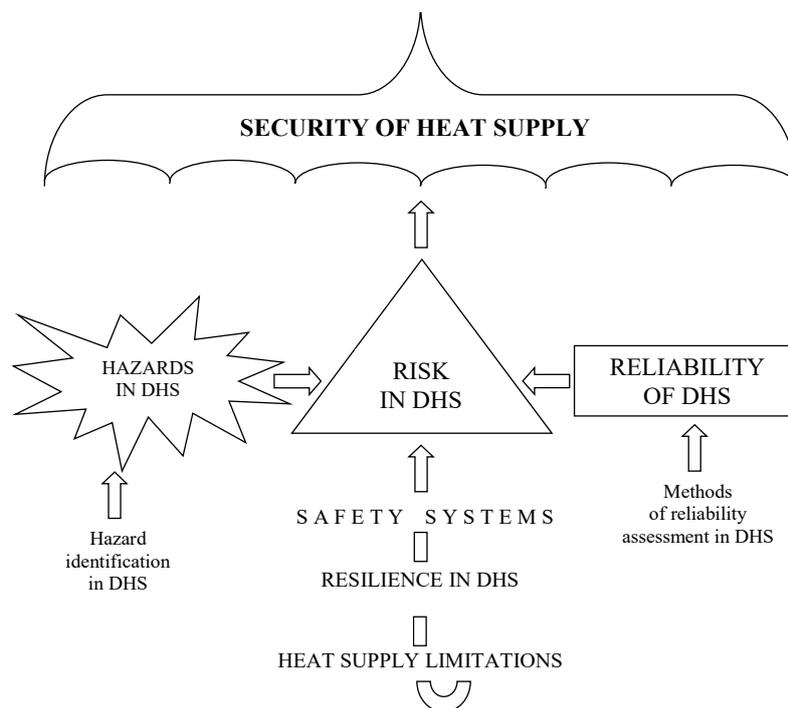


Figure 1. The concept of reliability, security and risk analysis in the district heating system (DHS).

The security of heat supply is described as partial security [5], which in addition to energy security enters energy security as a socio-economic category due to the need to meet environmental protection requirements.

The level of security of a system or facility (plant, agglomeration, etc.), as understood globally, depends on domain security levels (e.g., flood, chemical, fire). Due to the level of security, domain and general security can be distinguished.

The level of subject domain security is achieved in many ways not only by ensuring the specific effectiveness of the emergency system directly counteracting the incidents. Its value can be influenced by:

- preventing the emergence of a given type of security threats;
- preparing the entity in the event of activating a given type of security risk in the form of an event (education, training, deployment and availability of forces and counter-measures);
- increasing the effectiveness of the forces and resources of the rescue system while counteracting the effects of a given event;
- effectiveness of actions in removing the consequences of a given event.

The structure of this article includes, in addition to the introduction, taking into account terminology and legal aspects of safety in heat supply systems, review of literature in the subject matter analysed, a description of the methodology used and an example showing the use of elements of decision theory with a summary.

2. Review of the Literature

The heat supply system, in other words the district heating system (DHS) belongs to critical infrastructure systems, whose management plays an important role in the security of heat supply to recipients [6–13]. According to the Energy Law Act of 10 April 1997, as amended [2], energy companies involved in transmission or distribution of energy are obliged to maintain the capacity of devices, installations and networks to provide energy supply in a continuous and reliable manner, while maintaining quality requirements. Regulation of the Minister of Energy of 22 September 2017 on detailed conditions for the operation of district heating systems [3] also requires reliable operation and maintenance of the capacity of district heating networks to carry out heat supply. The continuous operation of these systems is inseparably connected with the possibility of various types of disturbances or adverse events affecting the reliability and security of heat supply to customers.

In the technical literature, special attention should be paid to the work on the risk and safety assessment of various complex technical systems and functional safety [14–29], as well as to a few touching problems of reliability in district heating [4,5,30–35].

Security assessment is crucial for the reliable and secure operation of technical systems [10]. A security level classification method to analyse the security level of various technical systems both qualitatively and quantitatively is presented in many works [36–49].

Managing of the security and reliability of heat supply are the fulfilment of the primary management objective in the heat supply sector, in addition to the care for the environment protection, implementation of the principle of sustainable development and economic reasons, [50]. It means a complex of actions aiming at achieving the intended state of reliability and security of the system and keeping it at a specified, fixed level. Reliability and safety management should aim at minimizing the probability of adverse events with simultaneous control and monitoring of possible hazards and assessment of the risks associated with them [51–55].

Problems of reliability, safety and risk management of technical systems are depicted in [56–68]. The reference to heat and energy distribution systems is visible in [32,50,69–72]. The analysis of resistance and sensitivity of energy distribution systems is presented in [11,40,56,73–77].

On the basis of the literature analysis of the subject of the work, it can be stated that there is a lack of ordering and development of methods for determining and assessing reliability, security and risk in DHS. The methodology proposed in the work using elements of the decision theory can be used in the conscious decision making related to the optimal heat supply to recipients.

3. Methodology

The decision theory examines, analyses and describes ways of making decisions. First, it was developed as a normative theory, dealing with methods of choosing the optimal action [78]. The choice

of method depends on the conditions in which the choice is made and on the information available. In general, there are three types of conditions in which decisions are made: conditions of certainty, risk conditions and conditions of uncertainty. These conditions determine the decision to be made. These conditions and consequently the ease of making decisions and its consequences, depend largely on the type of decision-making situation [79,80].

Depending on the level of knowledge of the conditions related to the decision, the following situations can be distinguished:

- a certain (deterministic) situation in which the action clearly determines the result. The decision maker can tell what he would achieve and what the effect of the particular choice would be;
- a risk situation in which the consequences of decisions can be both desirable and undesirable can bring profits and losses. However, you can specify at least a set of consequences and the probability of their occurrence;
- an uncertain situation in which all the consequences cannot be calculated or determined with what probability they will occur.

The utility function allows to calculate the perceptibility of risk. In the case of accepting a linear dependence of discounts on thermal power limitations, this function takes the form:

$$u(x) = f(x) = a \cdot x \quad (1)$$

It depends on many factors related to the size of the enterprise, its financial mobility or legal law requirements:

$$u(x) = f(x) \quad (2)$$

The general form of the utility function is shown in Figure 2.

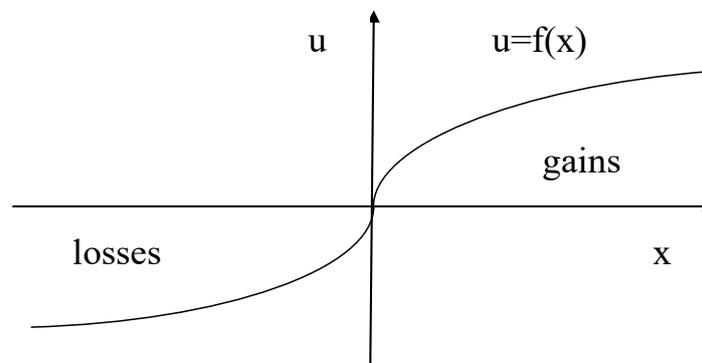


Figure 2. An example form of the utility function.

According to the Regulation of the Minister of Energy [3], depending on the size of the power limitation warmer as a result of an unfavourable event, two calculation intervals of discounts can be distinguished, defined as the degrees of failure of the energy company to meet the quality standards of customer service. If it is assumed that the values of the required thermal power and the duration of the disturbance are constant, the dependence of the total discount for the limitations in heat supply can be visualized in the form of a linear function of one variable from the power limitation, as shown in Figure 3. The discontinuity in Figures 3 and 4 results from the principles contained in legal law regulations, in particular in the Regulation of the Minister of Energy on detailed rules for the development and calculation of tariffs and settlements for heat supply. According to them, the value of the discount depends on the size of the restriction of thermal power supplied to customers.

Level I includes a more probable heat reduction of up to 40%, stage II takes into account a heat power limit of more than 40% [3,4]. The assumption was made that the probability of occurrence of limitations in a given degree of non-performance of parameters does not change.

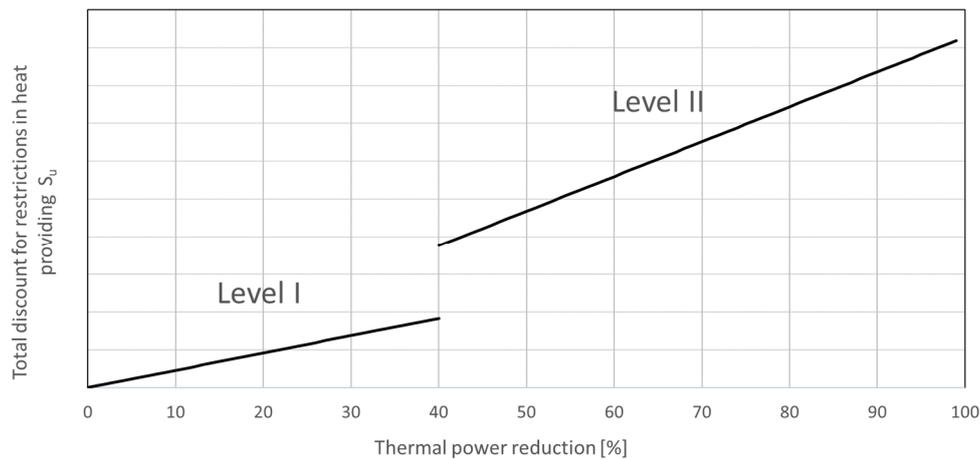


Figure 3. The general dependence of the number of discounts on the size of the restriction in the heat providing to recipients.

Discounts related to limiting the heat supply and heating power supplied to recipients can be presented in the form of a function of several variables [4]:

$$S_u = F(\Phi_n, t_i, x_i, \theta_e) \quad (3)$$

where:

Φ_n —ordered thermal power at the recipient n ;

t_i —duration of the thermal power limitation;

x_i —percentage of thermal power supply limitation, %;

θ_e —design temperature of the outside air, adopted depending on the climatic zone of the location of the object supplied with heat.

For fixed values: ordered thermal power Φ_n , duration of i -th limitation of thermal power supply to the recipient t_i and assuming the occurrence of design conditions, which also determines the outside air temperature, Equation (3) will take the form:

$$f(x) = F(\Phi_n, t_i, x_i, \theta_e) \quad (4)$$

The value of the discount therefore describes the function:

$$S_u = f(x_i) \quad (5)$$

In the functioning of the district heating system, there are different ways to deliver heat to the recipient, hereinafter referred to as district heating network configurations. They depend, among others, on the type and technology of execution and management of network or on a way of heat supply. From the point of view of risk measurement, three operating states can be distinguished in each network configuration: z_0 —a state defining the normal operation of the system, when there is no disruption of thermal power supply to the recipient and the probability of occurring the probability of the state (z_0) occurring is p_0 ; z_1 —a state in which a first level limitation of delivery of the thermal power may occur, that is, a reduction in thermal power is $0 \div 40\%$ of the ordered power value (Figure 3) (probability of s_1 state is p_1); z_2 —a state in which a limitation of the thermal power supply of the second degree may occur. It means that the reduction in thermal power is $41 \div 100\%$ (it occurs with the probability p_2).

If two different configurations of district heating networks supplying heat to the customer are taken into consideration: S_1 and S_2 , then the probability of thermal power decrease for configuration S_1

in the state z_0 is designated as $p_0^{(S1)}$ and in states z_1 and z_2 as $p_{1i}^{(S1)}$ and $p_{2i}^{(S1)}$, respectively. Similarly, in the case of the S2 district heating network configuration, the probabilities of thermal power reduction occurrence in the following states: z_0 , z_1 and z_2 are respectively: $p_0^{(S2)}$, $p_{1i}^{(S2)}$ and $p_{2i}^{(S2)}$, according to Tables 1 and 2.

Table 1. Probability determination for particular states of the S1 network configuration.

State	z_0	z_1	z_2
Probability	$p_0^{(S1)}$	$p_{1i}^{(S1)}$	$p_{2i}^{(S1)}$

Table 2. Probability determination for particular states of the S2 network configuration.

State	z_0	z_1	z_2
Probability	$p_0^{(S2)}$	$p_{1i}^{(S2)}$	$p_{2i}^{(S2)}$

Assuming that X is a random variable describing the risk related to the limitation of thermal power, the average value of the allowance per unit of time can be calculated as the expected value of the risk related to the payment of a premium due to the restriction of heat supply using the equation:

$$E(X) = \sum_{i=0}^{i=100} p_i \cdot f(x_i) \quad (6)$$

when:

p_i —the probability of limiting the thermal power in the percentage x_i ,

x_i —percentage of thermal power limit, %.

If X_1 is a random variable describing the risk related to the limitation of heat supply to the recipient A at level I of the thermal power limit, then taking into account the configuration of the district heating network designated as S1, the probability of the S1 network configuration without limitations is as follows:

$$p_0^{(S1)} = \Pr(X_1 = 0) \quad (7)$$

The probability of the S1 network configuration work with constraints at level I determines the dependence:

$$p_{1i}^{(S1)} = \Pr(X_1 = x_{1i}) \quad (8)$$

If X_2 is a random variable describing the risk related to limiting the heat supply to the recipient A at level II of the thermal power limit, the probability of operation of the S1 network configuration with limitations at level II is:

$$p_{2i}^{(S1)} = \Pr(X_2 = x_{2i}) \quad (9)$$

In general, for the random variable X_i the probability of operation of S1 network configuration with restrictions:

$$p_i^{(S1)} = \Pr(X_i = x_i) \quad (10)$$

The expected value of the allowance related to the occurrence of the 1st level heat supply limitation:

$$E(X)_I = \sum_{i=0}^{i=40} p_i \cdot f(x_i) \quad (11)$$

The expected value of the discount related to the occurrence of the heat supply limitation of the level:

$$E(x)_{II} = \sum_{i=41}^{i=100} p_i \cdot f(x_i) \quad (12)$$

You can formulate a task, which is to choose a better network configuration. Its solution is to choose a configuration for which the expected value of the risk associated with the occurrence of thermal power limitation and the need to pay the discount is the smallest.

The expected value of the allowance for the S1 network configuration:

$$E(x)_{S1} = E(x)_I^{(S1)} + E(x)_{II}^{(S1)} \tag{13}$$

Similarly, the expected discount value for the S2 network configuration:

$$E(x)_{S2} = E(x)_I^{(S2)} + E(x)_{II}^{(S2)} \tag{14}$$

If there is a case described by a dependency:

$$E(x)_{S1} \leq E(x)_{S2} \tag{15}$$

then it means that the configuration of the S1 network proves to be more advantageous than the S2 configuration.

4. An Example of Using the Method—Case Study

A heat supply was planned for the recipient A, the ordered thermal power of which is 100 MW. Two configurations of district heating networks were adopted: S1 and S2. These networks differ in layout, configuration, technology, and so forth. Moreover, they are characterized by different probabilities of occurrence of limitations in heat supply to the recipient. Discounts related to the limitation in the heat supply to the recipient [3,4] due to damage, assuming that the duration of the restriction will not be longer than one day (i.e., the failure will be repaired within one day) are described by the utility function $f(x_i)$, depicted for particular levels of heat supply restriction, previously designated as I and II, in Figure 4.

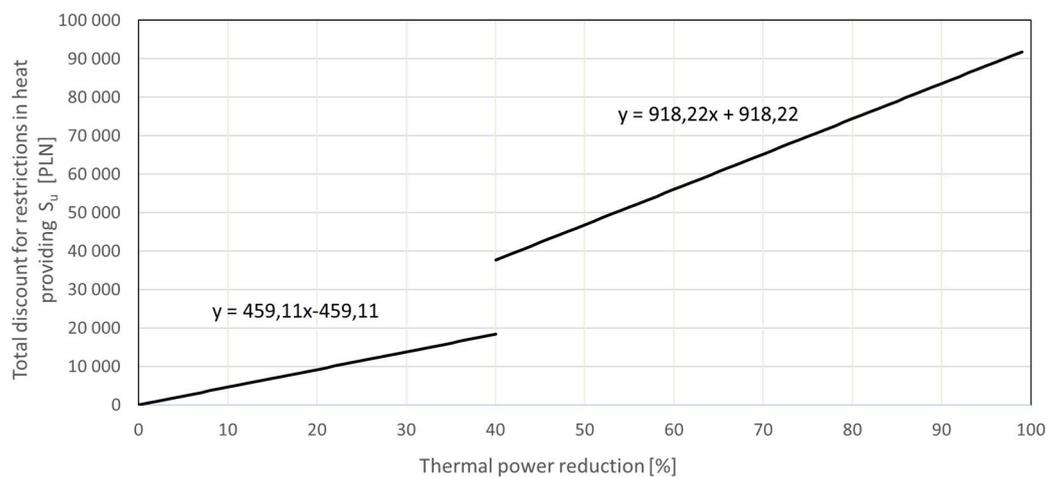


Figure 4. The dependence of the amount of the discount on the level of the restriction in the supply of thermal power to the recipients.

The probability values for particular states of the S1 network configuration at levels I and II are presented in Table 3.

Table 3. Probability determination for particular states of S2 network configuration.

u_{S1}	0	z_1	z_2
Probability	0.85	0.10	0.05

If X_1 is a random variable describing the risk related to limiting the heat supply to the recipient A, at level I of the thermal power limit, taking into account the configuration of the district heating network S1, then the probability of operation of S1 network configuration without interference—without restrictions:

$$p_0^{(S1)} = \Pr(X_1 = 0) = 0.85.$$

The probability of S1 network configuration work with limitations on level I:

$$p_{Ii}^{(S1)} = \Pr(X_1 = x_{Ii}) = \frac{0.1}{40} = 0.00250.$$

The probability of S1 network configuration work with limitations on level II:

$$p_{IIi}^{(S1)} = \Pr(X_2 = x_{IIi}) = \frac{0.05}{60} = 0.00083.$$

It was assumed, that the probability distribution at a given level of heat supply limitations is uniform. The values of probabilities of disturbances in the operation of the S1 network corresponding to the b discount, respectively on the levels I and II of the thermal power limit, are presented in Tables 4 and 5.

Table 4. The probability values of disruptions in the operation of the S1 network corresponding to the b discount on the first level.

$u(b_i)$	$u(b = 0\%)$	$u(b = 1\%)$	$u(b = 2\%)$	$u(b = \dots)$	$u(b = 40\%)$
p_i	0.85000	0.00250	0.00250	0.00250	0.00250

Table 5. The probability values of network disruptions in the operation of the S1 network corresponding to the b discount on the second level.

$u(b_i)$	$u(b = 41\%)$	$u(b = 42\%)$	$u(b = 43\%)$	$u(b = \dots)$	$u(b = 100\%)$
p_i	0.00083	0.00083	0.00083	0.00083	0.00083

The expected value of the allowance related to the occurrence of the risk of limiting the heat supply of 1st level for the S1 network configuration:

$$E(x)_I^{(S1)} = 0 \cdot 0.85 + 459 \cdot 0.0025 + 918 \cdot 0.0025 + \dots + 18364 \cdot 0.0025 = 9412 \text{ zł.}$$

The expected value of the allowance related to the occurrence of the II level thermal power limitation risk for the S1 network configuration:

$$E(x)_{II}^{(S1)} = 37647 \cdot 0.00083 + 38565 \cdot 0.00083 + 39483 \cdot 0.00083 + \dots + 91822 \cdot 0.00083 = 3224 \text{ zł.}$$

$$E(x)_{S1} = 9412 + 3224 = 12636 \text{ zł.}$$

The probability values for the configuration states of the S2 network in the individual levels of constraints I and II are presented in Table 6.

Table 6. Probability values for individual S2 network configuration levels.

u_{S2}	0	$u_I(x)$	$u_{II}(x)$
Probability	0.95	0.04	0.01

Similarly, if X_2 is a random variable describing the risk related to limiting the heat supply to the recipient A at level I of the thermal power limit, taking into account the configuration of the district heating network S2, then the probability of operation of the S2 network configuration without interference—without restrictions:

$$p_0^{(S2)} = \Pr(X_2 = 0) = 0.95.$$

The probability of the S2 network configuration work with constraints on level I:

$$p_{Ii}^{(S2)} = \Pr(X_2 = x_{Ii}) = \frac{0.04}{40} = 0.001000.$$

The probability of S2 network configuration work with II level limitations:

$$p_{IIi}^{(S2)} = \Pr(X_2 = x_{IIi}) = \frac{0.01}{60} = 0.000167.$$

Assuming uniformity of the probability distribution at a given level of heat supply limitations, the values of probabilities of disturbances in S1 grid operation corresponding to the b discount, respectively on levels I and II of thermal power limitations, are presented in Tables 7 and 8.

Table 7. The probability values of disruptions in the operation of the S2 network corresponding to the b discount on the first level.

$u(b_i)$	$u(b = 0\%)$	$u(b = 1\%)$	$u(b = 2\%)$	$u(b = \dots)$	$u(b = 40\%)$
p_i	0.95	0.001	0.001	0.001	0.001

Table 8. The probability values of disruptions in the operation of the S2 network corresponding to the b discount on the second level.

$u(b_i)$	$u(b = 41\%)$	$u(b = 42\%)$	$u(b = 44\%)$	$u(b = \dots)$	$u(b = 100\%)$
p_i	0.000167	0.000167	0.000167	0.000167	0.000167

The expected value of the risk associated with the occurrence of the first level power limit for the S2 network configuration:

$$E(x)_{I}^{S2} = 376 \text{ PLN}$$

The expected value of the risk related to the occurrence of the second level power limit for the S2 network configuration:

$$E(x)_{II}^{S2} = 649 \text{ PLN}$$

Summing up both values, you can determine the expected value of the risk associated with the occurrence of thermal power limitation for the S2 network configuration:

$$E(x)_{S2} = E(x)_{I}^{S2} + E(x)_{II}^{S2} = 376 + 649 = 1025 \text{ PLN}$$

Comparing the values $E(x)_{S1}$ and $E(x)_{S2}$, it can be concluded that there was a case described by the dependence:

$$E(x)_{S1} > E(x)_{S2}.$$

This means that the configuration of the S1 network generates much higher costs in relation to the expected values of discounts related to the lack of heat supply to recipients. Therefore, the configuration of the S2 network layout is more advantageous.

5. Summary

Energy security and policy associated with it is a critical element of general state security. Ensuring security becomes a problem of the highest rank. The increase in the importance of energy security in the hierarchy of goals is a derivative of the awareness of a growth progressing dependence on external, imported energy carriers. In the context of infrastructure responsible for ensuring the security of heat supply, an important issue is its assessment in the aspect of supply security, taking into account economic and environmental conditions.

The results of the analyses carried out are helpful in risk assessment in the DHS as a category directly related to energy security, heat supply security and human safety. Current regulations adjust issues related to energy security and determine the need for companies to develop procedures for introducing restrictions in the supply of heat in case of danger. The binding legal regulations affecting the issue of granting discounts oblige energy companies also to grant discounts in the event of certain circumstances of failure to meet the quality standards for the service of heat consumers. One of the conditions for the modern operation of the DHS is the necessity of risk assessment, informing about its size and initiating actions that must be taken in the face of risk occurrence. The approach to risk assessment in the DHS presented in the work takes into account the system's decomposition in the analysis of the degree of fulfilment of tasks in the operation process. The comprehensive approach to risk assessment in DHS requires its location, identification and classification of threats. The estimation of risk and the reaction to it involves setting management priorities and comparing the determined risk levels with pre-determined target thresholds. It is not insignificant to monitor risk and to check compliance with established procedures. The final product of risk identification, assessment and measurement occurring in the DHS may be risk maps, which are useful tools in the process of effective management of centralized heat supply to recipients. The risk assessment presented in the paper using the event tree can be useful in counteracting hazards arising as a result of damage to system components, taking into account the variability of atmospheric conditions affecting the heat load. An adaptation of matrix methods for initial risk estimation in the DHS has also been made. The presented methods may be an additional element in conducting preventive activities related to prevention of damage, standardization of repairs, as well as in the preparation of rescue scenarios.

The described method can be used to select the most advantageous network configuration system at the design stage. In the operation process, it can be used to assess the security of heat supply to the recipient, taking into account different configurations of heat supply in the system by optimizing the distribution areas of supply heat.

The use of the elements of decision theory illustrated in the work also gives the opportunity to assess the risk and to manage the security of heat supplies to the recipient. It takes into account the possibility of different heat distribution configurations in the system at the operational stage, as well as optimizing the distribution of subsystem of heat supply power supply areas from individual DHS and selecting the most advantageous network configuration at the design stage.

Additional conclusions require comparison of analyses for different heating centres and reference to the required level of reliability, which should be determined taking into account many factors affecting the failure rate of heating networks and the size and shape of the network and ensuring thermal comfort for network users.

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Abbreviations

The following abbreviations are used in this manuscript:

DHS District heating system

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