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CRITERIA OF OPTIMALITY AND CONDITION OF THE COMPARISON OF DESIGN SOLUTIONS OF SYSTEMS OF HEAT SUPPLY

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Statement of the problem. The design of optimal heating systems of cities and settlements is a complex task involving many engineering calculations often performed repeatedly. This fact leads to the necessity of the development of automated systems for calculation and design. The accuracy of the solution of optimization problems for the design and construction of these systems depends on the correct choice of optimality criteria and their weight values.
Results and conclusions. The optimality criteria and their definitions typical of the solution of optimization problems of the construction industry are considered. The criteria of construction technology of a system, the production time of work, reliability and economic efficiency through static and dynamic reduced costs are identified. The method of determining the criterion of reduced costs by using material characteristics of thermal networks, which facilitates the comparison of various options at the initial design stage, is described. The qualitative criterion of reliability is provided in the form of quantitative characteristics, allowing one to determine these costs given the probabilistic nature of the additional costs.

Keywords: heat supply, criteria of optimality, designing of pipelines, comparison conditions.

Introduction. While designing systems of heat supply in cities and districts, there arises a problem of determining the most optimal parameters of a system overall or its individual elements [6, 9, 21]. There are the following issues emerging as this is addressed [14]: choosing a location and productivity of heat-generating sources; choosing an optimal configuration of a network of pipelines; choosing parameters of elements of heat supply systems. Each designing solution that is taken should be evaluated using a multitude of indices (criteria) that would normally have a variety of influences.

Therefore while designing new built engineering systems the central issue is economic efficiency that is characterized by construction costs, annual operating expenses, labor costs, opportunities for recurrent construction and commissioning [12]. Along with these, the parameters of a construction technology [1] and construction times are essential in the reconstruction of existing heat supply networks.

An evaluation involving a multitude of criteria while addressing technical optimization tasks is due to invalid or absurb solutions it is highly likely to produce that are way beyond a range of acceptable parameters. E.g., searching for an optimal structure of a heat supply network based merely on minimal costs might cause the operating costs associated with increasing heat losses to grow as well as the pressure and temperature to fluctuate at the receiver's end and the overall realibility of a system to decline due to a lower quality of the components of a network and lack of savings.

This indicates that the accuracy of solutions of optimization tasks in design and construction of heat supply networks of cities and towns depends on the choice of the optimal criteria and their weighted values. This is what this paper looks into.

1. Criteria for searching for economic efficiency of a designing solution of a heat supply network. The choice of the best designing solution generally involves the following: searching for an abolsute (total) economic efficiency of an object in question or a certain solution and search for a comparative economic efficiency of a few options [12].

The first problem has to be addressed in order to evaluate an option by comparing it economically with similar ones that have been implemented. A total economic efficiency is determined with a cost-efficiency coefficient [16] or a total economic [12] given by the formula

$$Э_{общ} = П / К , \quad (1)$$

where $П$ is an annual profit; K are total construction costs (of a heat supply network).

Generally this index is typical of a planned economy and in the construction industry it can be used only in the reconstruction of existing systems and analysis of different economic and energy indices of individual objects [16] as it cannot be applied unless there are any equivalents (ehich is typical of modern developing engineering systems).

Thus it is of interest to investigate comparative economic efficiency that is crucial for choosing a more viable solution which is determined by comparing costs of suggested designing solutions [1, 3, 10, 12, 16, 18, 19] that are the optimal criteria in this case:

$$З_{пр} = И + Е_н К \to \min , \tag{2}$$

where $И$ are operating expenses; $Е_н$ is a standard coefficient of the efficiency of financial costs (a value that is reverse to a standard payback period).

The dependence (2) can be used if the task is addressed statistically when a growth in the thermal energy consumption over a certain period is not considered. It is of more importance to address this as a dynamic task when a possible development of a heat supply system over a specified period is considered [10, 12, 18, 19]. In this case the condition (2) takes the following form

$$З_{пр} = \sum_{t=1}^{T} \left(Е_н К_t + \Delta И_t \right) \left(1 + Е_{н.э} \right)^{T-t} + И_{н.э} \to \min , \tag{3}$$

where $И_{н.\,э}$ are operating expenses at the time of normal operation; $К_t$ are financial costs for the t^{th} year; $\Delta И_t$ is a growth in annual operating expenses for the t^{th} year ($\Delta И_t = И_t - И_{t-1}$); $Е_{н.\,э}$ is a standard coefficient of reducing to an equal effect of costs at different points; T is the length of a calculation period and year of incurring the expenses; t is the year of financial investments into the start of a construction.

The dependence (3) is the simplest generalization of a statistic criterion (2) under the condition of a gradual development of an energy system and corresponds with a conditional discrete process of construction and operation of a s heat supply system as a gradual introduction of series with extra costs. In [19] there is another dynamic criterion for comparative economic efficiency where capital investments and expenses in construction are equal:

$$З_{пр} = \sum_{t=1}^{T_в} \left(К_t + И_t \right) В_t + \sum_{t=T_в+1}^{T_k} И_t В_t \to \min , \tag{4}$$

where $В_t$ is a coefficient of discounting or devaluation of annual costs t: $В_t = (1 + Е_{н.\,э})^{-t}$; T_k is a period of construction and operation of a system that includes that of construction and temporary operation $T_в$ and normal operation $T_н$.

For more convenient practical use of an integral criterion (4) in [19] there are assumptions where $t > T_в$, the expenses are constant ($И_t = И_{Тв}$), T_t for central heat supply systems can reach 40…50 and $Е_{н.\,э} = 0.08…0.1$. In this case $В_t \to 0$ and T_k can be considered equal to ∞, then the formula (4) can be written as

$$З_{пр} = \sum_{t=1}^{T_в} \left(К_t + И_t \right) В_t + \frac{И_{T_в}}{Е_{н.э} \left(1 + Е_{н.э} \right)^{T_в}} \to \min . \tag{5}$$

Capital investments in designing and construction of engineering systems can be identified in the following ways [12]:

— using financial reports based on the amount of construction and assembly works (requires a lot of calculations and design documentation);

— using increased report standards (no design documentation is needed, but the diameters of the pipelines, lengths of areas should be preliminarily calculated and the method of laying them should be identified);

— using the data of similar projects based on the final reports of specific capital costs per 1MWatt of thermal energy (the conditions for comparing with the considered option have to be considered);

— using specific capital costs of increasing energy indices (used for approximate economic comparison).

The above criteria are instrumental in choosing economic solutions out of a large number of design options by reducing the function of the expenses to the minimum. They became most common in dealing with optimization in the construction industry [4, 5, 11, 13, 20]. However, it is not always that capital investments into the construction of a particular system are accurately and easily found. Besides, as was shown above, search for an optimal solution using only a criterion of minimal costs might lead to incorrect solutions.

2. Material characteristics of a heat supply network. While choosing an optimal configuration of a heat supply network (when there is no design documentation available), in [12, 14—16] it is suggested that a material characteristics of a heat supply network *M* is used that is given by the formula

$$M = \sum_{i=1}^{n} D_{вні} l_i , \tag{6}$$

where $D_{вн}$ is the internal diameters of a pipeline in the area of a heat supply network; l is the length of the area of a heat supply network; n is the amount of areas in a heat supply network.

Using *M,* capital investments into the construction of a heat supply network can also be determined. Then the optimal criterion is as follows

$$К_{т.с} = a\sum_{i=1}^{n} l_i + bM = a\sum_{i=1}^{n} l_i + b\sum_{i=1}^{n} D_{вні} l_i \to \min , \tag{7}$$

where a and b are constant coefficients depending on the type and structure of a heat supply network.

For preliminary calculations it is typical when there are no data on the diameter of pipelines of a heat supply network. Then capital costs can be determined using the method described in

[15]. According to the method, a material characteristics of each area of a heat supply network can be presented as a product of a calculation consumption of a heat carrier in this area G by a specific material characteristics M_y related to a unit of a calculation consumption of a heat carrier and the material characteristics of a heat supply network is given by the formula

$$M = \sum_{i=1}^{n} M_{yi} G_i \,, \tag{8}$$

where n is the amount of areas of a heat supply system; M_y is a specific characteristics of the area of a network determined by the formula

$$M_y = \frac{17.5}{G^{0.03} q_в^{0.48} q_п^{0.14} m^{0.12} R_л^{0.19}} \,, \tag{9}$$

where $q_п$ is a calculation consumption of a heat carrier of one user a; $q_в$ is the density of the consumption of a heat carrier of this heat supply area (it is determined as a ratio of a calculation consumption of a hear carrier of this area per the area of this heat supply area); m is the coefficient that means a reduction in the shape of an area to a rectangular ratio of the smaller side of the heat supply area to the larger one; $R_л$ is the specific linear drop in the pressure of the main pipeline.

A total length of the pipelines of the entire heat supply system can also be determined using specific indices according to the formula

$$\sum_{i=1}^{n} l_i = \sum_{i=1}^{n} l_{удi} G_i \,, \tag{10}$$

where $l_{уд}$ is a specific length of the area of a network related to a unit of a calculation consumption of a heat carrier in this area:

$$l_{уд} = \frac{170}{G^{0.09} q_в^{0.45} q_п^{0.47} m^{0.1}} \,. \tag{11}$$

Therefore the criterion (7) for determining minimal capital costs for the construction of a heat supply network takes the following form

$$K_{т.с} = a \sum_{i=1}^{n} l_{удi} G_i + b \sum_{i=1}^{n} M_{yi} G_i \to \min \,. \tag{12}$$

3. Indices of the reliability of a designing solution of a heat supply network. Reliability of a heat supply system along with capital and operating costs is one of the major indices of technical and economic optimization of designing solutions and can thus have a direct influence on the former and latter [7, 8]. E.g., in heat supply of consumers of the first category of reliability (perinatal centers, hospitals, chemical enterprises, etc.), it is necessary to set up local heat-saving resources. It is also acceptable to save from other heat supply networks provided that a consumer is fully catered for with heat energy. Therefore choosing a particular saving method (i.e. improving reliability) has an impact on capital and operating costs of designing solutions.

Reliability can be characterized with such properties as durability, longevity, shelf life and repairability [1, 2, 15]. Durability is a system's property to retain its performance up to a limited state when its further use is not reasonable or acceptable. Longevity is a system's property to retain a performance of a heat supply network over a standard operating period. Repairability is a system's capacity to detect, remove and prevent failures of elements. Repairabilty is characterized with time to restore a failed element, which is of importance to prove saving is essential. Shelf life is a ssytem's property to retain its durability, longevity and repairability over a conservation period [15, 17].

Search for optimal realibility of a heat supply system can cause one to choose a maximum acceptable level of some value whose increase is not economically viable. A certain level of reliability can be achieved in a few ways: 1) improving the quality of components of a system's elements; 2) saving the elements. The first method involves extensive experimental studies and credible statistical data, which is not always achievable. The second method, which is called a way of enhancing reliability due to improving the structure of a network in [2], is used when reliability of a system should be higher than that of its individual elements. This method involves a transition from a complete uncertainty of the original information, which is typical of the first method, to a range of probabilistic logics and synthesis of reliable systems of unreliable elements using a tool of theories of reliability and probability [2]. For heat supply networks saving can be performed by doubling, ringing and sectioning.

Reliability of a heat supply network is generally evaluated using a reliability index that cannot be lower than a certain level. The higher it is, the more reliable is the system. Therefore the optimization criterion takes the following form [1, 2, 17]

$$R_{cucm}(t) = \frac{Q(t)}{Q_0} = 1 - \sum_{j=1}^{j=l} \frac{\Delta Q_j}{Q_0} \frac{\omega_i}{\sum \omega_i} \left(1 - e^{-\Sigma \omega_i t}\right) \to \max, \quad (13)$$

where Q_0 is a calculation heat consumption; ΔQ_j is an undersupply of heat; $Q(t)$ is a mathematical expectation of a characteristics of the quality of the operation of a system; t is the time; ω_i is a parameter of a series of failures given by the formula

$$\omega = \frac{\sum_{i=1}^{N} m_i}{N \Delta t} = \frac{m_{cp}(t)}{\Delta t}, \quad (14)$$

where m_i is the number of failures; N is the number of the same areas of a heat supply network; Δt is the time of observation; m_{cp} is the average number of failures.

In order to evaluate the most essential nods of a heat supply network, a reliability criterion should be determined using the formula

$$R_{узел}(t) = e^{-\Sigma\omega_i t} \to \max. \tag{15}$$

These criteria are used to evaluate a qualitative characteristics of a system. If quantitative evaluation of realibility of a heat supply network is made, there are a lot of random factors merging that are evaluated in combination using the theories of probability, mathematical statistics and random processes.

According to [2], a connection between the indices of reliability and efficiency can be determined using the equation

$$э = M\sigma\left[\Phi\left(x(t), T\right)\right] + f(K), \tag{16}$$

where $\sigma[\Phi\ (x\ (t),\ T)]$ is a characteristics of efficiency of a system over its service life T considering costs of repairs following failure; $\Phi\ (x\ (t),\ T)$ is a quantitative characteristics of reliability of a system; $f\,(K)$ is a characteristics of initial capital investments.

Since the state of a system at a random moment of time depends on several parameters, the value of a function should be identified in each area individually. Additionally, the resulting expression

$$э = \sum_{i=1}^{i=l} M\sigma_i\left[\Phi\left(x(t), T\right)\right] + f(K) \to \min, \tag{17}$$

is equal to that of the specified costs that are associated with a characteristics of reliability of a system.

As a result, the specified costs considering a probabilistic nature of extra expenses are as follows [2]

$$З_{пр} = \sum_{i=1}^{i=l} H_i(t)\left[И_{о.д} + C\right] + И + EK, \tag{18}$$

where $H_i\,(t)$ is a renewal function; $И_{о.\,д}$ are expected extra expenses in case of a failure; C are expenses associated with failure; $И$ are operational expenses (not associated with the reliability characteristics); E is a coefficient of specifying capital costs.

4. Construction and technological criteria of an optimal design solution of a heat supply network. Technological efficiency of construction is a series of technical properties and construction solutions that describe their compliance with the technical standards of construction and operation. Analysis of technological efficiency of construction of a design solution for heat supply systems are performed using the following indices [1]:

— labor costs:

$$\theta_{cmp} = \sum_{j=1}^{m} \sum_{k=1}^{n} \theta_{kj} v_{kj} , \tag{19}$$

where θ_{kj} are labor costs per a unit of construction works; v_{kj} is the amount of works; k are typical sizes ($i = 1, 2,\ldots, n$); j are types of structures виды конструкций ($j = 1, 2,\ldots, m$);

— machinery costs:

$$M_{cmp} = \sum_{j=1}^{m} \sum_{k=1}^{n} M_{kj} v_{kj} , \tag{20}$$

where M_{kj} are machinery costs per a unit of construction works.

Each of the above indices can be employed as a function of searching for an optimal solution as they are reduced to a minimum. However, labor costs ($\theta_{cmp} \rightarrow \min$) associated with construction works are commonly used as an optimal criterion to evaluate technological efficiency in construction of design solutions of heat supply systems [1]. In order to minimize the function boundary conditions where $v_{kj} \geq 0$, $T_{cmp} < T$ (T = const is a direct construction period; T_{cmp} is the time for the construction of an object) are introduced.

It is commonly of importance to look at the iindex of time for the construction or reconstruction of a heat supply network. A similar sutation might occur as works are conducted during the heat supply season or they interfere with standard operation of other infrastructure objects (highways, railways, water supply and drainage systems, etc.). Then construction time [1] is the central optimal criterion:

$$T_{cmp} = \sum_{j=1}^{m} \sum_{k=1}^{n} \frac{\theta_{kj} v_{kj}}{N_{kj}} \rightarrow \min , \tag{21}$$

where N_{kj} are the construction team members.

The criteria mentioned in Sections 1—4 are most commonly assumed to be of prominence in addressing optimization of heat supply systems in design and construction. However, in each particular case, there might be other indices, e.g., an optimal pressure differential, minimal heat losses, an optimal temperature of a heat-carrier, etc. In this paper they are not considered as they are of little significance in addressing the task in question.

5. Conditions for comparing design solutions. Comparisons design solutions are only possible if they are economically and energetically similar, which can only be if certain conditions are met [12, 19].

First, solutions being compared should be analyzed for optimal parameters and standard condtions of operation of each element of a system. They should also indicate an equal energy effect, i.e. provide users with an equal amount of energy (both in terms of power and mode). If there are any differences in place (different efficiency factors heat losses, etc.), they should be considered. If solutions involve objects that generate several types of production or a combination of objects to be constructed, an overall effect of all the objects and types of production should be taken into account. If there is a significant amount of investments into similar industries, this should also be considered.

In addition, costs should be specified in the same year, i.e. a comparison should be made possible in terms of time the costs were incurred and the effect that was achieved. An equal level of prices, accuracy of calculations and credibility of original data should be provided.

Although these are necessary but not sufficient, it is only if all of these conditions are met that optimization of heat supply systems should be further addressed. They are to be supplemented and extended for each particular task.

Conclusions. The use of the above criteria of economic efficiency (identified based on static and dynamic costs), technological efficiency of construction, time of construction works and reliability of a system allow one to consider the major aspects of designing, construction and operation of heat supply systems of cities and towns, which leads to fairly accurate results in addressing optimization tasks.

The above method of determining a criterion of specified costs using material characteristics of heat supply networks facilitates comparisons of different options of networks at the initial stage of designing when no design documentation is available. This characteristics can also be one of the optimal criteria. A qualitative optimality criterion of reliability is presented as a qualitative characteristics that allows specified costs to be determined considering a probabilistic nature of extra costs.

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