Methods of routing and sizing of water supply networks

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Abstract. One of the first steps in water distribution systems (WDSs) design process is the pipeline routing, defined as geometrical projection of a designed network. The analogical step can also be found in designing of other elements of technical infrastructure, such as energy lines or roads. Moreover, the pipeline routing process influences pipe's sizing and determinates investment, exploitation and maintenance aspects of the whole WDS. Despite its significant meaning, the routing process is still unsatisfactorily supported by mathematical methods and computer aided tools. Therefore, there are continuous researches of more effective pipeline routing and sizing methods. This paper presents a literature review about currently developed methods of network routing and methods of optimal pipeline sizing.

1 Introduction

Duringthe designing of water distribution systems (WDS) one of the first steps is the network routing. The analogical step can also be found in designing of other elements of technical infrastructure, such as energy lines or roads. In water supply sector, the routing process is defined as geometrical projection of a designed network, dependent on settlement unit plan, landform, localisation of water demand points or communication scheme. Network routing is determined by different rules, in accordance to the type of pipelines. Additionally, the routing process is divided on cross-section and plan routing. Plan routing is the initial action in designing process and means routing of pipelines on situation map. On the other hand, cross-section routing is the final step of designing and means the term of distances between the designed water supply pipe and other existing elements of technical infrastructure. Due to the great importance of routing process and its influence on further designing steps such as hydraulic calculations, investing costs or even operational costs, there are continuous researches of more effective way of water supply designing, including the searches of optimal network routing methods [1-4].

The multiplicity of routing methods developed so far, results in various ways of describing water supply networks. One of the most used water supply representation way is the graph theory, where water supply nodes responds to the graph vertexes, while pipes and connection branches respond to graph edges. That kind of representation allowed to applicate, in the process of shaping geometrical structures of networks, many different algorithms for finding the connection route between selected graph vertexes (source and demand points). The other, relatively new, way to describe geometrical shape of network structures is the application of elements of fractal geometry [5]. However, no method developed so far has a universal character and is possible to apply for any urban territories. It is caused by individual character of each design, which is determined by geographical, social, environmental, economic and technical factors [6,7].

The great number of factors influencing the designing process testify its complexity, which causes that the potential designing method should include many options and criteria [8]. Such requirement causes that water supply design task is the complex optimisation problem. So far, the process of plan routing was performed of the basis of knowledge and experience of the designer [9] - in accordance to specified requirements the designer proposed one or a few possible network variants. Such approach corresponded with searching of the local optimal solution. Recently, researches are developing the global optimisation methods fulfilling all designing requirements. The complexity of water supply designing problem causes the necessity of dividing this optimisation task into two steps: searching for optimal network shape (routing) and optimal network parameters (pipes' dimeters, pump curves, etc.) [10]. The following paper presents the literature review of the most important methods of routing and sizing water supply networks and optimisation of the design process.

2 Routing methods

The history of modern water supply systems shows that the network shape always determined its proper

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operation. Among the biggest water supply network of XIX century, many were designed as a structure of one or a few main loops of the greatest diameters with small branches [11]. It is worth to notice that in former designs the structure of water supply pipes was connected into loops, even if the calculations were made for branched structures. That approach proved, that even without the mathematical substantiation, the importance of water delivery certainty was taken into account. Finally, the Cross method [12] significantly influenced the calculations of looped networks, encouraging the designers to applicate the closed water supply networks.

The other major impact on pipelines routing was the idea of describing network by graph theory. It allows to applicate the least cost path algorithms (LCPA). The least cost path algorithm in accordance to water supply networks, most often means the shortest paths because the edge weight are lengths of particular pipes. The most important LCPA are: Dijkstra [13], Bellman-Ford [14,15], Floyd-Warshall [16,17] and Johnson [18]. One of the most popular is Dijkstra algorithm (DA) developed to find the shortest path from a single source in a graph of non-negative edges weights. For over 50 years since publishing, the DA was frequently modified and optimised [19-24]. One of the problems in application of LCPA is the fact, that these algorithms analyse the single connection between neighbouring nodes. It causes difficulties in representation of technical object such us bridges or tunnels, which do not connect neighbouring nodes but in practice are possible way to significantly shorten the path [25]. The other limitation of LCA application is the fact that the shortest path between two nodes responds to a single water pipe. In order to route the whole network, it was needed to applicate the selected algorithm many times repeatedly. Such approach resulted in significant computer processor overload and considerable calculation time.

Despite the great progress in network routing thanks to the graph theory, no universal method has been developed so far. The possible reason of that state was the assuming that the edge weight is the distance between nodes. The calculated on that basis connection paths were therefore the shortest paths. However, the best (optimal) connections between nodes is not always the shortest path [7], which deny the paradigm that 'shorter is better'. Such approach face the researchers with the task to find the parameter which could be decisive in choosing the connection path. One of the possibilities is the lower path resistance [26], calculated in geographic information system (GIS) environment. As the result, the designer receives information not only about the distance but also about time of delivery or reliability factor. Therefore, the final decision about the selected path is often supported by multi-criteria decision analysis (MCDA), according to which the selected solution should fulfil all requirements [27].

Another method of network routing is based on elements of fractal geometry [5], where every network can be presented as dendric structures. In the developed method the iterative duplication and rotation of a basic section is used to shape the geometrical structure of a network. Similar method is also presented in [7], where in addition to the total distance also the total rotation angle is analysed. Basing on analysed methods, it can be said that despite its significant meaning, the routing process is still unsatisfactorily supported by mathematical methods and computer aided tools.

3 Sizing methods and water supply networks optimisation

Proper dimension sizing determines the total investing and operating costs of water supply network, which make pipe sizing an optimisation task. Therefore, the problem of optimal designing the water supply network is searching for global minimum cost dependent on selected diameters [27]. Such approach has several primary assumptions such as: constant geometrical network shape and defined demands in nodes [9]. While the optimal designing of branched networks is well presented in the literature, there is only few looped structures optimal designing methods [10], because of the unknown direction of water flow [28], nonlinear dependence between flow and pressure losses and presence of discrete decisive variables [29]. In addition, in looped networks, the process of pipe sizing is more dependent on the network's shape [10]. In order to optimally design looped network, it is required to optimally route pipelines. However, it is not possible to optimally route network pipes without the knowledge of pipe sizing and vice versa. Therefore, the optimisation of looped water supply networks is an NP-hard combinatorial problem (NPH) [30].

One of the methods of solving NPH problem is linear programming (LP). In paper [31], the successive linear programming gradient (LPG) was used to solve the problem. To more complex water supply structures also the nonlinear programming (NLP) and dynamic programming (DP) is used to find the solution including several required parameters. However, the mathematical programming can be applied only for finding the local optimum, which is not fully satisfactory in accordance to complex looped water supply structures [32]. To find global optimal solution the heuristic methods are used. The heuristic methods allows to find the solution which in acceptable level fulfil the requirements of the optimal solution, but not always is the optimal solution. While traditional methods are impossible or impractical, the heuristic approach allows to solve the NPH problems fast and easy, thanks to available data analysis and predictions of forthcoming phenomenon basing on logical combinations and iterative improvements of developed solution. The example of heuristic method for finding global optimum is the Branch and Bound (BB) algorithm [33].

The more advanced methods are metaheuristics technics, which allows to find the final solution in indirect way – the applied algorithm does not find the precise solution but indicate the heuristic algorithm which will find the solution fulfilling the requirements of optimal solution in an acceptable level. The metaheuristic approach is most common used when the input data is incomplete or inaccurate. The basis of metaheuristic technics are analogies from real world – the rules of natural phenomenon. One of the most popular metaheuristic algorithm is the genetic algorithm (GA) [34]. Both GA and other evolutionary algorithms (EA) found its application in water supply sector: simulated annealing (SA) [35], harmony search (HS) [36], Tabu Search (TS) [37], ant colony optimization (ACO) [7], shuffle frog leap algorithm (SFLA) [38], particle swarm optimization (PSO) [39] orsoccer league competition (SLC) [40]. However, despite many developed methods there is still no universal algorithm ensuring the satisfactory results and effective optimisation process for water supply networks of a real size [11].

4 Conclusions

The necessity of improving WDS reliability enforced delivering water to every consumer with at least two possible paths, which was obtained by connecting branched networks into looped structures. Automatically, it increased the investment and operational costs of water supply networks and therefore in recent years the significant development of optimisation technics and tools can be observed.

Basing on literature review, it can be said that pipeline routing still can be treated as a separate design step but it is mainly used in transmission pipelines routing. For this purpose, the GIS environment is used most often, together with design supporting tools such as MCDA. Network routing, in dependence on selected describing network method, in most often combined with pipe sizing. So, nowadays the most popular are hybrid optimisation methods, which parallel develop the network structure and pipe diameters.

However, despite many developed optimisation methods, there is still no one universal tool, which could be used in any real-size water supply network. Therefore, it is reasonable to continue the researches on such method, which could be use not only in references conditions but also in real water supply networks with multiple water sources.

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