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Evaluation and optimization of secondary water supply system renovation*

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Abstract: Due to pollution in second water supply system (SWSS), nine renovation alternative plans were proposed and comprehensive evaluations of different plan based on Analytical Hierarchy Process (AHP) were presented in this paper. Comparisons of advantages and disadvantages among the plans of SWSS renovations provided solid foundation for selecting the most appropriate plan for engineering projects. In addition, a mathematical model of the optimal combination of renovation plans has been set up and software Lingo was used to solve the model. As a case study, the paper analyzed 15 buildings in Tianjin City. After simulation of the SWSS renovation system, an optimal scheme was obtained, the result of which indicates that 10 out of those 15 buildings need be renovated in priority. The renovation plans selected for each building are the ones ranked higher in the comprehensive analysis. The analysis revealed that the optimal scheme, compared with two other randomly calculated ones, increased the percentage of service population by 19.6% and 13.6% respectively, which significantly improved social and economical benefits.

Key words: Secondary water supply system (SWSS), Renovation plan, Analytical Hierarchy Process (AHP), Hierarchical model, Optimization
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INTRODUCTION

The renovation to secondary water supply system (SWSS) is a huge and complicated project. The methods and cost are varied regarding to different architecture styles, locations, pollution sources and the pressure of municipal pipe network system. With consideration of variable factors of economy, technology and social environment, Analytical Hierarchy Process (AHP) (Saaty, 1990) was used to comprehensively evaluate and optimize SWSS renovation plans in this paper. Then, a mathematical model with combination of renovation plans was established based on the optimal solution. Through SWSS case study in Tianjin, a conclusion was made that economical, technological and social benefits of engineering system can be optimized by rational choosing of renovated targets and combination of renovation alternatives under the condition of water quantity, pressure, and quality.

EVALUATION OF SWSS RENOVATIONS BY THE METHOD OF AHP

In recent years, more and more researches have been trying to use multi-objective decision making method (Abrishamchi *et al.*, 2005) to determine the optimal alternative in urban water supply design and operation. As a decision-aiding method developed by Saaty, AHP has been demonstrated in a number of studies because of its simplicity and utility, including evaluation and analysis of the supply and demand of

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agricultural water resource (Lu *et al.*, 2003), comprehensive risk evaluation of water supply (Liu *et al.*, 2006), ranking the elements of water-supply networks (Michaud and Apostolakis, 2006), and so on. The decision-making process aims at prioritizing a given set of alternatives based on the judgment of the decision-makers, and stressing the importance of the intuitive judgments of each decision-maker as well as the consistency of the comparison of alternatives (Al-Harbi, 2001). The objective of this paper is to introduce the application of AHP in evaluating and optimizing SWSS renovation.

The pollution sources in SWSS mainly come from pipeline corrosion, dust deposition, low quality tank material, aged facilities, and so on. Other reasons causing pollution are poor management, bad maintenance without disinfecting apparatus for regular cleaning, and some water supply tanks containing both domestic water and hydrant water which gives rise to long residence time so that bacteria can thrive. In renovation project, there are some recommendations to make changes on the existing setup to improve water supply reliability, improve utilization of original facilities, and reduce the costs of renovation: replacing roof-tank material with stainless steel, adding disinfecting apparatus, or changing to pressure pump or inline pump (Tang *et al.*, 2003). On the other hand, it is suggested to abort roof-tank and change to variable-speed pump or air-lift pump with assistance of suitable regulative measures to ensure water quality, increase the equipment life term, and keep the safe operation of the system (Wang, 2006). Hereby, 9 SWSS renovation plans are proposed as follows, shown in Table 1.

Build a hierarchical model

Overall goal: sorting SWSS renovation plans.

Basic criteria: according to the current normal secondary water supply method, several criteria must be considered in the evaluation process, which include:

(1) Technical standard: water supply reliability (WSR), water quality security (WQS), the utilization of municipal water pressure (UMP), remove interference from external municipal pipe network system (IEP), easiness in operation and arrangement (EOA) (Liu, 2002);

(2) Economic criteria related to the cost of water supply, such as: construction expenditure (CE), power cost (PC);

(3) Environmental-friendly criteria: easiness in construction (EC); noise nuisance (NN);

Layer of alternative solutions: 9 renovation plans shown in Table 1.

Following the AHP procedure, the hierarchy of the problem can be developed as shown in Fig.1.

Synthesizing the pair-wise comparison matrices

Firstly, the elements of criteria layer *B* should be compared pair-wise with respect to the overall goal *A*.

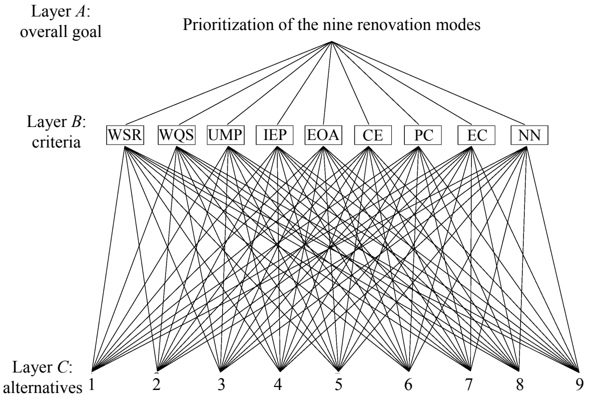

Fig.1 A hierarchal representation of the problem with nine criteria and nine alternatives

Table 1 SWSS renovation plans

Classifications	Serial number	Renovation plans
Restructure roof-tanks	①	Set up new stainless steel tank and add disinfecting apparatus
	②	Pump water from water pool. Set up stainless steel tank and add disinfecting apparatus
	③	Supply water from pipe pump. Set up new stainless steel tank and add disinfecting apparatus
	④	Supply water from water pool and pipe pump. Set up new stainless steel tank and add disinfecting apparatus
Abandon roof-tanks	⑤	Supply water with variable-speed pump
	⑥	Supply water with variable-speed pump and setting regulation with air-tank
	⑦	Pump water from underground water tank and supply with variable-speed pump
	⑧	Supply water with air-tank
	⑨	Supply water with airtight water supply apparatus

Therefore, every criterion along with their different relative importance should be judged and prioritized (Saaty, 2000). Obviously, securing water supply in terms of both quality and quantity is the most important, while noise nuisance should also be of concern. The outcome of this comparison is shown in Table 2.

Table 2 The prioritization of each criterion (A~I)

Criterion	Ranking	Criterion	Ranking
WSR	A	UMP	F
WQS	B	EOA	G
IEP	C	NN	H
PC	D	EC	I
CE	E	–	–

Hereby, the matrix for pair-wise comparison of criteria layer was constructed, presented as $\boldsymbol{B}^A$:

$$\boldsymbol{B}^A=\begin{bmatrix}1 & 1/2 & 1/3 & 1/4 & 1/5 & 1/6 & 1/7 & 1/8 & 1/9\\ 2 & 1 & 1/2 & 1/3 & 1/4 & 1/5 & 1/6 & 1/7 & 1/8\\ 3 & 2 & 1 & 1/2 & 1/3 & 1/4 & 1/5 & 1/6 & 1/7\\ 4 & 3 & 2 & 1 & 1/2 & 1/3 & 1/4 & 1/5 & 1/6\\ 5 & 4 & 3 & 2 & 1 & 1/2 & 1/3 & 1/4 & 1/5\\ 6 & 5 & 4 & 3 & 2 & 1 & 1/2 & 1/3 & 1/4\\ 7 & 6 & 5 & 4 & 3 & 2 & 1 & 1/2 & 1/3\\ 8 & 7 & 6 & 5 & 4 & 3 & 2 & 1 & 1/2\\ 9 & 8 & 7 & 6 & 5 & 4 & 3 & 2 & 1\end{bmatrix}.$$

It is suggested that a 1~9 scale be used to transform verbal judgments into numerical quantities (Saaty, 2000), representing the values of B_{ij}. The scale is explained as follows: 1: equal importance; 3: weak importance; 5: moderate importance; 7: strong importance; 9: extreme importance; 2, 4, 6, 8 and their reciprocals: intermediate values (Saaty, 2000).

For each a_{ij} in matrices constructed in AHP, there is $a_{ji}=a_{ij}^{-1}$.

Each value in line i stands for the pair-wise comparison of the relative importance of each criterion in layer B with criterion i, e.g., $a_{62}=5$ means Criterion ② (WQS) is of moderate importance compared with Criterion ⑥ (UMP). Other values have similar meanings.

Then, judgmental matrices in layer C are developed with respect to each criterion in layer B, denoted as $\boldsymbol{C}^i$ (i=1,2,...,9), which were used to compare the relative importance of renovation alternatives versus criteria i. The setup of judgmental matrices was similar, so only $\boldsymbol{C}^1$ was given here, i.e. the pair-wise comparison of every renovation plan with respect to WSR:

$$\boldsymbol{C}^1=\begin{bmatrix}1 & 5 & 3 & 7 & 3 & 5 & 7 & 1 & 7\\ 1/5 & 1 & 1/3 & 3 & 1/3 & 1 & 3 & 1/5 & 3\\ 1/3 & 3 & 1 & 5 & 1 & 3 & 5 & 1/3 & 5\\ 1/7 & 1/3 & 1/5 & 1 & 1/5 & 1/3 & 1 & 1/7 & 1\\ 1/3 & 3 & 1 & 5 & 1 & 3 & 5 & 1/3 & 5\\ 1/5 & 1 & 1/3 & 3 & 1/3 & 1 & 3 & 1/5 & 3\\ 1/7 & 1/3 & 1/5 & 1 & 1/5 & 1/3 & 1 & 1/7 & 1\\ 1 & 5 & 3 & 7 & 3 & 5 & 7 & 1 & 7\\ 1/7 & 1/3 & 1/5 & 1 & 1/5 & 1/3 & 1 & 1/7 & 1\end{bmatrix}.$$

The numerical values in these matrices ($\boldsymbol{C}^1$~$\boldsymbol{C}^9$) were obtained through consultation with some experienced experts, as well as from references, in which the characteristics of the secondary water supply methods were evaluated (Wang, 2000; Tang *et al.*, 2003; Dong, 2006). Each value in line i stands for the pair-wise comparison of the relative importance of each plan in layer C with plan i, e.g. $a_{14}=7$ means plan ④ is much more important in water supply reliability compared with plan ①. The rest of the values have similar meanings.

Layer sorting and consistency check

After these judgmental matrices are set up, the next step is to prioritize elements in each layer and determine the consistency of the judgments. Generally, these priorities can be estimated by searching the principal eigenvector $\boldsymbol{w}$ of each matrix through the equation $\boldsymbol{Aw}=\lambda_{\max}\boldsymbol{w}$ ($\boldsymbol{A}$ represents a matrix) (Al-Harbi, 2001). Then the vector $\boldsymbol{w}$ is normalized, in which weights are normalized to sum to 1 and reflect the relative importance of the elements, and it becomes the vector of priorities of every matrix. $\lambda_{\max}$ is the largest eigenvalue of matrix $\boldsymbol{A}$, and the corresponding eigenvector $\boldsymbol{w}$ contains only positive entries (Al-Harbi, 2001). The last step is to calculate coincidence indicator and check the judgment consistency. In order to obtain a consistent matrix, judgmental matrices should be reviewed and reconstructed, maybe several times (Saaty, 1994).

Table 3 Relative weights of every matrix

Criteria	w_i	b_1^i	b_2^i	b_3^i	b_4^i	b_5^i	b_6^i	b_7^i	b_8^i	b_9^i
WSR (B_1)	0.3100	0.2677	0.0641	0.1365	0.0273	0.1365	0.0606	0.0273	0.2529	0.0273
WQS (B_2)	0.2247	0.3066	0.1407	0.1407	0.1407	0.0287	0.0287	0.0609	0.1245	0.0287
IEP (B_3)	0.1578	0.0301	0.0301	0.2711	0.0688	0.2711	0.1354	0.0301	0.0301	0.1354
PC (B_4)	0.1090	0.0225	0.0460	0.0460	0.0996	0.2213	0.2213	0.2213	0.0225	0.0996
CE (B_5)	0.0746	0.0238	0.1150	0.0496	0.1150	0.0238	0.0496	0.1150	0.2547	0.2547
UMP (B_6)	0.0512	0.0257	0.2323	0.0257	0.1137	0.0257	0.0561	0.2323	0.2323	0.0561
EOA (B_7)	0.0352	0.1137	0.2323	0.2323	0.2323	0.0257	0.0257	0.0257	0.0561	0.0561
NN (B_8)	0.0194	0.0206	0.2198	0.2198	0.2198	0.0420	0.0420	0.0420	0.0970	0.0970
EC (B_9)	0.0181	0.0420	0.2198	0.0970	0.2198	0.0206	0.0420	0.0420	0.0970	0.2198

Note: Values in w_i are the ratings of every criterion with respect to the overall goal; b_j^i (j=1,2,…,9) stands for the relative weight of each alternative with respect to criterion B_i; $\sum w_i=1$; $\sum_i b_j^i=1$

In this paper, the details of the matrix calculation are not presented and only the relative weights of every matrix are calculated, as shown in Table 3.

From Table 3, we could get the composite weight (CW) of the different renovation plans according to the overall goal, based on the formula $\sum_i b_j^i w_i$, as shown in Table 4 (Al-Harbi, 2001).

Table 4 Final priorities of alternatives in contributing to the overall goal

Alternatives	CW	Alternatives	CW
①	0.0532	⑥	0.0540
②	0.1954	⑦	0.0745
③	0.1397	⑧	0.1143
④	0.1859	⑨	0.1348
⑤	0.0483	–	–

The sum of all alternatives' composite weights (1~9) is 1

Result and analysis

This result indicated that renovation plan ②—"Pump water from water pool, set up stainless steel tank and add disinfecting apparatus" is the best one. The rankings of alternatives with respect to the relative weights are: ②>④>③>⑨>⑧>⑦>⑥>①>⑤.

From this ranking, it can be seen that roof-tank restructure is practical and can be put into extensive use. This can be explained by its merits such as: simple installation, low cost, slight environmental impact, as well as its stability of water supply when encountered with emergency or service interruption, etc. (Wang and Sun, 2005). Nowadays, more and more new buildings are installed with variable speed pump to supply drinking water, and water tank seems to be out of date. However, the disadvantages of this technologically-demanding plan are also apparent: the system is complex and needs higher construction and operating cost, and its maintenance requires more skills. So in underdeveloped regions, roof-tank is still the first choice for many high-rise buildings.

This ranking comprehensively considered many factors, such as: water supply stability, assurance of water quality, the utilization of municipal water pressure, construction expenditure, power cost, and so on. Each renovation plan has its own scope of application, so each different situation should be dealt with individually in projects.

OPTIMAL MODEL OF SWSS RENOVATION

At present, the implementation of renovations to SWSS is still in the initial stage, so the number of systems to be reconstructed will be huge. Given the limitation of finance and city planning, the renovation projects are always processed by batch. Therefore, it is suggested to apply system optimization to take full advantage of limited funds to obtain the best social benefits. Through the renovation of SWSS in Tianjin City, this paper briefly introduced the optimization model development and solution of this optimization process.

Background information

Due to insufficient data and the complex nature of the problem, 15 buildings in Tianjin City were selected for renovation consideration in this paper. Here, each building is given 1 to 3 suitable renovation

Table 5 Basic information of each building and their available renovation plans

Building No.	Number of storeys	Households	Number of residents	Problems to be settled	Renovation plans*
(1)	9	80	280	Domestic and hydrant water are stored in the same tank, giving rise to long residence time so that bacteria might thrive	② ⑧
(2)	30	300	1050	Water tanks are running without disinfecting apparatus, and the existing pumps have been in use for too long time	②
(3)	7	210	735	Hydraulic pressure cannot meet the demand during peak time when consumption is high, especially for residents of top floors	③ ⑥
(4)	7	56	196	The aged water tanks leads to deterioration of water quality. Inadequate hydraulic pressure cannot meet the demand during peak times	② ⑧
(5)	8	84	294	Contamination arises with aged water tanks. Hydraulic pressure cannot meet the demand during peak time	⑦ ⑧
(6)	29	130	455	Contamination arises with aged water tanks and pumps	②
(7)	8	384	1344	Hydraulic pressure cannot meet the demand	⑦
(8)	18	144	504	Domestic and hydrant water are stored in the same tank, giving rise to long residence time so that bacteria can thrive here. Also, the aged water tanks and pumps can lead to deterioration of water quality	⑥ ⑦
(9)	18	162	567	Same with (8)	⑦ ⑨
(10)	18	162	582	Same with (8)	⑦ ⑨
(11)	15	525	1838	The aged water tanks lead to deterioration of water quality	① ⑦
(12)	17	216	756	Contamination arises with the aged water supply system	⑥ ⑦
(13)	15	225	788	With the aged water tanks and pumps, contamination arises in drinking water	② ⑧
(14)	16	192	672	Contamination arises in drinking water as the aged water supply system	⑥ ⑦
(15)	15	180	630	Same with (8)	② ⑥ ⑦

* Renovation plans in Table 5 correspond with those in Table 1

plans. The available renovation fund is limited to RMB 600×10^3 Yuan. Table 5 shows the basic information of each building and existing problems in the SWSS.

Development of optimal renovation plan

1. Model establishment and solution

The objective of this model is to choose the most suitable combination of renovation, so that the service to population is maximized:

$$\max P(x)=\sum_{i=1}^{15}\sum_{j=1}^{3}a_{ij}x_{ij}, \tag{1}$$

where $P(x)$ is the population number served by this renovation project; x_{ij} stands for whether or not building i will be reconstructed with plan j.

$$x_{ij}=\begin{cases}1, & \text{if building } i \text{ will be reconstructed} \\ & \text{and plan } j \text{ be adopted;} \\ 0, & \text{otherwise,}\end{cases}$$

where i=1,2,…,15 is the serial number of buildings to be reconstructed, j=1,2,3 is the renovation plans to be selected; a_{ij} is the number of served population, if building i will be reconstructed, and plan j be adopted.

Subject to:

(1) Funds available constraint:

$$F(x)=\sum_{i=1}^{15}\sum_{j=1}^{3}b_{ij}x_{ij}\leq 600000, \tag{2}$$

where b_{ij} is the renovation cost of x_{ij}.

The rest of the symbols have the same meaning as mentioned before.

(2) Constraint of renovation plans to be adopted:

$$0\leq\sum_{j=1}^{3}x_{ij}\leq 1,\ \ i=1,2,\ldots,15. \tag{3}$$

This constraint ensures that only one renovation plan is adopted for building i at most. That is: no more than 1 plan should be adopted in x_{ij} (j=1,2,3).

(3) Constraint of project:

$$k_1\leq\sum_{i=k}^{k+p}\sum_{j=1}^{m}x_{ij}\leq k_2, \tag{4}$$

where k~$k+p$ is the serial number of buildings to be reconstructed, $k+p\leq n$; k_1 and k_2 are the lower and upper limits of the number of buildings to be reconstructed respectively. The rest of the symbols have the same meaning as mentioned before.

Some renovation projects are interrelated with multiple factors, such as: the maintenance and renewal of municipal pipe networks, residential district planning, so the renovation projects are restricted by practical conditions. This constraint ensures that the number of buildings to be reconstructed will not exceed the upper and the lower limit.

This mathematical model is a kind of integer programming problem, and professional software Lingo is available to settle it. The outcomes are below:

$$\begin{aligned}&x_{11}=1,\ x_{21}=1,\ x_{52}=1,\ x_{61}=1,\ x_{71}=1,\\&x_{82}=1,\ x_{92}=1,\ x_{102}=1,\ x_{112}=1,\ x_{132}=1.\end{aligned} \tag{5}$$

The rest were all zeros. The total cost of this optimal scheme was RMB 599.7×10^3 Yuan, with a maximum service population of 7355.

2. Result analyses

(1) Analyzing the rationality of this optimal renovation

In the optimal scheme, 10 out of those 15 buildings were selected to go through optimal renovations, while the rest have no change. Two renovation methods were provided for seven buildings. The optimal scheme chose the more reasonable one between offered methods. For example: building No. 1 prefers plan ② mainly because only a newly-built drinking-water tank is added to the existing system in plan ②, making it far more economical than plan ⑧. For buildings No. 9 and No. 10, Plan ⑨, which ranks higher in the analysis result is preferable to plan ⑦. This new-style water supply system is gaining popularity gradually with merits such as: energy-saving, easy maintenance, no secondary pollutant, and so on.

(2) Comparison of social benefits among different schemes

The mathematical model (Eqs.(1)~(4)) was to gain the maximum social benefits and service the largest population. Eq.(5) revealed the number of favored people by an optimal scheme is 7355, which ranks top 1 among all renovation schemes. As an illustration, the paper randomly selected another two schemes for analysis, as indicated in Table 6. Scheme 1 was to choose the minimal cost from each building renovation. Scheme 2 was to select each building that has a maximum number of service populations. Those two schemes were also restricted within the available funds RMB 600×10^3 Yuan.

Table 6 Comparisons of the three renovation schemes

Schemes	Total cost (×10^3 Yuan)	Service population (person)	Number of building facing reconstruction
Optimal scheme	599.7	7355	10
Scheme 1	594.3	6148	10
Scheme 2	573.4	6475	10

With comparisons among those three schemes, it is apparent that their renovation costs are close, whereas the optimal scheme raised the service population by 19.6% and 13.6% respectively.

CONCLUSION

The renovation of SWSS is a challenging and complicated engineering project which has a lot of restrictions. It involves complex decision making situations that require discerning abilities and methods to make sound decisions. Therefore, AHP presented in this paper is to evaluate and prioritize the renovation of SWSS. Then, an optimal renovation model was solved based on the principle of system optimization, which helps to make sound decision in complex renovation project. Finally, the simulation of buildings renovation in Tianjin City indicated its practicability and feasibility.

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