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Managing expert knowledge in water network expansion project implementation

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Abstract: The implementation of expansion projects of water networks supplying growing cities is deemed to be a complex decision-making problem involving both technical aspects and expert knowledge. Management and control processes must rely on experts in the field whose know-how must be coupled with techniques able to deal with the natural subjectivity that affects input evaluations. Given the presence of many decision-making elements, the choice of proper hydraulic technical parameters may be linked to the main aspects of analysis requiring formal expert evaluation. In this contribution, the simulation of hydraulic indicators is integrated with a multi-criteria approach able to eventually determine those areas of a water network through which organising the expansion may be more beneficial. The software EPAnet 2.0 is first used for hydraulic simulations, whereas the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) will eventually rank network's nodes. A case study is solved to demonstrate the applicability and effectiveness of the proposed approach.

Keywords: Complex Systems; Management and Control; Water Distribution Networks; Expansion Project; EPAnet software 2.0; TOPSIS.

1. INTRODUCTION, GOAL AND STRUCTURE

Complex systems management and control frequently rely on expert knowledge as a crucial support for optimisation opportunities. This contribution deals with the topic of expansion projects of complex water networks, aiming at extensively improving water supply in growing cities. In this context, networks should be preferably expanded towards specific areas identified in a structured way. Experts are commonly required to actively participate in such decision-making processes and express their opinions by pairwise comparing possible solutions that, in this case, may be represented by the nodes of the original water network. Unfortunately, the complexity of this problem lies on the large (sometime huge) number of nodes to be simultaneously compared, what may potentially lead to difficulties when mathematically manipulating linguistic judgments elicited by the experts. Consistency of judgments may indeed likely waver, and the presence of intransitive preference relations should be considered. Given this evidence and being several quantitative variables involved, some of them may be selected and directly related to the qualitative aspects for which evaluations from experts are required. For example, such an important aspect of analysis as reliability of water networks may be represented by resilience, pressure uniformity, and so on. Experts would then support the decision-making problem by selecting the hydraulic parameters of interest and their qualitative comparisons would be directly replaced by values simulated for the quantitative variables of interest. The EPAnet 2.0 software is herein used to first lead hydraulic simulations. Once collected, the input values will be treated through the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). This method will rank the nodes of the network to show the more convenient areas for expansion without implying any *a posteriori* check of mathematical consistency for stakeholders' evaluations.

The main objective of this research consists in manipulating stakeholders preference relations by linking the main aspects of expert-based assessment to quantitative and measurable parameters. The paper is organised as follows. Section 2 offers a literature review in the field of water network expansion projects with particular reference to the current methodological approaches. Section 3 suggests the integration of hydraulic simulations and a multi-criteria perspective to deal with the topic of research. Section 4 presents a real case study to test the effectiveness of the proposed approach. Lastly, section 5 presents the conclusions along with potential future developments.

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2. LITERATURE REVIEW

Water distribution networks play a key role for urban life quality and also for the developemnt of cities (Liu et al., 2020). For many years, water networks have been designed based on mathematical models able to obtain economical and reliable systems (Di Nardo et al., 2018).

Nevertheless, due to the growth of cities associated to urban area expansion and population increase, water networks are stressed and usually lose capacity to delivery water in quantity and quality to the users. So, the management of water systems and the expansion of the cities should be studied and analyzed to reduce the impacts on the existing systems. Indexes related to economical interest, reliability, vulnerability and efficiency can be used for better understanding the expansion of the systems.

According to Yazdani et al. (2011), the design of large water networks is complex and involve different stakeholders. Not only full service to the users should be guaranteed, but also the quality of service (e.g. water quality) and the health of water system (e.g. resilience and pressure distribution). The authors developed a methodology for evaluating and expanding water distribution systems based on modifying the resilience index Todini (2000) and applying complex network theory.

Considering the impacts of expansions on the population health, Galiani et al. (2009) evaluates diseases reduction in already populated zones of Buenos Aires after expanding the water network. The impacts on population health are highlighted by the authors, but the impacts on the original network is not evaluated.

To make water network expansion feasible, some authors, in addition to evaluate the impacts of the expansion, include an optimization process for replacing pipes, pumps or strategically build new reservoirs in the system Bhave (1985). To identify bottlenecks on expanding water networks, Hsu et al. (2008) join complex network analysis with meta heuristic optimization. The authors evaluate the original water system based on four complex network indexes (e.g. Shortage Index, Stability Degree, Loading Rate, and Congestion Frequency). These indexes point to complex regions of the water network where engineering actions should be performed to make the water network expansion feasible.

3. METHODOLOGICAL APPROACH

The methodology for evaluating and ranking expansion scenarios is divided into two parts: hydraulic analysis and multi-criteria evaluation. In the first part, several simulations are carried out and the hydraulic and water quality results are evaluated under a set of indicators. In the second part, these scenarios are treated by the Multi-Criteria Decision-Making (MCDM) method TOPSIS, useful to rank various alternatives in many application areas (Ouenniche et al. (2018); Carpitella et al. (2018)).

3.1 Hydraulic analysis

The expansion scenarios are developed based on the average water demand of the original water network. Several nodes in the system are selected as candidate for expansion. For each node, six percentages (0.5%, 1%, 2%, 5% and 10%) are evaluated, simulating the growth of population in that zone.

For the hydraulic simulations, the software EPAnet 2.0 (Rossman (2000)) is used. The base demand of an expansion node is changed, resulting a cumulative demand, equal to the original base demand increased by the expansion demand. Since the water network has a 24-hour demand pattern, the simulation is performed considering the period of one day.

With the hydraulic (pressure, flow, water tank level) and water quality results (water age), pressure uniformity (PU), hydraulic resilience (I_{res}) and weighted water age (WA) are calculated. Pressure uniformity is an index proposed by Al-Hemairi and Shakir (2006) for evaluating the pressure of a water network in relation to the minimal pressure required to the system and also to the average pressure of the system. While high pressures make the system more resilient in case of accidents, this hydraulic state also leads to high leaks in the case of small orifices or bad pipe connections. For economic reasons, the lower the operational pressure, the cheaper the operation process. Furthermore, high differences of pressure in the systems turn the operation of valves and pumps a hard task; to this end, pressure uniformity measures both surplus pressure and deviation to the average pressure. PU is calculated by:

$$PU = \sum_{t=1}^{T} \left\{ \frac{1}{N} \sum_{i=1}^{N} \frac{P_{i,t} - Pmin}{P_{min}} \right\} + \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_{i,t} - P_{avg,t})^2}}{P_{avg,t}}; \quad (1)$$

where $P_{i,t}$ is the pressure at node i in a network with N nodes, at time step t in a simulation during T time steps, P_{min} is the minimal operational pressure of the system, and $P_{avg,t}$ is the average pressure of the water network at time step t.

The second index used for evaluating the changes in the original water network due to the expansion of the system is related to water quality. Hydraulic changes in the system lead to changing flow velocity in the pipes and, consequently, to changing the mass transport capacity of the system. For generic evaluation, the water age, calculated as the time travel of water in the pipes, is used as a base parameter. Weighted average water age above operational limit (WA), presented by Marchi et al. (2014) is an index used to evaluate the quantity of consumed water above standardized limits. This index is written as:

$$WA = \frac{\sum_{t=1}^{T} \sum_{i=1}^{N} k_{i,t} q_{i,j} (WA_{i,t} - WA_{lim})}{\sum_{t=1}^{T} \sum_{i=1}^{N} k_{i,t} q_{i,t}}; \quad (2)$$

where $WA_{i,j}$ is the water age at node i in the evaluation time t, WA_{lim} is the standard limit for water age, avoiding bad water quality, $q_{i,t}$ is the demand at node i in the evaluation time t, and $k_{i,t}$ is a Boolean variable assuming the value 1 if $WA_{i,t} > WA_{lim}$ and 0 if $WA_{i,t} \leq WA_{lim}$.

Finally, the resilience index, proposed by Todini (2000) is used to evaluate the capacity of the water network for absorbing the impacts of expansions. In a nutshell, expansion impacts are directly associated with demand increases, which mainly produce increased flow through the pipes, with its associated flow velocity increase and, eventually of hydraulic head loss. The reduction of available head, in its turn, leads to the reduction of reliability of the system in non-conventional scenarios, such as pipe bursts, fire fight, etc. This evaluation is based on the required power for guaranteeing the minimum operational pressure in the system in relation to the available power offered by reservoirs, tanks and pumps. The resilience index can be written as:

$$I_R = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} q_{i,t}(h_{i,t} - h^*)}{\sum_{t=1}^{T}\sum_{r=1}^{N_r} H_r Q_r + \sum_{k=1}^{N_p} P_k/\gamma - \sum_{i=1}^{N} q_{i,t} h^*}; \quad (3)$$

where $h_{i,t}$ is the hydraulic head at node i at evaluation time t, h^* is the required hydraulic head for supply the system, Q_r and H_r are the flow delivered by reservoir/tank r and the hydraulic head of the reservoir/tank r, respectively. P_k is the power of pump k, and *gamma* is the specific weight of the fluid.

Not only hydraulic criteria play an important role in the process of expansion in urban zones, but also economic interest is important. To evaluate this criterion, the zones of water distribution system are classified based into the district metered areas (DMAs) already existing in the system. DMAs are partitions of the network that have a set of demand nodes supplied by specific tanks or reservoirs and that also have specific sets of pumps for controlling the hydraulic head of the system. The four criteria are used in the multi-criteria analysis, resulting in a ranking of zones for urban expansion.

3.2 Multi-criteria evaluation

The TOPSIS technique, first developed by Hwang and Yoon Hwang and Yoon (1981), is aimed at ranking alternatives representing potential solutions of the decision-making problem object of analysis (Avikal et al. (2021)). The evaluation is carried out according to different criteria, which are the aspects recognised to be as the most important by selected stakeholders, experts in the field. The technique is based on the concept of distance between each alternative and two ideal solutions, which are a positive ideal solution and a negative ideal solution (Chodha et al. (2021)). Those alternatives closer to the positive ideal solution will occupy the first positions in the final ranking. Similarly, those alternatives closer to the negative ideal solution will occupy the last positions of the ranking. As already mentioned, the TOPSIS method offers a flexible decision-making tool for varied application areas. This technique has been proposed within the context of water quality evaluation (Li et al. (2018)) also in integration with other MCDM techniques (Xu et al. (2016); Zyoud et al. (2016); Fu et al. (2013)). Regarding the set of input data to be collected to lead the application, it is necessary to establish the vector of criteria weights, reflecting the mutual importance of the considered aspects according to opinions provided by the involved team of decision makers. It has to be specified if criteria need to be maximized or minimized. Once weighted criteria and specified their preference directions, alternatives will be evaluated and ranked by means of the following steps.

- Building the input decision matrix by providing assessments g_{ij} of each alternatives i under each considered evaluation criterion j.
- Computing the weighted and normalised decision matrix, being the generic element u_{ij} determined as:

$$u_{ij} = w_j \times z_{ij}, \forall i, \forall j; \quad (4)$$

  w_j being the weight of criterion j, and z_{ij} the score of the generic solution i under criterion j, normalised as follows:

$$z_{ij} = \frac{g_{ij}}{\sqrt{\sum_{i=1}^{n} g_{ij}^2}}. \quad (5)$$

- Identifying two ideal solutions, namely the positive ideal solution A^* and the negative ideal solution A^-, through the following equations:

$$A^* = (u_1^*, \ldots, u_k^*) = \left\{(\max_i u_{ij} | j \in I'), (\min_i u_{ij} | j \in I'')\right\}; \quad (6)$$

$$A^- = (u_1^-, \ldots, u_k^-) = \left\{(\min_i u_{ij} | j \in I'), (\max_i u_{ij} | j \in I'')\right\}; \quad (7)$$

  I' and I'' being the sets of criteria to be, respectively, maximised and minimised.
- Computing the distance S^* from each alternative i to the positive ideal solution A^* and the distance S^- from each alternative i to the negative ideal solution A^- by the equations:

$$S^* = \sqrt{\sum_{j=1}^{k} (u_{ij} - u_{ij}^*)}, i = 1, \ldots, n; \quad (8)$$

$$S^- = \sqrt{\sum_{j=1}^{k} (u_{ij} - u_{ij}^-)}, i = 1, \ldots, n. \quad (9)$$

  Distances S^* and S^- are computed by considering evaluations of alternatives under each criterion taken into account.
- Calculating the closeness coefficient C_i^* for each solution i, representing how alternative i performs with respect to the ideal solutions:

$$C_i^* = \frac{S^-}{S^- + S^*}, 0 < C_i^* < 1, \forall i. \quad (10)$$

- Ranking alternatives by ordering the calculated closeness coefficients in a decreasing way. In other terms, referring to two generic alternatives i and z, if $C_i^* \geq C_z^*$ then solution i must be preferred to solution z.

4. REAL-WORLD CASE STUDY

The methodology proposed in this work is applied to the water network called C-TOWN. This network has an average consumption around 270 l/s, 388 nodes, 1 reservoir, 7 tanks, 11 pumps and 4 valves. The network is fully segregated into 5 DMAs (Figure 1).

For each node indicated in Figure 1, a set of expansions is simulated. Each expansion, from the hydraulic point of view, is simulated as an increase in the base demand of the node. This base demand increase is a percentage of the total base demand of the water network: 0.5%, 1.0%, 2.0%, 5.0% and 10.0% of the total base demand are simulated. For each scenario at each node, the criteria, in the sequel called C_1 economic interest, C_2 pressure uniformity, C_3 water age and C_4 resilience are evaluated. Based on the set of criteria evaluated for the maximal expansion (10.0%) of the base demand, the TOPSIS technique is

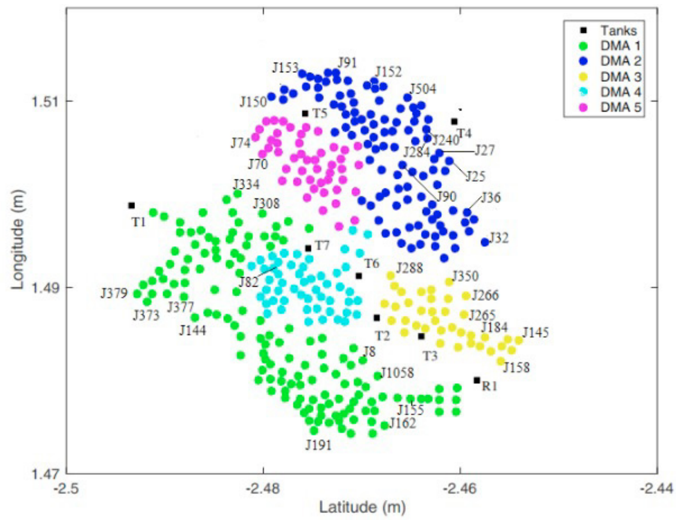

Fig. 1. Water network C-Town with DMAs and expansion nodes indication

applied to rank the nodes. We specify that an increasing preference direction has been considered for criteria C_1 and C_4, whereas a decreasing preference direction has been assumed for criteria C_2 and C_3.

The methodology described in 3.2 has been applied and the obtained results are now described.

Table 1 shows the input decision matrix whose cells represent the values simulated for the chosen indicators, along with results obtained by means of the multi-criteria approach. The expansion nodes in Table 1 follow the order of implementation and simulation of the demand increase scenarios.

The output has been obtained by attributing first the same weights to the considered criteria, namely [25%, 25%, 25%, 25%]. This situation represents the baseline scenario (BS), from which a sensitivity analysis has been led on criteria weights. The following values have been considered: I scenario (IS), [40%, 20%, 20%, 20%]; II scenario (IIS), [20%, 40%, 20%, 20%]; III scenario (IIIS), [20%, 20%, 40%, 20%]; and IV scenario (IVS), [20%, 20%, 20%, 40%]. Table 2 shows how the final ranking varies by varying criteria weights, confirming the robustness of the evaluations.

Observing the results and considering all the weighing scenarios assigned to the results, it is noted that nodes J74 and J70 are the best nodes to expand the network capacity. This is because the nodes have maximum economical interest and, following demand increases at this nodes, the network still has high hydraulic resilience, i.e. high potential on recovering or reestablishing itself after some failures in the system. In addition, nodes J74 and J70 show low weighed average water age, which determines a shorter time interval to supply the demand nodes and, consequently, to improve the quality of the supply water. The third best solution varies between node J82 and J145. J82 belongs to DMA 4, the second highest for economical interest, but with higher pressure uniformity, a parameter that should be minimized. In contrast, J145 belongs to DMA 3 with lower economical interest; but this solution has better pressure uniformity and higher resilience, when compared to node J82. It is also worth noticing that the worst expansion nodes are nodes J379 and J1058. This can be observed by the high values of pressure uniformity and weighted average age of water in the network. High values for pressure uniformity and water age harm the operational state of the supply system due to the stress conditions caused by high pressures and the longer time of water transport to supply demand nodes.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper proposes a structured approach to deal with decision-making problems involving complex systems and related complex operations of management and control. Specifically, we focus on the topic of implementing expansion projects for water networks serving growing cities. In such a context, relying on experts' judgments is definitely strategic for making effective decisions. However, managing stakeholders' evaluations is necessary because of the potential presence of intransitive relations when simultaneously assessing many and diverse elements. If, on the one hand, meeting mathematical modelling requirements is desirable, on the other hand, adhering to the practical - and often inconsistent - human judgment is fundamental for the analysed field of research. Our approach suggests that expert stakeholders should be involved for determining quantitative indicators of interest instead of comparing all the nodes composing networks. The selected indicators have been simulated by means of the EPAnet 2.0 software, and the obtained numerical values have been treated by means of the TOPSIS, highlighting those physical nodes

Table 1. Input decision matrix and results (BS)

Node	C_1	C_2	C_3	C_4	S^*	S^-	C_i^*
J8	1	49.845	0.485	0.323	0.076	0.023	0.236
J1058	1	49.998	0.485	0.282	0.077	0.020	0.208
J162	1	50.310	0.473	0.405	0.074	0.031	0.297
J191	1	50.309	0.463	0.422	0.074	0.034	0.312
J144	1	50.258	0.456	0.351	0.075	0.028	0.269
J379	1	50.197	0.663	0.300	0.081	0.014	0.144
J377	1	50.260	0.662	0.387	0.080	0.024	0.230
J373	1	50.254	0.663	0.381	0.080	0.023	0.225
J334	1	50.342	0.442	0.305	0.076	0.025	0.249
J308	1	50.284	0.473	0.395	0.075	0.031	0.291
J70	5	50.294	0.505	0.373	0.019	0.078	0.801
J74	5	50.329	0.505	0.391	0.018	0.078	0.809
J150	2	50.285	0.443	0.344	0.057	0.033	0.368
J153	2	50.647	0.443	0.210	0.062	0.028	0.307
J155	1	50.434	0.452	0.414	0.074	0.033	0.311
J91	2	50.270	0.443	0.373	0.057	0.035	0.385
J152	2	51.054	0.443	0.185	0.064	0.027	0.302
J504	2	51.987	0.434	0.203	0.063	0.028	0.310
J240	2	51.704	0.430	0.389	0.056	0.037	0.399
J284	2	51.625	0.437	0.313	0.058	0.032	0.354
J90	2	50.543	0.461	0.385	0.057	0.035	0.384
J27	2	50.487	0.461	0.382	0.057	0.035	0.382
J25	2	50.487	0.461	0.374	0.057	0.034	0.377
J36	2	50.487	0.461	0.352	0.057	0.033	0.364
J32	2	50.482	0.461	0.354	0.057	0.033	0.366
J82	4	51.021	0.484	0.374	0.025	0.061	0.708
J288	3	50.257	0.484	0.406	0.040	0.048	0.546
J350	3	49.977	0.356	0.442	0.037	0.055	0.602
J266	3	49.969	0.357	0.439	0.037	0.055	0.601
J265	3	49.949	0.357	0.431	0.037	0.055	0.599
J184	3	49.914	0.333	0.388	0.037	0.053	0.591
J145	3	49.944	0.318	0.427	0.037	0.056	0.607
J158	3	49.946	0.323	0.439	0.036	0.057	0.610

Table 2. Sensitivity analysis on criteria weights

Ranking Position	BS	IS	IIS	IIIS	IVS
1^{st}	J74	J74	J74	J74	J74
2^{nd}	J70	J70	J70	J70	J70
3^{rd}	J82	J82	J82	J145	J82
4^{th}	J158	J158	J158	J158	J158
5^{th}	J145	J145	J145	J184	J350
6^{th}	J350	J350	J350	J350	J266
7^{th}	J266	J266	J266	J266	J145
8^{th}	J265	J265	J265	J265	J265
9^{th}	J184	J184	J184	J82	J184
10^{th}	J288	J288	J288	J288	J288
11^{th}	J240	J240	J240	J240	J240
12^{th}	J91	J91	J91	J91	J90
13^{th}	J90	J90	J90	J150	J27
14^{th}	J27	J27	J27	J284	J91
15^{th}	J25	J25	J25	J90	J25
16^{th}	J150	J150	J150	J27	J32
17^{th}	J32	J32	J32	J25	J191
18^{th}	J36	J36	J36	J32	J36
19^{th}	J284	J284	J284	J36	J155
20^{th}	J191	J504	J191	J504	J150
21^{st}	J155	J153	J155	J153	J162
22^{nd}	J504	J152	J504	J152	J308
23^{rd}	J153	J191	J153	J155	J284
24^{th}	J152	J155	J152	J191	J377
25^{th}	J162	J162	J162	J162	J373
26^{th}	J308	J308	J308	J334	J144
27^{th}	J144	J144	J144	J144	J8
28^{th}	J334	J334	J334	J308	J334
29^{th}	J8	J377	J8	J8	J153
30^{th}	J377	J8	J377	J1058	J504
31^{st}	J373	J373	J373	J377	J1058
32^{nd}	J1058	J1058	J1058	J373	J152
33^{rd}	J379	J379	J379	J379	J379

from which the expansion of networks should be preferably implemented. A final sensitivity analysis on criteria weights is useful to study possible variations of results by varying the importance associated to the chosen hydraulic parameters. Future developments of this work may regard the assumption of a fuzzy-based perspective to deal with several simulation scenarios. In such a way, achieving even more precise results would be possible.

Regarding the hydraulic structure, the evaluation of expansion scenarios allows the stakeholders also to know critical regions. In this sense, not suitable nodes for expansion can become suitable if engineering interventions are performed. More than creating a restrictive map of expansion, the multi-criteria analysis, can help the water system managers to decide where to invest efforts to make the system able to manage the associated increasing demand, mainly in fast growing cities.

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