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WATER QUALITY SENSOR PLACEMENT WITH A MULTIOBJECTIVE APPROACH

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Abstract *Water quality sensors help utilities to detect contaminant intrusion and to assess quality problems in water distribution systems by continuously measuring conductivity, PH, concentration of different substances and other related parameters directly from the network. Deciding where to place sensors in the network and how many of them should be placed is a very challenging problem because of the nature of the objectives involves. This research presents a multi-objective approach for supporting those decisions. More than a crisp single solution, the idea is to find a wide spectrum of solutions representing the best trade-off among all the objectives considered in the problem. This approach is not divorced from the practical experience of engineers. The final solution will use the calculations as a base but will rely on the practical experience of engineers and the characteristic of the utilities. A use case has been included for illustrating the solution process.*

1. INTRODUCTION

The identification of potential contaminant intrusion in water networks is a crucial point to fully guarantee the water quality in distribution systems. For utilities, it is convenient to be measuring water quality parameters continuously, and therefore a set of sensors should be installed at different points of the network. Placing sensors may seem simple at the beginning, but considering sensor station costs and the extension of pipes that should be covered, it turns into a challenging problem that has been studied by several researchers [1, 2, 3]. The plurality of potential contaminants, the identification of the contaminant sources in the network and the reaction time of the utilities to deal with a contamination event are also important elements to consider. This paper will not cover all the aspects necessary to protect networks against potential contaminant intrusion. It will be rather concentrated on proposing a solution only for the sensor placement problem with a multi-objective approach.

Several goals should be taken into account when placing water quality sensors. First, it is desired to identify quality problems as soon as possible, it means, to minimize the detection time. Second, at least one sensor should always be able to identify a quality problem no matter where the source of the problem is located. It means that the coverage of protection should be maximized. Additionally, the amount of water consumed with poor or bad quality should be minimized. It means that high population density areas should get a special attention compared to those areas where a much lower consumption rate is happening. Last but not least, the cost should be kept as low as possible and it will be directly proportional to the number of sensors to be installed.

The objectives that should be reached with a sensor placement solution are not going all in the same direction. Improving one of them will probably result in a detriment of another. For example, maximizing the protection coverage in the network will require either to increase the number of sensors (the cost) or to probably accept a higher value of detection time. As a consequence, the final solution will result from a compromise rather than from a unique “best alternative”. Solving properly this kind of problem requires the use of a multi-objective approach. The idea is not to find one single optimal solution but to find the Pareto front representing the best trade-off that can be done among all objectives involved. Weighting objectives and adding them into a single expression for solving a single objective problem will probably result in finding one point of the Pareto front. It is equivalent to make a trade-off a priori without having any idea of how the solutions that will be obtained relate to the rest of potential solutions of the problem. For example, it cannot answer if it is worth to buy an additional sensor because it has no way to know how much improvement in protection coverage and detection time will bring an additional sensor. Those are the kind of questions that a multi-objective approach helps to answer. Those are the kind of questions and answers needed to find at the end a sensor placement solution representing a good trade-off among all objectives involved.

2. CONTAMINATION SCENARIOS AND OBJECTIVES' EVALUATION

Basically, the average time for detecting a contaminant in a distribution system is calculated as follows: contamination is introduced in the first node of the network, then the simulation is started and the detection time will be the time interval from the beginning of the contamination to the moment when at least one sensor is reached by the contaminant. Then a contamination is introduced in the second node of the network, the simulation is started and the detection time will be calculated with the same idea. The same process is repeated for the third, fourth and all nodes in the network and after finishing, the average of all detection times is calculated.

The problem starts for those cases when the sensor located cannot detect the contaminant, for example, when sensors are located "very upstream" and a contaminant is injected "very downstream". In these cases what should be the detection time? In [4] it is assumed in this case a detection time equal to the simulation time (the simulation time is introduced as data to define how much time the simulation should be running. The other possibility is to say in these cases that the detection time is equal to zero, which is the approach followed in this research. Assuming detection time equals to zero when there is no detection, is not a problem if the calculation is using a multi-objective approach where other objectives like the detection failure and the contaminated water consumed are also considered.

3. MULTIOBJECTIVE OPTIMIZATION USE CASE

The first step for solving a sensor placement problem is the generation of a contamination matrix. This matrix will store for every single contamination alternative how long it takes to reach each of the network nodes. Once all the contamination alternatives have been calculated, the search of Pareto dominant solution can be started.

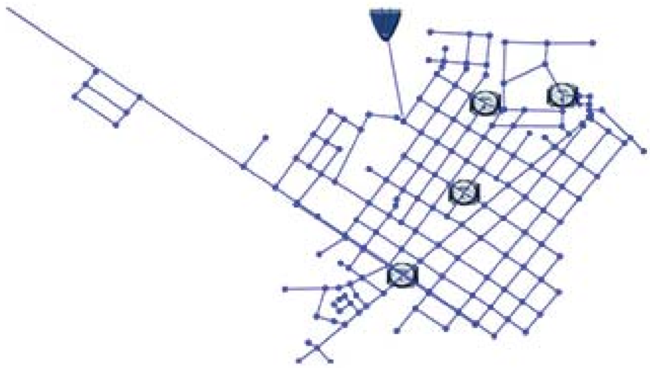

Figure 1. Network model of San José with 4 water quality sensors

In this research, for illustrating the solution process it has been used a modified version of the water network of San José de las Lajas. It is a small town in Cuba closed to Havana with more than 24 km of pipes and one single entry point, as a consequence of the modifications in the original model. Figure 1 represents the network with a solution for placing 4 water quality sensors. This solution will be specially marked in red in figures 2-4 for a better interpretation of results.

There are several approaches that can be used for finding the Pareto front in a multi-objective optimization problem [5, 6, 7]. In this research, the algorithm behind the solution search process is based in Agent Swarm Optimization [8]. It is a unique combination of multi-objective evolutionary algorithms and data analytics. It intelligently combines the hydraulic engineering knowledge with the optimization process and learns engineer's preferences in order to achieve better results. The algorithm has been integrated in Water-Ing, a software package for analysis and decision support in water distribution systems. Water-Ing connects with the EPANET toolkit in order to perform the necessary hydraulic simulations that generate the contamination matrix. Using that information, it starts analyzing different alternatives for locating sensors and selects from them those alternatives representing dominant solutions.

For the analysis of optimization solutions Water-Ing includes and advanced visualization environment. The software can be created practically as many 2D Pareto charts as desired and it can be represented in each of them different relations between costs, detection time, protection coverage and bad water quality impact. Selected solutions in one chart will be automatically selected in the rest of charts indicating how they behave with respect of all aspects involved in the problem. If more than one screen is used, any chart can be detached from the application and it can be moved to a different screen to expand the visualization capabilities.

The execution of sensor placement results in the charts represented in figures 2 to 4.

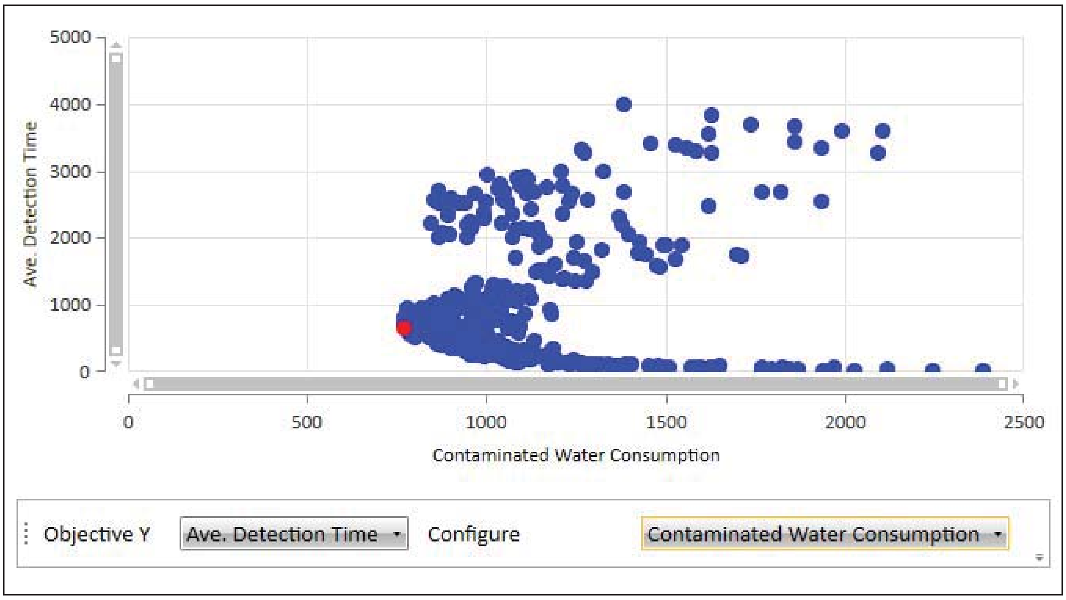

Figure 2. Average detection time vs contaminted water consumption

Figure 3 relates the amount of detection failure with the contaminant detection time. Using solutions with very high detection time means that sensors will be located at nodes very downstream in the network. In these cases, it takes a little longer to detect a contaminant (as average considering all possible contamination) but the detection failure is much lower. Again, from figure 3 it can be seen that for higher values of detection time, the detection failure is relative lower.

Figure 4, on the other hand, shows that the average volume consumed of contaminated water can be increased because of two main reasons: either we are standing at solutions with higher detection failure in average (sensors located too close to the sources that cannot detect contamination downstream) or we are standing at solutions where sensors are located at nodes in very downstream positions, which requires longer in average to receive the contamination effects. The relation between detection time and detection failure was previously mentioned and can be seen in figure 3.

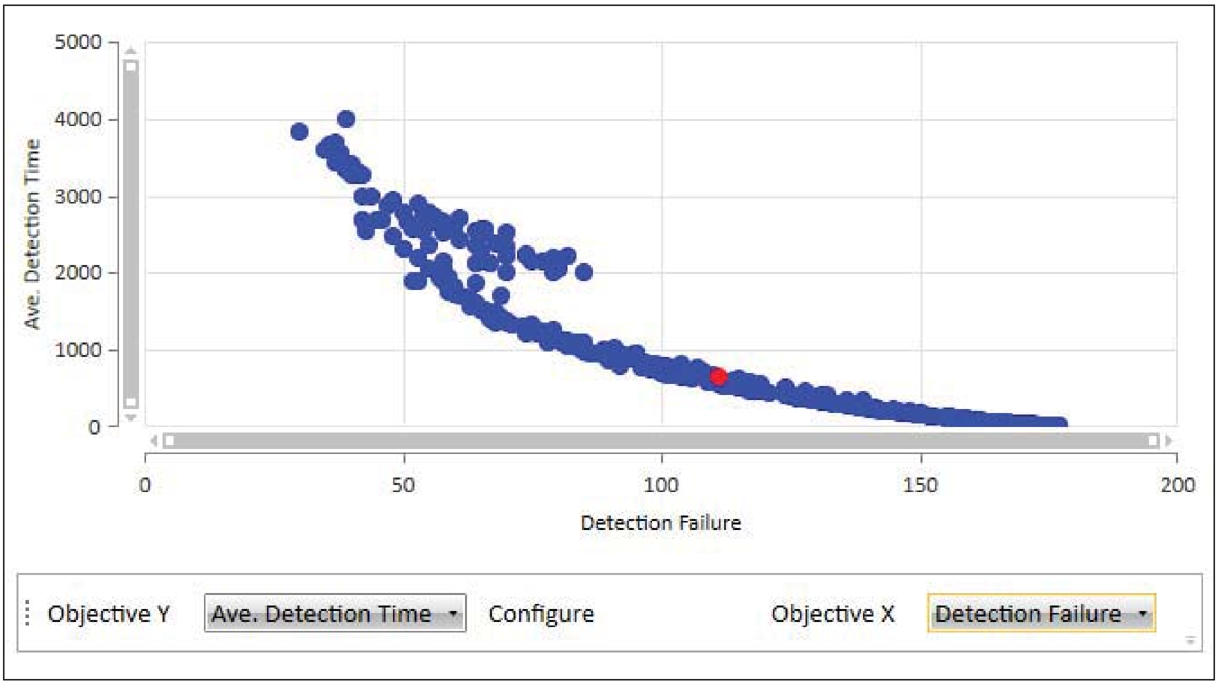

Figure 3. Average detection time vs detection failure

In figure 2 it can be seen what happens with the contaminated water that is consumed if the average detection time changes. For very low detection time we are not standing at solutions that can detect a significant number of contamination event. Note that the detection time is assumed equal to zero for those non-detected events.

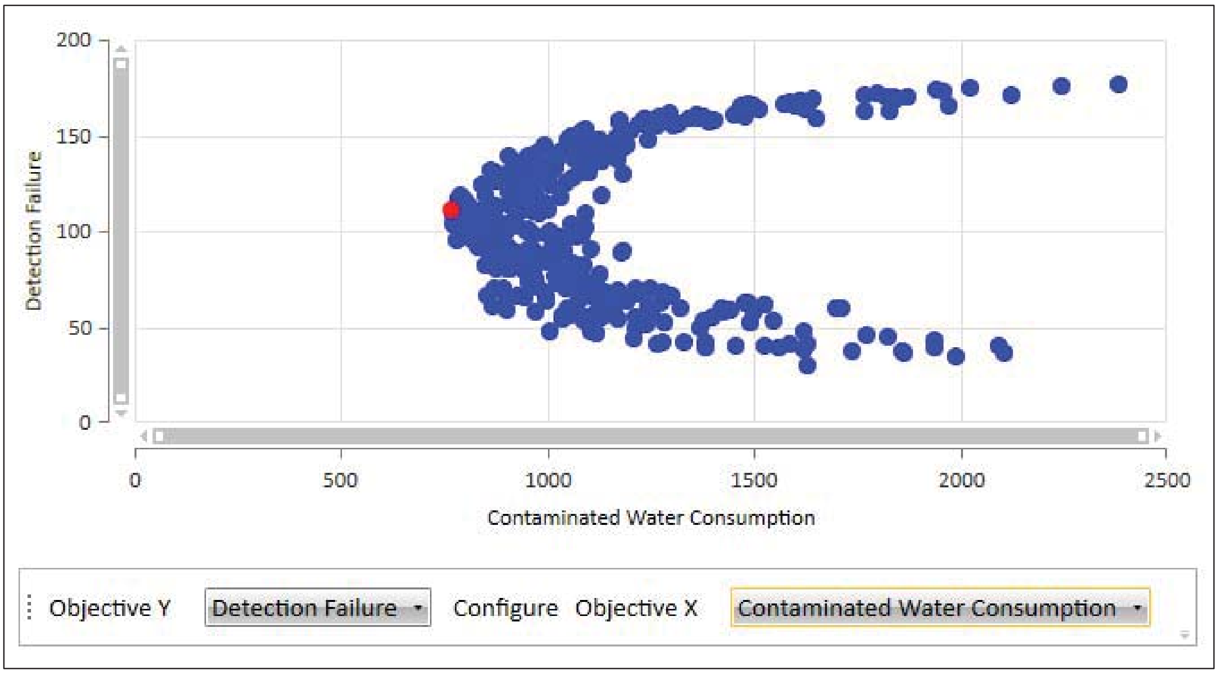

Figure 4. Average detection failure vs average contaminated water consumed

Figure 2-4 helps to locate certain number of sensors in the network, four for the case of the mentioned figures. Nevertheless, additional actions are required to assess how many sensors should be installed in a network. Adding sensor stations implies an investment that will limit how many of them can be installed. It will depend on the budget of the company and the rewards of installing them.

One approach would be to decide an objective budget and based on it, calculate the maximum number of sensors that can be installed. Despite it is a realistic approach, it is worth to ask, what about if for 10% more of the investment, the network coverage to detect contaminant intrusion is increased in 25%? Would one be adding 10% more to the budget? What about if the network coverage increased in 30% or if the detection time can be reduced in certain percentage? Following this perspective, the next question would be how much improvement/reward we would get if we complete our budget to acquire one more sensor? The same idea can bring us to the point to ask how much improvement/reward we would be losing if we get rid of one of the sensor in our budget? Answering this kind of questions requires a representation of the improvement/rewards received as a function of the number of sensors installed.

Deciding a budget a priori without considering the improvement/reward received as a function of the number of sensors installed won´t lead to a good decision. Despite an initial tentative budget can be decided, both aspects should be combined together before making a final decision. The improvements/rewards received will be expressed in terms of the objectives considered for placing sensors: reducing the detection time of contaminant intrusion or water quality problems, protecting the population from the consumption of water under minimum quality requirements and maximizing the protection coverage in the network. These three objectives have to be combined with the additional objective of maintaining the cost in the framework of a budget that can be paid by the company. For visualization purposes, it would be better to add new 2D projections of the Pareto front where solutions for different number of sensors can be compared like in figure 5.

With all the projections of the Pareto front it can be better decided not only where sensors should be located but also how many of them should be placed. In case your budget can not be extended under any circumstances, the analysis will still be valid for estimating how much you need for a realistic protection of your water network. It is true that some experience will definitively help in taking these kinds of decisions. Nevertheless, even for experienced engineers the Pareto charts shown in figures 2-5 constitute a great support for better evaluating alternatives.

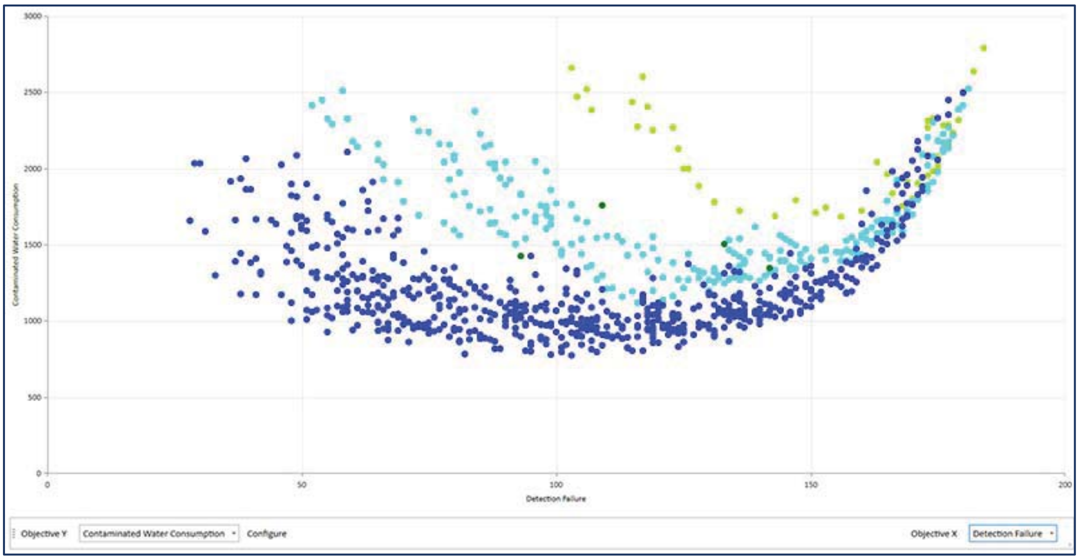

Figure 5. Contaminated water consumption (Y) vs Detection Failure (X). Solution comparisons between 3 (light green), 4 (light blue) and 5(dark blue) sensors

12. CONCLUSIONS

Two important questions have to be answered in order to properly protect a water network against accidental or provoked contamination events and water quality problems: how many sensors are needed and where to place them. Answering these questions requires a decision about the criteria and requirements to be considered for achieving a good solution combined with a multi-objective approach for solving the problem.

The final solution should be based on a trade-off among the objectives involved and the tolerance to "fail" that we could have in each of them. An improvement in all the objectives analyzed can be done by adding new sensors but this, of course, has the consequence of increasing the costs which can be a constraint for the implementation of the solution.

Additional information about the utility can also influence the final sensor locations adopted. This is the case for example of the average reaction time of the company when an event is detected. If the reaction time is relative large then it may be convenient to use solutions with the sensors located a little more upstream if it is desired to avoid at least to part of the population to receive contaminated water. Note that in this case in which there could be a higher number of detection failures too. Getting some improvement on both sides (reduced detection time and reduced detection failure) implies adding more sensors to the solution.
This paper shows a simplified overview about how to deal in practice with water quality sensor placement for protecting distribution systems. It is fully recommended not to base decisions on just practical experience but to run hydraulic model calculations. Both computer models and experience should be matched for achieving better results.

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