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# אבטחת איכות ואמינות במערכות אספקת מים

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## תקציר

אמינות של רשת אספקת מים היא מדד ליכולת שלה לספק את צריכת המים המתוכננת. ביצוע סימולציות מונטה קרלו היא אחת הדרכים לאמוד את אמינות הרשת. בסימולציות אלו, מוגרלות תקלות ברכיבי הרשת (משאבות, צינורות), ומחושבים ביצועי הרשת ה"מופחתת" (עם רכיבים בתקלה). כיוון שההסתברות לכשל של רכיבי הרשת קטנה, הכשלים של רשת אספקת המים נדירים, ונדרשות סימולציות רבות על מנת לאמוד את אמינות רשת אספקת המים בצורה טובה. על מנת להפחית את מספר הסימולציות הנדרשות, נעשה שימוש בשיטת מונטה קרלו המואצת. ההאצה מתבצעת ע"י הגדלת אי זמינות הרכיבים. לאחר ביצוע כל סימולציה, תוצאתה משוקללת בהתאם למידת ההאצה.

כאשר מתרחשת תקלה, ביצועי הרשת מחושבים ע"י סימולציה. בסימולציה מחפשים תוכנית הפעלה של המשאבות אשר שומרת את הלחץ בצמתים בתחום הנדרש. הדבר נעשה ע"י פתרון בעיית תכנות לינארי שהיא קרוב לינארי של מודל רשת אספקת המים. בעיית התכנות הלינארי נפתרת מספר פעמים (איטרציות), כשבכל איטרציה מעודכנות התנגדויות הצינורות עד שהתנהגות הרשת בנקודת הפתרון של הקרוב הלינארי שווה להתנהגות של המודל הלא לינארי של הרשת. בנקודה זו, אם קיים פתרון לבעיית התכנות הלינארי – הסימולציה נחשבת כמוצלחת, אחרת – תוצאת הסימולציה מצביעה על כשל רשת אספקת המים. בנוסף לתוצאת הסימולציה, נרשמים גם הלחצים בצמתים. מידע זה משמש לאמידת אי זמינות הרשת ואי זמינות הצמתים. בעזרת שיטה זו נותחו שתי רשתות אספקת מים מהספרות.

# QUALITY ASSURANCE AND RELIABILITY IN WATER DISTRIBUTION SYSTEMS

RESEARCH THESIS

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## Abstract

The objectives of this work are:

- To develop a quantitative estimate of the reliability of a water distribution network.
- To analyze the effect of components' unavailability on the system's unavailability.
- To provide a quantitative estimate of the reliability from the consumer's viewpoint.

Reliability of a water distribution network is defined by a performance index of the network. A specific form of the index can be the total annual volume of water supplied divided by the total volume required / promised. Another may be the number of hours per year (average, or some other measure of the random distribution over the years) during which there is no supply. And a third, the number of times water supply is interrupted during a prescribed period, for example a year. Reliability measures can also be defined on the service pressure, for example the number of hours per year that pressure is below a stipulated level.

In this work unavailability is the performance index of the water distribution network. Availability is defined as the <u>probability</u> that a <u>system</u> is operating <u>satisfactorily</u> at any point in time when operated under a set of <u>stated conditions</u>. In this work "system" is the water distribution network, "satisfactory" means that the water is supplied at the demand nodes within the allowed pressure limits and the "stated conditions" are the design conditions. Unavailability = (1-Availability) is chosen as a performance index because it is commonly used throughout the engineering world, from light bulbs to nuclear plants. Hence, the unavailability of the water distribution networks can be compared that of other services.

One way to estimate unavailability is to analyze a fault tree of the system. Unfortunately, it is not practical to model water distribution systems as fault trees, due to their complexity and flexibility in operation. The complexity is due to the large number of components. Flexibility means that when pipes or pumps fail, the water may be supplied by alternative paths and with different operating schemes of the

pumps and valves. Thus, the system is not "rigid" but rather can respond through operational decisions to the failure of certaine components.

Another way to evaluate unavailability is to conduct Monte Carlo simulations. It is chosen to estimate the unavailability because it can be seen as a weighted sum of outcomes of all possible network states. The "outcome" is defined as 0 if the network performs satisfactorily and 1 otherwise. A state of the network is defined as the vector of all pipe \ pump states (0 = available, 1 = failed). The "weight" is the probability of a network state to occur. In the Monte Carlo simulations, random component failures are imposed and the performance of the remaining system is evaluated.

Since failure probabilities of components are small, and system failures are therefore rare, it takes a large number of simulations to obtain a sufficiently large sample of system failures that provides a reliable estimation of system reliability. We use the accelerated Monte Carlo method to reduce substantially the number of simulation: the failure probability of the components is increaded artificially, thereby inclreasing the number of failures in a set of simulation runs. After the simulation is performed with the accelerated values, the simulation result is scaled back by the accelaration factor used in the accelaeration.

When a failure occurs, the performance of the system is evaluated by hydraulic simulation. A regular network solver is not sufficient to perform this simulation if the network contains pumps, since they can be operated in a variety of ways. Therefore, in each simulation, an operating scheme of the pumps is sought in order to maintain adequate pressure at the nodes. This is done by setting up and solving a Linear Program that describes the behavior of the system - approximately. The linear approximation of the network is an extension of the "Linear Theory" algorithm: the headloss curves of the pipes are linearized and a source-sink pair substitutes each pumps. The linearized network is modeled by a Linear Program that finds the flows through the pumps (sources and sinks) that maintain the pressure at the nodes within the required limits. The flow through the pumps, along with the head differences across the pumps, define the working points of that pumps which are interpreted as pump speed (in this work every pump is assumed to be have an adjustable speed). The Linear Program consists of the following constraints and objective:

- Kirchofs' law I: Continuity constraints at nodes.
- Energy constraints for pipes – the Hazen-Williams formula, linearized.
- Allowable pressure limits. These constraints contain artificial variables that enable the iterations to proceed despite violation of the pressure limits.
- Maximal pump curves (approximated by straight lines). These constraints ensure that the working point of the pump is below the pump curve at its maximum speed.
- The objective function is the sum of pump flow costs and a penalty for violating the pressure constraints.

The Linear Program is solved iteratively, the pipe resistance being adjusted between iterations until it corresponds to the true behavior of the system. At this point, a solution with a non-zero penalty on pressure limits violation means the system has failed, and is recorded. Additionally, the pressure at all nodes is recorded. The recorded data is used to evaluate the unavailability of the network and the unavailability of the nodes.

This work presents the basic building blocks that can be used for computing the unavailability of water distribution networks: A new type of a network solver in conjunction with a generic accelerated Monte Carlo procedure are introduced. This solver finds the working point of control devices (variable speed pumps in this case) in order to maintain adequate pressures at the nodes. The proposed procedure can be a basis for future development (without change in concept) to incorporate emptying of reservoirs, multiple loading conditions, demand uncertainty, and demand decrease due to low pressure.

The method is applied to two networks taken from literature.