WATER DISTRIBUTION SYSTEM RELIABILITY UNDER PIPE FAILURE CONDITIONS: ADVANCED MULTIPLE STATES/ASPECTS ANALYSES

by

Alireza Gheisi

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The undersigned certify that they have read, and recommend to the College of Graduate Studies for acceptance, a thesis entitled:

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submitted by Alireza Gheisi in partial fulfilment of the requirements of the degree of Doctor of Philosophy.

Dr. Bahman Naser, School of Engineering

Supervisor, Professor (please print name and faculty/school above the line)

Dr. Rehan Sadiq, School of Engineering

Supervisory Committee Member, Professor (please print name and faculty/school in the line above)

Dr. Abbas S. Milani, School of Engineering

Supervisory Committee Member, Professor (please print name and faculty/school in the line above)

Dr. Xiaohua (Adam) Wei, Irving K. Barber School of Arts and Sciences

University Examiner, Professor (please print name and faculty/school in the line above)

Dr. Yves Filion, Faculty of Engineering and Applied Science

External Examiner, Professor (please print name and university in the line above)

March 8, 2016

(Date Submitted to Grad Studies)

Abstract

Every water distribution system (WDS) fails (partially or completely) at some point(s) during its lifetime. Measuring the reliability of a system under various failure conditions has been recognized as a highly controversial issue in the field of WDS analysis. Accordingly, numerous techniques have been developed to estimate WDS reliability. This research provided an in-depth review of the relevant literature and developed advanced techniques for reliability analysis. The research organized and classified the available techniques into three major categories and discussed which technique should be used depending upon the type of a failure (mechanical failure, hydraulic failure, and water quality failure).

Previous studies have focused on WDS reliability when pipes fail individually. The current research developed an advanced technique to determine the reliability of a WDS experiencing different degrees of simultaneous pipe failure (i.e., higher-states reliability analysis). The technique was applied to two case studies including a hypothetical as well as an in-practice WDSs. Results demonstrated that a system might be able to achieve a higher level of reliability if more realistic expectations of simultaneous failure were assumed.

Studying various reliability measures, this dissertation revealed statistical flow entropy had stronger correlation with higher states of reliability and was a better surrogate measure. Using multiple criteria decision analysis (MCDA), an advanced technique of multiple states reliability analysis was developed and applied to rank a set of WDS layouts (alternatives) using various states of reliabilities (criteria). The analysis revealed that the higher-states reliabilities should have more contribution in the decision-making process.

A comprehensive reliability analysis should consider the system's responses to various states of failure. This research employed the techniques of quadrant and octant analyses to study the response of a hypothetical WDS to various simultaneous failures in two or three aspects. It was found that evaluating the reliability in one aspect without incorporating other aspects would lead to misleading results. The advanced technique of multiple aspects/multiple states reliability analysis was developed using MCDA. Multiple aspects/multiple states reliability analysis was employed to rank the WDS's layouts. Results revealed that multiple aspects/multiple states reliability analyses would assure more reliable operation of a WDS.

Preface

A version of chapter two has been accepted for publication in the Journal of Water Resources Planning and Management (ASCE). Gheisi, A., and Naser, G. (2016). "Water Distribution Systems Reliability - A Review of Research Literature." *Journal of Water Resources Planning and Management,* ASCE, Manuscript No. WRENG-2361. I wrote the manuscript, which was further edited by Dr. Bahman Naser and Mr. Mark Forsyth.

A version of chapter three has been published in the journal of American Water Work Association. Gheisi, A., and Naser, G. (2014). "Water Distribution Systems Reliability under Simultaneous Multicomponent Failure Scenario." *Journal of American Water Work Association*, AWWA, 106 (7), E319-E327. I developed the technique, conducted the simulations, analyzed the data, and finally wrote the article. Dr. Bahman Naser finalized the work by his edit.

A version of chapter four has been published as a journal article and two conference proceedings. Gheisi, A., and Naser, G. (2015). "Multistate Reliability of Water-Distribution Systems: Comparison of Surrogate Measures." *Journal of Water Resources Planning and Management*, ASCE, 04015018; Gheisi, A., and Naser, G. (2014). "Simultaneous multi-pipe failure impact on reliability of water distribution systems." *Procedia Engineering*, 89, 326-332. *In Proceedings of 16th Conference on Water Distribution System Analysis,* WDSA, Bari, Italy. 14 – 17 July, 2014; Gheisi, A., and Naser, G. (2014). "A surrogate measure for multi-component failure based reliability analysis of water distribution systems." *Procedia Engineering*, 89, 333-338. *In Proceedings of 16th Conference on Water Distribution System Analysis,* WDSA, Bari, Italy. 14 – 17 July, 2014. I developed the technique, conducted the simulations, analyzed the data, and finally wrote the article. Dr. Bahman Naser finalized the work by his comments/edit.

A small version of chapter five has been published in a conference proceeding. A more thorough version submitted for publication in the journal of Reliability Engineering and System Safety. It is currently under review. Gheisi, A., and Naser, G. (2015). "Multi-aspect Performance Analysis of Water Distribution Systems under Pipe Failure." *Procedia Engineering*, 119, 158-167. *In Proceedings of 13th Computer Control for Water Industry Conference*, CCWI 2015, Leicester, UK. 2 – 4 September, 2015; Gheisi, A., Lê, C., and

Naser, G. (2015). “Water Distribution System Reliability – Multiaspect/Multistate Analyses.” *Reliability Engineering & System Safety*, Manuscript No. RESS-D-15-00791. I developed the technique, conducted the simulations, analyzed the data, and finally wrote the article. Ms. Camille Lê conducted a part of simulations and analyzed the data based on the technique I developed. Dr. Bahman Naser finalized the work by his edit.

A version of chapter six has been published in a conference proceeding. Gheisi, A., Shabani, S., and Naser, G. (2015). “Flexibility Ranking of Water Distribution System Designs under Future Mechanical and Hydraulic Uncertainty.” *Procedia Engineering*, 119, 1202-1211. *In Proceedings of 13^th^ Computer Control for Water Industry Conference*, CCWI 2015, Leicester, UK. 2 – 4 September, 2015. I developed the technique, conducted the simulations, analyzed the data, and finally wrote the article. Mr. Sina Shabani provided some helpful comments and Dr. Bahman Naser finalized the work.

Publications from the study presented in this dissertation are listed as follows:

1. Gheisi, A., and Naser, Gh. (2015). “Water Distribution Systems Reliability - A Review of Research Literature.” Accepted for publication, *Journal of Water Resources Planning and Management*, ASCE, Manuscript No. WRENG-2361.
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3. Gheisi, A., and Naser, Gh. (2015). “Multistate Reliability of Water-Distribution Systems: Comparison of Surrogate Measures.” *Journal of Water Resources Planning and Management*, ASCE, 04015018.
4. Gheisi, A., and Naser, Gh. (2015). “Multi-aspect Performance Analysis of Water Distribution Systems under Pipe Failure.” *Procedia Engineering*, 119, 158-167.
5. Gheisi, A., Shabani, S., and Naser, Gh. (2015). “Flexibility Ranking of Water Distribution System Designs under Future Mechanical and Hydraulic Uncertainty.” *Procedia Engineering*, 119, 1202-1211.
6. Gheisi, A., and Naser, Gh. (2014). “Water Distribution Systems Reliability under Simultaneous Multicomponent Failure Scenario.” *Journal of American Water Work Association*, AWWA, 106 (7), E319-E327.

7. Gheisi, A., and Naser, Gh. (2014). "Simultaneous multi-pipe failure impact on reliability of water distribution systems." *Procedia Engineering*, 89, 326-332.
8. Gheisi, A., and Naser, Gh. (2014). "A surrogate measure for multi-component failure based reliability analysis of water distribution systems." *Procedia Engineering*, 89, 333-338.

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List of Symbols, Abbreviations and Mathematical Notations

A_{a1}	Availability of pipe a_1
AD	Anderson-Darling value
D_i	Diameter of a pipe i
F	Number of pipe failure combinations
f	Number of pipe-failure subsets
H_i	Pressure head at node i
H_i^{req}	Minimum pressure head required at node i
H_k	Head at reservoir k
I	Set of source nodes
L_i	Length of pipe i
$MCDA$	Multiple criteria decision analysis
N	Number of pipes
N_j	Upstream nodes directly connected to Node j
n_n	Number of demand nodes
n_p	Number of pumps
NR	Network resilience
n_r	Number of reservoirs
$P(a_1,a_2)$	Probability of simultaneous failures for pipes a_1 and a_2
$PI(a_1,a_2)$	Water distribution system performance index when pipes a_1 and a_2 are unavailable
PI^{ad}	Performance index for the adequacy of water delivery
P_i^{ave}	Average residual pressure in pipe i
PI^{ef}	Performance index of efficiency
PI^{eq}	Equity performance index
PI_x	Performance of the system in x direction
PI_y	Performance of the system in y direction
PI_z	Performance of the system in z direction
P_j	Power of the pump j
Q_i^{leak}	leak from pipe i

Q_i^{req}	Water demand required at node *i*
Q_j	Demand or supply at Node *j*
Q_k	Flow provided by reservoir *k*
Q^{re}	The demanded or required water
Q^{su}	Supplied water
R^k	k^{th} state of reliability
RI	Resilience index
S	Entropy
T	Amount of water supplied by reservoir
TF	Tolerance to failure
T_j	Total incoming discharge to Node *j*
TOPSIS	Technique for order of preference by similarity to ideal solution
U_{a1}	Unavailability of pipe a_1
UN_i	Uniformity index with respect to Node *i*
WDS	Water distribution system
WPM	Weighted product model
WSM	Weighted sum model
γ	Specific weight of water

Glossary of Key Terms

Adequacy: The term “adequacy” in a WDS has been used to measure the ratio of supplied water to the demanded water.

Aspect: The term “aspect” has been used to refer to a particular way in which a WDS respond to pipe failure.

Availability: The term “availability” is defined as the fraction of a pipe lifetime that the pipe is in the state of being available and ready to use.

Connectivity: The term "Connectivity" for a WDS is defined as the situation in which every nodal demand in the system is linked to at least one source of water.

Efficiency: The term “efficiency” in a WDS has been used to measure the ratio of water supplied to the summation of water supplied and leaked in the system.

Equity: The term “equity” denotes how uniformly and equally the water shortage is shared among consumers in a WDS at a pressure deficient condition.

Flow entropy: The term “flow entropy” has been used to measure the amount of information contained in the volume rate of flow distributed in a WDS.

Pipe failure: The term “pipe failure” is defined when a pipe can no longer accomplish its mission and need to be isolated, replaced, or repaired.

Reachability: The term “reachability” for a nodal demand is defined as the condition where the node is linked to at least one source of water.

Redundancy: The term “redundancy” demonstrates the existence of numerous flow paths in a WDS by the inclusion of extra pipes, which are not strictly needed.

Reliability: The term “reliability” is defined as the ability of a WDS to perform its task during a period of time under operating and failure conditions.

Resilience: The term “resilience” is defined as the ability of a WDS to recover readily from pipe failure and bounce back to a satisfactory condition.

State: The term “state” has been used to refer to particular condition that a number of pipes fail at the same time.

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I would like to dedicate this doctoral dissertation to my fiancée, parents, brother and sisters for their love, encouragement and support.

Chapter 1: Introduction

> "*With the coming of computerized hydraulic analysis, it became easier to "fail" a pipe in a distribution system to assess its impact on service. However, when a failure occurs in a real system, it does not remove a single pipe from a distribution system but rather a "segment" which can be isolated using valving. A segment will often include several nodes, portions of pipes, and other elements.*" (Walski et al., 2006)

The above quotation indicates failure of a single pipe in a water distribution system (WDS) result in a simultaneous outage of several pipes or other elements due to the closure of neighboring isolation valves. In this dissertation, the inclusion of this simple but often ignored fact resulted in four novel and advanced techniques in the area of WDS reliability analysis. The concepts of reliability engineering and pipe failure analysis have recently received increasing attention from water supply authorities. While the total cost of a WDS is always a key concern for authorities, a cost-optimized WDS may operate unsatisfying in the event of pipe failure. In addition to the cost, reliability as a measure of system performance play a crucial role in all decisions for a WDS at different phases of planning, design, operation and maintenance (Su et al., 1987).

Over the years researchers have proposed numerous WDS reliability techniques. Existence of numerous techniques and lack of a universally accepted definition and approach in the context of WDS reliability analysis has made it a nebulous and an unclear concept (Goulter et al., 2000; Ostfeld, 2004; Raad et al., 2010). An attempt was made in this dissertation to organize and classify the proposed WDS reliability-analysis techniques and introduce the advanced techniques of multiple states and aspects analyses. Application of such advanced approaches in the context of WDS reliability analysis can highly secure continuous delivery of demanded water with acceptable pressure to the consumers throughout the lifetime of a WDS.

1.1 Research Significance

A WDS is a network of various interconnected elements such as tanks, pipes, pumps, joints, valves, and etc. comprising vast variety of mechanical, hydraulic and electromechanical components. While a WDS is often designed to continuously deliver a demanded amount of water with acceptable quality and adequate pressure to various consumers, it may have subsidiary intents such as firefighting (Ang and Jowitt, 2003). The continuous delivery of water to consumers may be interrupted in some circumstances (i.e. harsh climatic conditions, natural disasters, corrosion, and hydraulic pressures) due to occurrence of a component failure. Interruption for repair is more prevalent in a WDS at advanced state of corrosion, and larger systems with more components are more prone to simultaneous failure of several pipes (Gargano and Pianese, 2000; Jacobs and Goulter, 1991). Failure may undermine the hydraulic integrity of a WDS and drop the pressure at demand nodes. Consequently, consumers may be supplied partially (or not at all). Thus, it is essential to evaluate the performance of the system for various failure situations.

Infrastructures for collection, treatment, transmission, storage, and distribution of water are the key elements of every municipal water supply systems. As the last infrastructure for safe delivery of drinking water to customers, a WDS is highly vulnerable with various components which are spatially scattered in wide area. Failure in the exposed components can undermine the integrity of the entire system. Treatment plants, transmission mains and storage tanks have regular monitoring which makes them safer and more secure than WDS (Fragiadakis et al., 2013; Perelman and Amin, 2014).

An urban WDS has several elements to distribute the treated water in a fairly manner among customers to fully satisfy consumers' demand. Elements such as pipes to distribute the water, pumping stations to maintain the pressure, and tanks to store the water are the key components in a WDS (Cullinane et al. 1992). Among the aforementioned key elements, pipes commonly constitute a vast portion of a WDS and major cost of an urban WDS is generally attributed to pipes installation. Distribution pipes are mostly installed over a vast area without any regular monitoring, but pump stations and storage tanks are commonly integrated in small areas with regular monitoring (Watson et al., 2001; Perelman and Amin, 2014). Pumping stations often have back-up pumps to provide more security in emergency conditions when the regular pump(s) is (are) broken. Due to high degree of vulnerability for pipes, researchers have traditionally focused on pipe break despite the fact that every component (pipe, pump, valve, tank, etc.) of a WDS may mechanically fail.

Every WDS fails (partially or completely) at some point(s) during its lifetime. Undesirable events such as unplanned failures can always interrupt (and sometimes stop) the continuous operation of a WDS. Hence, it is crucial to measure the reliability of a WDS defined as the ability of the system to accomplish its mission during a specific time interval at various situations. It is imperative and very informative to check the worst failure scenarios. While such scenarios may not happen very frequently, they can have catastrophic aftermaths.

1.2 Research Objectives and Goals

The overall objective of this dissertation is to highly secure the continuous delivery of demanded water with acceptable pressure to the water consumers of a WDS. Results of this study provide researchers and/or designers with a deep understanding about the reliability of their WDSs. Furthermore, this dissertation provides water authorities with advanced methodologies to realistically measure future performance of WDSs at planning-, design-, operation- and maintenance-level. The overall objective will be achieved through a set of short-term goals as indicated on Figure 1.1 and discussed below. On the figure, the colored boxes demonstrate the original contributions of this research to the field of WDS reliability analysis. However, the uncolored boxes in the Figure 1.1 represents the studies, which were previously conducted in the area of WDS reliability analysis.

1. Higher-State WDS Reliability Analysis: The goal here is to develop an advanced reliability model to test WDS functionality under simultaneous multiple pipes failure scenario.
2. Surrogate Measure for Higher-State Reliability: This is to propose a proper surrogate reliability measure for studying higher states of reliability to increase the computational efficiency.
3. Multiple states WDS Reliability Analysis: This is to create a ranking tool to classify a set of WDS layouts considering various states of reliability.

4. Multiple aspects WDS Performance Analysis: The goal here is to study the operational performance or the response of a WDS to pipe(s) failure from different aspects (e.g. quantity/quality of delivered water, and water leakage).
5. Wide-Range Reliable WDS: Given the future uncertainties, the goal is to introduce a technique to find the most reliable layout for a WDS among a set of design layouts. A wide-range reliable WDS design is a long-lasting layout, which can operate under wide range of future uncertainties.

1.3 Structure of Thesis

This dissertation is structured based on a number of published/submitted journal and conference papers. This dissertation includes seven chapters as follows:

- **Chapter 1 – Introduction:** This chapter introduces the significance, objectives and structure of this research.

- **Chapter 2 – Literature Review:** Conducting a comprehensive review of the relevant literature, this chapter aims to organize and also classify the available literature on WDS reliability analysis. Moreover, this chapter demonstrates the contribution of this dissertation and also the need for simultaneous multiple aspects/states performance response analysis of a WDS.

- **Chapter 3 – Higher-State Water Distribution System Reliability Analysis:** Literature has mainly focused on WDS reliability when a single pipe fails at a time. This study developed a technique to determine the reliability of a WDS under simultaneous multiple pipes failure scenario.

- **Chapter 4 – Multiple States Water Distribution System Reliability Analysis:** This chapter introduces a proper surrogate measure for higher states of WDS reliability analysis to lessen the associated computational work load. Applying the multiple criteria decision analysis (MCDA), this chapter also introduces a multiple states WDS reliability analysis technique to rank a set of WDS layouts using various states of reliability.

- **Chapter 5 – Multiple Aspects Water Distribution System Reliability Analysis:** Techniques, which evaluate the performance of a WDS in two aspects separately, cannot truly demonstrate the interaction that may exist between these aspects. This chapter applies the novel technique of quadrant/octant analysis to study the performance response of a WDS in two/three aspects simultaneously at different states of failure. The two/three-aspect study can be conducted for each state of reliability analysis.

- **Chapter 6 – Reliability under a Wide Range of Future Uncertainties:** Water authorities spends annually a large amount of money to adapt and update WDSs to the latest client's needs and variations known as adaptation cost. To prevent or lessen WDSs' adaptation cost it is essential to insert a wide range of reliability or flexibility into WDS layouts from the very beginning in planning or designing stages. This chapter provides water authorities with a useful tool to rank a set of WDS layouts based on their level of reliability under wide range of future mechanical and hydraulic uncertainties.

- **Chapter 7 – Conclusion, Contributions, Limitations, and Recommendations for Future Research:** This chapter presents the key findings and the contributions of this dissertation along with some recommendations for future study.

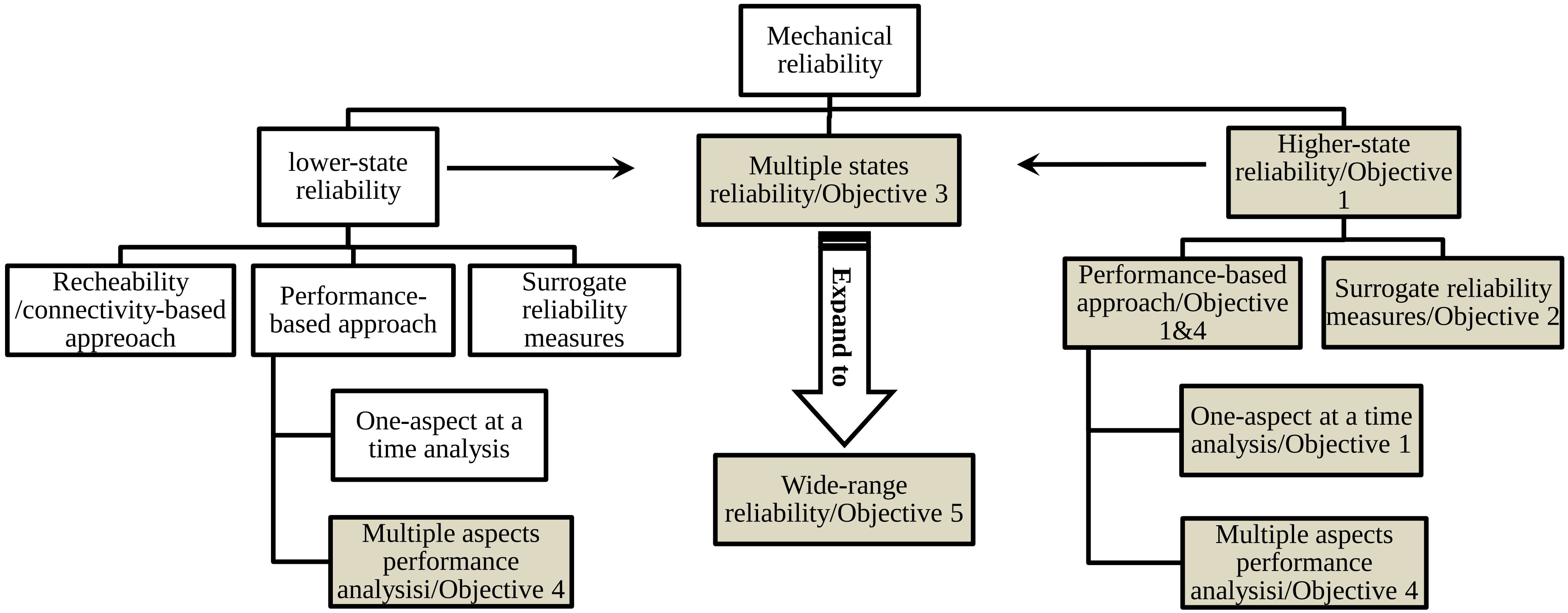

Figure 1.1 Short-term objectives of this thesis (colored boxes illustrate the contributions of this Ph.D. dissertation to knowledge)

Chapter 2:Literature Review[1]

Every water distribution system (WDS) fails (partially or completely) at some point(s) during its lifetime. It is necessary to measure WDS reliability under various failure conditions. For this, numerous techniques have been developed to estimate WDS reliability. This chapter provides an in-depth review of the relevant literature in the context of WDS reliability. This chapter organized and classified the available techniques into three major categories and discussed which technique should be used depending upon the type of a failure. A particular state of failure could have several simultaneous unfavorable impacts on a WDS operation. Deep insight into the relevant literature revealed that simultaneous multiple aspects/states analysis has received relatively no attention. The chapter also demonstrated the need for simultaneous multiple aspects/states performance analysis of a WDS.

2.1 Need for an In-depth Review of Literature on WDS Reliability Analysis

Infrastructures for collection, treatment, transmission, storage, and distribution of water are the key components of every municipal water supply system. As the last and vulnerable infrastructure in a supply system, a water distribution system (WDS) is responsible for delivering safe drinking water to consumers. A typical urban WDS delivers treated water to customers through widely scattered mechanical, hydraulic and electromechanical components such as pipes (to distribute the water), pumps (to maintain the pressure), and tanks (to store the water) (Cullinane et al., 1992). Treatment plants, transmission mains and storage tanks have regular monitoring, which makes them safer and more secure than WDS (Fragiadakis et al., 2013; Perelman and Amin, 2014). Furthermore, pipes commonly constitute a vast portion of a WDS and major cost of an urban WDS is generally attributed to pipes installation. While pipes are mostly installed over a vast area without any regular monitoring, pumps and storage tanks are commonly integrated in small areas with regular

[1] A version of chapter two has been accepted for publication in the Journal of Water Resources Planning and Management (ASCE). Gheisi, A., and Naser, G. (2015). "Water Distribution Systems Reliability - A Review of Research Literature." *Journal of Water Resources Planning and Management*, ASCE, Manuscript No. WRENG-2361.

monitoring (Watson et al., 2001; Perelman and Amin, 2014). Pumping stations often have back-up pumps to provide more security in emergency conditions when the main pumps are not in operation. Due to their high degree of vulnerability, this research focused on pipe failure/break despite the fact that every component of a WDS may mechanically fail.

Failure (partially or completely) is inevitable during the lifetime of a WDS. Failure in each component can undermine the integrity of a WDS. Undesirable failures interrupt (and sometimes stop) the continuous operation of a WDS. Hence, it is crucial to measure the reliability of a WDS under failure conditions. Reliability is defined as the ability of the system to accomplish its mission during a specific time interval at various operating conditions. It is also imperative to check the worst failure scenarios. While such scenarios may happen less frequently, they can have catastrophic aftermaths.

WDS failure can have physical (or mechanical), hydraulic or water quality origin. Literature provides various researches on physical and statistical pipe failures (Kleiner and Rajani, 2001; Rajani and Kleiner, 2001; Nishiyama and Filion, 2013). Gheisi and Naser (2013, 2014a, b, c) discussed various combinations and states of pipe failure for a WDS. While lower states of pipe failure occur when one pipe fails at a time, higher states of failure happen when a number of pipes fail simultaneously.

Substantial attention has been paid to WDS reliability analysis over the past three decades. Various reliability measures and approaches have been proposed in the literature. A WDS is a complex and nonlinear system and still no widely accepted measure or methodology was introduced for WDS reliability analysis (Ostfeld, 2004). Lack of a universally accepted definition and existence of numerous techniques have made WDS reliability a nebulous concept (Goulter et al., 2000; Raad et al., 2010). Relevant literature is vague as types of failure and techniques of reliability analysis are mixed up inappropriately. Indeed, type of failure in a WDS can necessitate certain techniques for reliability analysis. Conducting an in-depth literature review, this chapter aimed at differentiating types of failure from the techniques of reliability analysis. The chapter classified WDS reliability techniques into three major categories and discussed which technique should be employed given the type of a failure.

2.2 Types of Failure

Reliability is a measure of performance or ability of a WDS to supply consumers' demands in quantitative and qualitative aspects at operating and failure circumstances (Gheisi and Naser, 2014a). WDS reliability has been studied repeatedly in the literature to assess the performance of the system when it is partially or completely failed due to mechanical/physical, hydraulic, and water quality failures (Quimpo and Shamsi, 1991; Ostfeld et al., 2002; Tanyimboh and Setiadi, 2008; Nazif and Karamouz, 2009; Gheisi and Naser, 2013). Figure 2.1 shows a conceptual framework describing the three types of failure and the interrelations among them.

Natural disasters, harsh climatic conditions, freezing, external or internal loadings, corrosion, aging, and permeation process may lead to mechanical/physical failure in a WDS (National Research Council, NRC, 2006; Tabesh, 1998). The rate of mechanical failure and system interruption for repair is usually higher for WDS at advanced age; accordingly there is more chance of simultaneous multiple failures (Gargano and Pianese, 2000). Mechanical-failure-based-reliability demonstrates functionality of a WDS under mechanical or physical failure. Hydraulic failure may happen in many situations when 1) demand exceeds the flow capacity of the system (e.g., fire-flow situations) and undermine the hydraulic integrity of the entire system, 2) demands grow over time due to population increase as well as urbanization and industrialization, 3) pipes roughness grow due to aging and corrosion. Tuberculation, maintenance activities and improper operational control may also affect hydraulic integrity of a WDS. A hydraulic failure undermines the hydraulic integrity of WDS when pressures at demand nodes drop. Water quality failure may occur due to biofilm growth, scale formation and dissolution, internal corrosion, contaminant intrusion (accidentally or intentionally), leaching, nitrification, chemical reactions, and many others (NRC, 2006). Water quality reliability concerns the quality of supplied water under any mechanical, hydraulic, or water quality failure over time (Li et al., 2013).

2.3 Reliability Analysis

Gheisi and Naser (2013) enumerated the key factors that can significantly affect the results of a reliability analysis for a WDS. They highlighted rate of failure in pipes, pipes failure combinations as well as reliability measures and relevant criteria as the key influential factors. Figure 2.2 summarizes the influential factors.

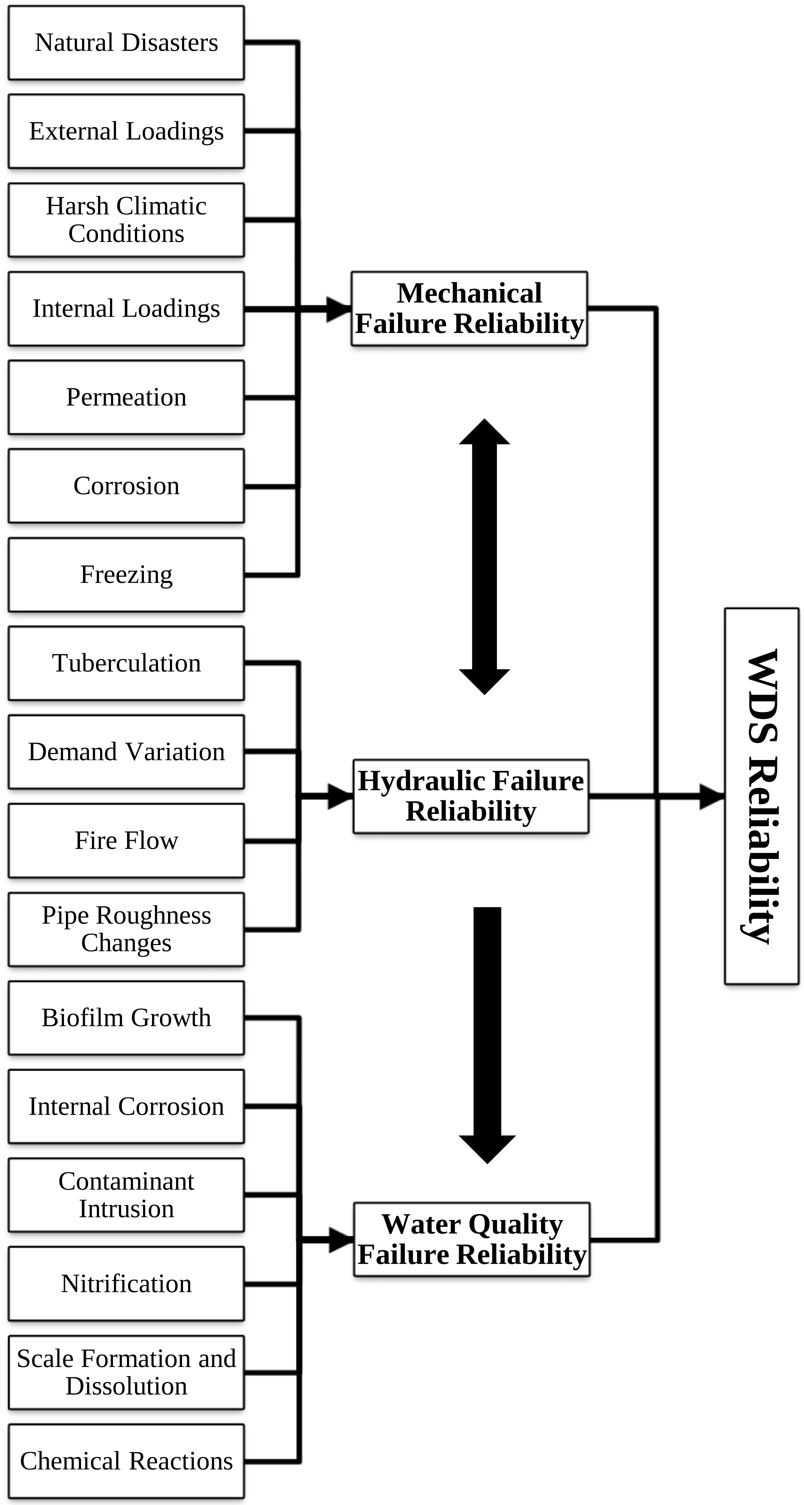

Figure 2.1 A conceptual structure for three types of failure dictating three types of WDS reliability

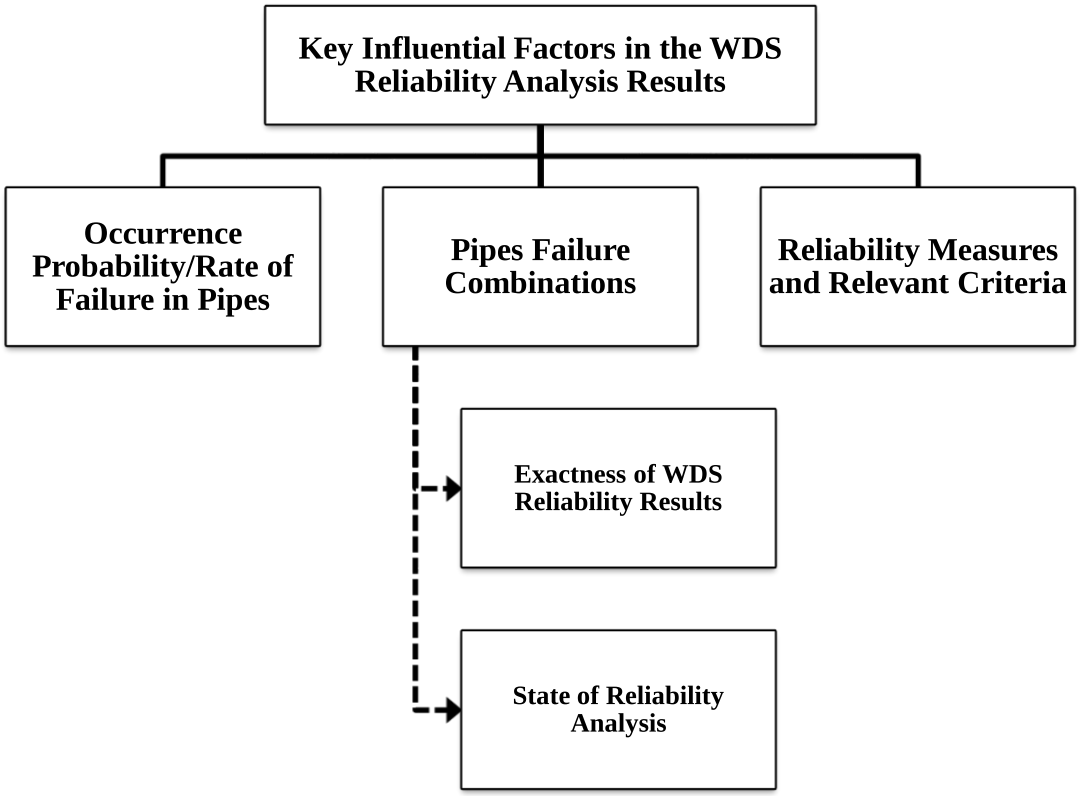

Figure 2.2 Key influential factors affecting WDS reliability results (adapted from Gheisi and Naser, 2013)

2.3.1 Rate of Failure in Pipes

Every pipe eventually fails to operate properly, but exact estimation of failure time is a very difficult task (Andrews and Moss, 2002). An estimation of failure rate or probability of failure in pipes is essential for WDS reliability analysis (Watson et al., 2001; Perelman and Amin, 2014). Figure 2.3 shows failure of a buried pipe over its lifetime follows a bathtub curve with three distinct phases (Kleiner and Rajani, 2001).

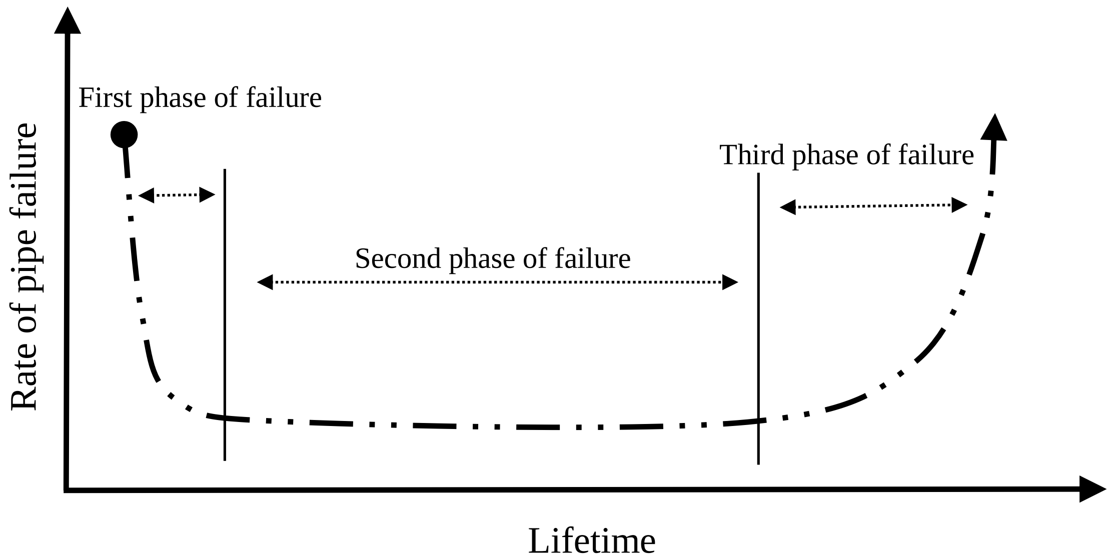

Figure 2.3 The bathtub curve and its three distinct phases of failure over the entire lifetime of a buried pipe from © Kleiner, Y., and Rajani, B. (2001). "Comprehensive review of structural deterioration of water mains: statistical models." *Urban water, 3*(3), 131-150. Page 133. Adapted with permission from publisher Elsevier Ltd.

The first phase, known as settling or childhood period, starts from very beginning of a pipe installation and is commonly accompanied with early and high frequency of failures. The rate of pipe failure is initially high in this phase due to faulty installation or pipe material imperfection but gradually decreases as the pipe settles down. The second phase or useful lifetime of a pipe starts afterwards when early failures are almost settled down. In this phase, the failure rate is relatively low and constant for long time. The only major source of failure in this phase is random or accidental events due to external interferences such as extreme loads or natural disasters. When a pipe age advances, its failure due to aging and deterioration gradually becomes dominant and the third phase of failure, known as wear-out life period, initiates. The rate of a pipe failure in this phase increases gradually. When the rate of a pipe failure exceeds a specific limit, it is economically feasible to replace it (Juran and Gryna, 1993; Goulter et al., 2000; Kleiner and Rajani, 2001; Watson et al., 2001; Singh and Adachi, 2013). Singh and Adachi (2013) studied main break data at Honolulu Board of

Water Supply. While failure rate followed the bathtub profile for cast iron, ductile iron, and asbestos pipes, the bathtub profile was not reported for the concrete pipes. A PVC pipe's probability of failure followed the bathtub profile with almost no failure at the second phase.

Relevant literature indicated several factors affecting the rate of pipe failure (Shamir and Howard, 1979; Su et al., 1987; Harada, 1988; Sacluti, 1999; Kleiner and Rajani 2001; Hu and Hubble, 2007; Tabesh et al., 2009). They are classified into quantitative and qualitative factors. The quantitative factors may include diameter/length/age of pipe, depth of pipe installation, internal pressure, and characteristics of the surrounding soil. The key qualitative factors are the condition of decay or corrosion of pipe, imperfection of the applied materials, bad installation, weather conditions, and operation, maintenance, and traffic conditions. While quantitative factors are measurable, qualitative factors are not. Trifunovic (2012) tabulated the major parameters contributing to WDS failure in three categories of physical factors (e.g. pipe material, wall thickness, age, diameter, vintage, lining and installation) environmental factors (e.g. pipe bedding, backfill materials, soil type, groundwater level, climatic conditions and seismic activities) and operational factors (e.g. internal pressure, transient pressure, leakage, water quality, flow velocity and possible backflows). Each one of these factors may have quantitative or qualitative nature. Quantitative–physical, –operational, and –environmental factors have received more attention in the literature.

Several techniques have been proposed to predict failure of water mains over the past three decades. Kleiner and Rajani (2001) made a comprehensive review about deterioration of water distribution mains and classified the pipe break prediction models into two major categories of physically– and statistically–based techniques. Replicating the physical mechanism of failure in pipes, physically–based models evaluate the capacity of pipes to resist internal loads (operational and surge pressures) or external loads (earth, frost, and traffic loads). The mechanism of pipe deterioration and failure is very complex and hard to be simulated. If the mechanism of failure is replicated in a proper way, the predicted failure time could be more accurate (Kleiner and Rajani, 2001). Physical models can be probabilistic or deterministic. Physical probabilistic pipe failure models commonly deal with uncertainties and likeliness of physical/mechanical failure of pipes, while deterministic models reveal the deterioration process in water mains to predict the exact failure time. Physically–based models are complex and require large set of input data. They are computationally demanding and costly. They are economically justifiable for analysing the major water transmission mains, which their failure can cause a substantial financial loss (Nishiyama and Filion, 2013). Statistically–based models are classified as deterministic, probabilistic or soft computing approaches (Nishiyama and Filion, 2013). Statistical deterministic models study the historical pipe failure data to recognize any patterns or trends for failure. The identified patterns are then applied to predict the failure rates (Kleiner and Rajani, 2001). In contrast, soft computing approaches (e.g. evidential reasoning, fuzzy logic, genetic algorithms, artificial neural networks) deal with the domain of uncertainty, fuzziness, and partial truth (Zadeh, 1994). To find the dominant failure pattern, the governing relationship among pipe failures and influential parameters must be identified. The key advantage of soft computing models is their ability in considering more independent influential factors that can eventually lead to more realistic predictions of failures (Tabesh et al., 2009).

2.3.2 Pipes Failure Combinations

In addition to the rate or probability of failure in pipes, the combination of pipe failure incorporated in reliability analysis is crucial (Gheisi and Naser, 2013). It controls the exactness of reliability results and determines the state/level of reliability analysis.

Exactness of Reliability Results: A pipe can be either in failed (partially or completely) or operating condition. When estimating reliability of WDS with n number of pipes, the total possible number of failure combination is 2^n. This number is extremely large even for a small-sized WDS. Thus, considering all pipe failure combinations in reliability analysis is computationally demanding and impractical. The exactness of reliability results depends on the number of pipe failure combinations incorporated into the analysis. An overlooked pipe failure subset causes truncation error in the analysis. To assure the exactness of results, Tanyimboh and Sheahan (2002) proposed using an upper limit for reliability defined as one minus the amount of unreliability of the system. They suggested adding half of the difference between reliability and its relative upper bound to the estimated reliability to reduce the truncation error and increase the exactness of the reliability. Gheisi and Naser (2013) estimated the error due to maximum number of pipe failure combinations. Introducing the concept of maximum acceptable truncation error, they developed graphical aids to exercise reasonable and computationally efficient decisions about the number of failure combinations. They found availability of pipes in large and moderately sized systems (with more than 100 pipes) and the degree of complexity in small systems had major roles. Accurate estimation of the availability of pipes in large systems is crucial in making decision on the minimum required number of pipe failure combinations (Gheisi and Naser, 2013).

State/Level of Reliability Analysis: WDS reliability can be assessed at various states. The first, second, third or higher states of reliability measure the ability of a WDS to continuously provide consumers demanded amount of water with acceptable quality when one, two, three or more pipes fail simultaneously. A system that is reliable at lower states of failure may be unreliable when higher states of failure are considered. The prevailing belief among researchers is that it is unlikely to have more than one pipe-failure at a time. Accordingly, they have studied the reliability and damage tolerance of a WDS representing the 0^{th} and 1^{st} state of reliability (Su et al., 1987; Cullinane et al., 1992; Gupta and Bhave, 1994; Tanyimboh and Templeman, 1998; Tanyimboh et al., 2001; Ostfeld et al., 2002). Studying the WDS of the City of Winnipeg (Canada) for the period of 1975 to 1984, Jacobs and Goulter (1991) reported more than 80 pipe breaks in a single calendar day. Gheisi and Naser (2014a) concluded that the Winnipeg's WDS was in multiple pipes failure condition for 78.5% of the times. Simultaneous failure of several pipes is more likely for a WDS located in harsh climatic conditions and those located in developing countries (Goutler and Kazemi, 1989; Kansal and Arora, 2002). Failure of a single pipe in a WDS generally leads to closure of several pipes simultaneously due to closure of neighbouring isolation valves (Walski, 1993). The smallest area and the least number of affected pipes in the valve-enclosed-segment of WDS depend on the pattern and density of isolation valves. Walski (1993) suggested using the concept of "water distribution segment" instead of traditional idea of "link-node" as the basic building block of reliability analysis. The segment-based reliability analysis needs identification of segments in the system. A large number of studies in the literature have been focused on the concept of segment identifying (Walski, 1994; Goulter et al., 2000; Walski, 2002) and the associated number of components outage and disconnections. To identify segments one by one, Jun and Loganathan (2007) used moving artificial mark, while Kao and Li (2007) and Li and Kao (2008) applied search algorithm using topologic matrix. To identify segments, Giustolisi et al. (2008a and 2008b) and Giustolisi and Savic (2008) practiced head-driven hydraulic simulation considering valves as pseudo-pipes. Despite its first application for pipe network analysis (Kesavan and Chandrashekar, 1972), literature also provides wide range of recent application of graph theory to identify a WDS segments (Creaco et al., 2010 a and b; Giustolisi and Savic, 2010; Evan, 2011; Alvisi et al., 2011; Nardo et al., 2013; Gao, 2013). To identify valve-enclosed segments in a WDS, detailed information about the number and location of existing valves and their installations are required. Unfortunately, such details do not always exist. To ease the segment-based WDS reliability analysis and to have more realistic results, Gheisi and Naser (2014a) developed the concept of higher states reliability. Most recently, Gheisi and Naser (2015a) introduced the novel concept of multiple states reliability and applied the multiple criteria decision analysis to rank various layouts for a WDS considering higher and lower states of reliability. They assigned higher objective weights to higher states of reliability indicating their higher level of importance in decision-making.

2.3.3 Reliability Measures and Relevant Criteria

Literature reveals various techniques and criteria to measure WDS reliability (Figure 2.4). They are classified into three categories of analytic, systemic-holistic, and heuristic approaches (Wagner et al., 1988a and 1988b; Mays, 1999; Ostfeld, 2004; Trifunovic, 2012).

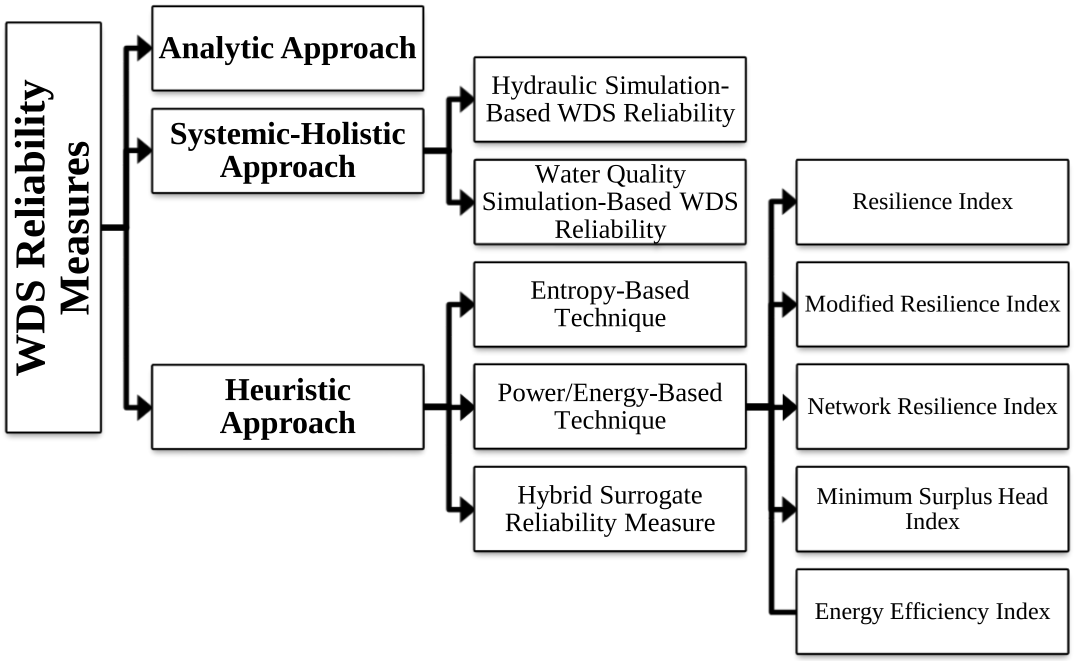

Figure 2.4 Techniques and criteria employed in literature to measure the reliability for a WDS.

Analytic or Reachability- or Connectivity-Based Approach: An analytic approach breaks down a WDS into its rudimentary components and studies the interactions or connections among them. The principal focus is on finding the constituent elements of a WDS (e.g. storage tanks, pumps, nodes) and looking for the connectivity among them (Wagner et al., 1988a; Trifunovic, 2012). Having enough connection to the source node is the basis of an analytic approach. This approach determines whether enough connections exist to link a node to a source. That is, a node in a WDS is reachable when it is connected to at least one source node in the system (Wagner et al., 1988a). If a node has connection(s) to a source, it does not guarantee receiving demanded water. Having connection to a source may show the existence of more redundancy in WDS, which can increase the chance of receiving water. Therefore, analytic approaches should be applied as an initial reliability screening strategy and systemic-holistic methods should be employed later as a complementary way to find the system's reliability (Goulter and Coals, 1986; Wagner et al., 1988b). Using graph theory and principles of complex networks, Yazdani and Jeffrey (2010, 2011, 2012a, 2012b) applied a range of advanced topological metrics to quantify the redundancy and degree of connectivity for a WDS. As a more realistic form of connectivity analysis, availability analysis considers a pipe as a repairable component and incorporates the probability of failure rather than connectivity checking (Shinstine et al., 2002; Atkinson, 2013). Using the concepts of mean time between failure and that to repair, Ross (1985) and Cullinane (1986) studied the availability of pipes. Knowing the pipes availability, the probabilities of various failure combinations can be obtained (Tanyimboh et al., 2001).

Systemic-Holistic or System-Performance or Simulation-Based Approach: In contrary to analytic method, the systemic-holistic approach does not break down a WDS into its constituent parts. Indeed, systemic-holistic is an event-oriented technique that studies WDS as a unit containing several subunits or components. Any disturbance in the system's operation due to component failure is investigated using discrete simulation (Wagner et al., 1988b). Thus, WDS simulation is the primary element of a systemic-holistic approach. Simulation techniques may model the hydraulic or quality aspect of the supplied water. This research divides the systemic-holistic reliability analysis into two classes of hydraulic- and water-quality-simulation-based approaches. Through a comprehensive hydraulic and water quality analysis, systemic-holistic approaches measure the probability that a failed WDS can continuously supply the consumers' demands with acceptable quantity and quality.

a) **Hydraulic-Simulation-Based WDS Reliability Techniques:** They simulate the hydraulic performance of a WDS in case of mechanical or hydraulic failures. An example of these techniques is the minimum cut-set method that employs hydraulic simulation to find a set of pipe failures (Su et al., 1987; Shinstine et al., 2002). When conducting a hydraulic simulation, modelers often assume that nodal demands are fully satisfied regardless of the available pressure at nodes (i.e., demand-driven approach). The volume of supplied water at nodes can be pressure-independent (or volume-based which is a constant volume of water) or pressure-dependent in which supply varies in accordance to the available pressure head at nodes (Tabesh et al., 2014). Demand-driven hydraulic simulation cannot produce satisfactory results particularly for a failed (partially or completely) WDS. Pressure-deficient conditions occur when pressure at demand nodes drop to less than the minimum required pressure due to failure. These conditions can be modeled more realistically using a head- or pressure-driven approach (Tabesh 1998; Tanyimboh et al. 2001; Tabesh et al. 2002, Shirzad et al. 2012). In head-driven simulation, the available pressure head at each demand node dictates the deliverable water to consumers. Thus, it is essential to find the governing head-discharge relationship at each demand node (Tanyimboh et al. 2001; Kalungi and Tanyimboh, 2003). Literature reveals numerous continuous and discontinuous head-discharge functions (Bhave, 1981; Germanopoulos, 1985; Wagner et al., 1988b; Fujiwara and Ganesharajah, 1993; Gupta and Bhave, 1996; Tanyimboh and Templeman, 2010; Shirzad et al., 2012; Tabesh et al., 2014). Wagner et al. (1988b) employed a parabolic head-discharge relationship to estimate the supply of water from a node in pressure-deficient conditions. This parabolic relationship modifies the full supply based on the square root of the fraction of the available pressure head in excess of minimum service head. Wagner et al. (1988b) defined the pressure deficient condition as that when pressure at a node is below the service head but not less than the minimum service head. Tanyimboh (1993), Tanyimboh and Templeman (1995), Tanyimboh and Templeman (1998) and Tanyimboh et al. (2001) described the node-head equation and employed single-source-head approach rather than node-head counterpart. A node-head approach uses the concepts minimum required and desirable heads to fix the outflow at the pressure-deficient nodes. The single source-head equation fixes the nodal discharge using minimum and desirable heads at the source node rather than the demand node. Desirable head is pressure, which should be available at a node to fully satisfy the demand. While commercial software for WDS analysis often use the demand-driven approaches, they have been modified to approximate the pressure deficient conditions (Tanyimboh et al. 2001; Kalungi and Tanyimboh, 2003). Ozger and Mayer (2003) and Ang and Jowitt (2006) proposed the idea of assigning artificial tanks to each pressure-deficient node and running the demand-driven model iteratively as a solution to get semi-head-driven results. Kalungi and Tanyimboh (2003) categorized the pressure-deficient nodes into no-flow, partial flow and key partial-flow nodes and proposed the critical node head-driven method. Cheung et al. (2005) introduced an extension for EPANET2 by an object-oriented toolkit to directly modify the source codes of solver based on head-discharge rate at demand nodes without changing the user-interface. Pathirana (2010) modified the EPANET2 and developed EPANET-EMITTER, which applies an emitter-based demand simulator. Using an emitter/nozzle function at each node, EPANET-EMITTER finds the demand based on the available pressure via an iterative procedure. CWSNET (the Centre for Water Systems, the University of Exeter, United Kingdom) is also a substitute toolkit for EPANET2 (Guidolin et al., 2010). CWSNET modifies WDS topology dynamically during runtime without interruption and perform parallel simulations of the same or different WDS. Siew and Tanyimboh (2012) developed EPANET-PDX, a head-dependent extension for EPANET2, to incorporate pressure-deficient analysis. Muranho et al. (2014a) developed an EPANET extension of WaterNetGen to incorporate head-demand and head-leakage relations in head-driven analysis. WaterNetGen models pressure-deficient scenarios using pressure-discharge relationship at demand nodes. WaterNetGen employs the techniques proposed by Germanopoulos (1985) and Giustolisi et al. (2008c) to estimate the leakage through a pipe.

b) Water Quality Simulation-Based WDS Reliability: The level of public health in a city highly depends on the quality of delivered water rather than its quantity. Water quality failure is the most unfavorable and crucial one compared to mechanical and hydraulic failures. A widespread morbidity or even mortality may happen in an urban area due to the consumption of contaminated water. While hydraulic-simulation-based techniques are studied extensively, limited studies exist on water-quality reliability. Huang et al. (2005) reported a comprehensive review of the water quality reliability models in the literature. Most studies on water quality reliability are mainly scenario-based and limited to residual of a specific disinfectant (Gauthier et al., 2000; Constans et al., 2003; Rossman et al. 1994; Boulos et al., 2005; Huang et al., 2005). As such, reliability was defined as the probability that disinfectant's residual concentration stay in a safe and standard domain. Mechanical and hydraulic failures may lead to water quality failure. For instant, contaminant intrusion (water quality failure) may happen due to pressure reduction (hydraulic failure) in a WDS and formation of crack in pipes or pipe breakage (mechanical failure). As the time passes, an existing WDS gets more corroded, while population and water demand per capita increase. Aging weakens the structural integrity of WDS and increases the chance of pipe breakage. A corroded WDS with high hydraulic roughness and pressure reduction is highly susceptible for contaminant intrusion and water quality failure. As time passes, it is more necessary to check the water quality reliability of such system (Huang et al., 2005). Component failure can change the water age and its residence time or disinfectant's residual concentration (Kansal and Arora, 2002). Kansal et al. (2004) proposed two indices to check the hydraulic and water quality performance of a WDS separately due to pipe failure. Hydraulic performance was investigated through computation of supply ratio at demand nodes and water quality as the time ratio in which supplied water had standard quality. Kansal et al. (2004) modeled the system using demand-driven approach and then corrected the flow at demand nodes using the parabolic head-discharge relationship. Gupta et al. (2007) argued incapability of the aforementioned technique in satisfying the flow continuity at nodes and associated problem in computing the chlorine concentration. They introduced a single performance index to evaluate hydraulic and water quality-based performance of a WDS simultaneously. Using head-driven approach, they employed WQRNET (Ganguly, 2007) to simultaneously satisfy flow continuity and head-discharge relationships at demand nodes.

Heuristic or Surrogate-Measure-Based Approach: A heuristic approach applies mental shortcuts to quickly produce satisfactory reliability results, which may not be necessarily the optimal. The approach is an experienced-based technique using the intuitive judgment. Literature lists several heuristic reliability techniques (Ang and Jowitt, 2005; Raad et al., 2010; Tanyimboh et al., 2011; Gheisi and Naser, 2014b). To decrease the computational workload, these techniques do not compute the reliability of a WDS directly. Rather, they assess some attributes or measures of a WDS, which are expected to have strong correlation with reliability (Gheisi and Naser, 2014b). The heuristic approaches are classified into three categories of entropy-based, power/energy-based, and hybrid surrogate measures.

a) **Entropy-Based Technique:** An entropy-based technique uses the concept of information entropy initially introduced by Shannon (1948). As surrogate reliability measure, entropy estimates the amount of available information regarding supply of water in a WDS. The higher flow entropy in a WDS, the more random and scattered the water is distributed in the system. Redundancy (existence of more flow paths) and flow uniformity can increase the flow entropy of a WDS. Awumah et al. (1991) and Tanyimboh and Templeman (1993a) applied the Shannon's information entropy as a measure of redundancy and flow uniformity in a WDS, respectively. Proposing a computationally efficient entropic model, Awumah et al. (1990 and 1991) estimated the degree of redundancy and existence of alternative pathways in a WDS. Water in a WDS can flow through different pathways to reach a specific consumer. Tanyimboh and Templeman (1993a) developed a flow entropy function for a single-source WDS. They assumed the probability of water to flow through a specific set of pipes was related to the discharge in each pipe. Applying the concept of path probability, Yassin-Kassab et al. (1999) extended the flow entropy function to multiple sources and multiple demands systems. Flow entropy in a WDS is proportional to degree of uniformity of flow in the system. A WDS with higher degree of redundancy or flow uniformity is expected to handle mechanical failures more easily. Several studies in the literature have shown a strong correlation between flow entropy and mechanical-failure-based reliability (Tanyimboh and Templeman, 1993b and 2000; Tanyimboh and Sheahan, 2002; Setiadi et al., 2005; Tanyimboh and Setiadi, 2008; Di Nardo et al., 2010; Tanyimboh et al., 2011). Gheisi and Naser (2014a, b) showed that the correlation becomes stronger in higher states reliability analysis when several pipes fail at the same time. Arguing the insensitivity of flow entropy to variation of pipes' diameter, Liu et al. (2014) developed diameter-sensitive flow entropy.

b) Power/Energy-Based Technique: Power/energy-based technique is a heuristic method, which uses the total input power/energy provided by source(s) to determine the ability of a WDS to handle failures. Resilience index (Todini, 2000), modified resilience index (Jayaram and Srinivasan, 2008), minimum surplus head index and network resilience index (Prasad and Park, 2004), and energy efficiency index (Dziedzic and Karney, 2014) are widely used in literature.

Resilience Index: The total power provided by storage tanks or pumps should be enough to overcome the major and minor head losses in a WDS as well as to supply the demanded water with standard pressure at delivery points. When a hydraulic failure happens in a WDS, the amount of head losses increase dramatically in the vicinity of the failed region. A WDS with surplus power at demand nodes is expected to be more resilient and should be able to handle the sudden extra head losses more easily (Todini, 2000). Considering the advantage of having surplus power in a WDS, Todini (2000) introduced the concept of resilience index. The index was defined as the ratio of the surplus hydraulic power arriving at demand nodes to the maximum hydraulic power, which can be dissipated in the system due to major and minor head losses to meet the consumers' demands (Todini, 2000; Prasad and Park, 2004; Farmani et al., 2005; Saldarriaga and Serna, 2007; Reca, 2008). Raad et al. (2010) and Baños et al. (2011) indicated that resilience index is not a good representative of mechanical reliability. The index is mainly correlated with hydraulic-failure-based reliability (Todini, 2000; Farmani et al., 2005; Reca, 2008; Raad et al., 2010; Di Nardo et al., 2010; Baños et al., 2011; Atkinson et al., 2014). Optimizing the cost of Anytown WDS, Atkinson et al. (2014) came across with a trade-off between resilience index and flow entropy (increasing one lead to decreasing the other), which made the optimization process almost impossible. Optimizations based on resilience index and flow entropy revealed that the system optimized with resilience index was more reliable and cheaper in hydraulic failure conditions rather than mechanical. While optimized system based on flow entropy was able to handle mechanical failures more readily, it was more expensive and less reliable when hydraulic and water quality failures were taken into account.

Modified Resilience Index: Jayaram and Srinivasan (2008) found inconsistency in computing the Todini's resilience index (Todini, 2000) when multiple sources of water exist in a WDS. The inconsistency is due to dramatic increase of input power, which may compromise the effect of surplus power. Jayaram and Srinivasan (2008) defined/applied the modified resilience index as the ratio of nodal surplus power against the nodal minimum required power. Baños et al. (2011) questioned the advantage of modified resilience index over the resilience index as it is case dependent and cannot be generalized (Atkinson, 2013).

Network Resilience Index: Dealing with mechanical failures, resilience index and its modified version suffer from incorporating the degree of redundancy. A branched WDS with high surplus power at demand nodes (high resilience index) cannot properly handle mechanical failure. Although the excess power in demand nodes are high, but in case of pipe failure many consumers particularly those located at the end of branches may not receive water due to lack of redundancy in the system (Prasad and Park, 2004). To address this issue and find the reliable loops in WDS, Prasad and Park (2004) introduced the concept of "pipe diameter uniformity" to Todini's resilience index. The pipe diameter uniformity measures the degree of diameter consistency among the set of pipes ending at each node. Pipe uniformity was computed by dividing the average of pipes diameters connected to a node to the maximum diameter reaching that node. Higher pipe uniformity and less variation in diameter of pipes can increase redundancy and the number of reliable loops in WDS (Prasad and Park, 2004). Atkinson (2013) argued that pipe diameter uniformity applied in network resilience index should be modified to consider the uniformity of incoming/outgoing flows at each node. WDS with higher degree of flow uniformity and entropy is expected to handle pipe failures more easily (Tanyimboh and Templeman, 1993b).

Minimum Surplus Head Index: The minimum required head is the pressure required at each node to fully satisfy consumers' demands. Surplus head is the amount of available pressure head more than the minimum required pressure. Minimum surplus head reflects the available head in a WDS, which is found in the most stressed nodes (Prasad and Park, 2004). The index of minimum surplus head is commonly applied as an auxiliary reliability index. While the maximization of the minimum and total surplus head in a WDS along with the resilience index might increase the surplus pressure head or power at demand nodes, it cannot warranty the redundancy required to handle the mechanical failure (Park, 2004). Farmani et al. (2005) used the index of minimum surplus head as a complementary reliability index to improve the performance of the resilience index in handling mechanical failure. Atkinson et al. (2014) observed a strong positive coloration between minimum surplus head and resilience index in optimized Anytown WDS for cost and resilience index. They reported a weak negative coloration between minimum surplus head and flow entropy in the optimized WDS for both cost and entropy. They argued the maximization of the minimum surplus head index as third optimization objective alongside entropy and resilience indices enhanced performance of all cases in mechanical and hydraulic aspects.

Energy Efficiency Index: Dziedzic and Karney (2015) proposed an energy-efficiency-based index to measure performance of a WDS. Energy efficiency was defined as the ratio of energy delivered to consumers to the total energy supplied by tanks and pumps (Dziedzic and Karney, 2013, 2014 and 2015). The performance index was obtained as the geometric average of four other metrics including reliability, vulnerability, resilience and connectivity. Integrating four indices, the performance index is expected to be more comprehensive. Reliability was defined as the average of computed energy efficiencies over different scenarios of failure. Vulnerability was defined as the minimum energy efficiency occurred in various failures. Resilience was defined as the average energy efficiency during the recovery period after failure. Connectivity was defined as the minimum percentage of delivered water to consumers during different failure scenarios. Unlike the commonly applied performance indices in literature, the energy-efficiency-based performance index took the advantage of applying efficiency and energy balance of a WDS to estimate the performance of a WDS. Dziedzic and Karney (2015) evaluated the performance of two WDSs under three different scenarios of normal flow, fire flow, and pipe burst. The performance index incorporated both energy and mass balances into a WDS performance analysis and was easily adaptable to various failure scenarios. The proposed performance index showed the same trend as other indices in the literature. However, the proposed index penalized the WDS in cases of having unnecessarily high pressures (perhaps due to increase in leakage rate) and it was not unreasonably increased with the increase in the pressure or surplus power of systems.

c) Hybrid Surrogate Reliability Measure: Hybrid surrogate measures take the advantage of combining the reliability surrogate measures in hope of getting more comprehensive and realistic reliability results. Raad et al. (2010) proposed the hybrid index by combining the normalized flow entropy and resilience index. Compared to the uncombined surrogate measures, WDS with higher combined index showed less sudden discontinuity in adjacent pipe diameter and also better performance under different scenarios of pipe failure. The uncombined surrogate reliability measure of resilience index was found to be the best criteria under demand variation conditions (to find the hydraulic-failure-based reliable WDS). Though having flow entropy and resilience index, the hybrid index was unable to handle simultaneous hydraulic and mechanical failures (Raad et al., 2010).

2.4 Need for Multiple Aspects and States Performance Analysis

Failure and response of a WDS to that are the two key concepts in reliability analysis. A particular state of pipe failure could have several simultaneous unfavorable impacts on a WDS. Failure can adversely affect the, quantity, quality, efficiency and/or equity in water supply. While literature lists a large number of studies on various types and combinations of pipe failure (Kleiner and Rajani, 2001; Rajani and Kleiner, 2001; Nishiyama and Filion, 2013; Gheisi and Naser 2013, 2014a, b, c), few studies have focused on the simultaneous multiple aspects response of a WDS to failure (Bertola and Nicolini, 2006; Shafiqul Islam et al., 2014; Ermini and Ataoui, 2014). Using/defining relevant indices, researchers often evaluated the operational performance (hitherto referred to "performance") of a WDS in one aspect. In few cases where two aspects (adequacy in water delivery and water supply with acceptable quality) were considered, they were studied separately (Ostfeld et al., 2002 and 2004). Techniques, which evaluate the performance of a WDS from various aspects separately, are unable to show the possible interactions among the aspects. To study such interactions, a simultaneous multiple aspects/states analysis must be employed. This section discussed the need for simultaneous multiple aspects/states reliability analysis of a WDS.

Response analysis can reveal the conditions of flow when failures occur in a WDS. Such analysis requires defining a performance index for WDS. Tanyimboh et al. (2001) indicated that an ideal performance index for reliability analysis should be able to demonstrate the flow, pressure, and leakage variations due to failure. Bertola and Nicolini (2006) conducted the reliability and efficiency analysis separately. They evaluated the overall performance of a WDS as the product of reliability and efficiency. They estimated reliability analysis considering mechanical and hydraulic failure and measured efficiency using water leakage modeling. They showed that a highly reliable WDS could suffer from low efficiency and high amount of leakage, which cannot be distinguished using a simple performance index. Traditionally, researchers have applied a simple index to evaluate the performance of a WDS in one specific aspect or two aspects separately; providing the consumers with adequate amount of water or water with acceptable quality (Ostfeld et al. 2002 and 2004; Kansal et al., 2004). Gupta et al. (2009) introduced and applied a single performance index to evaluate hydraulic and water quality aspects simultaneously. The index was defined as the ratio of total amount of water with acceptable quality delivered to the total amount of water with acceptable quality demanded. Using fuzzy sets, Shafiqul Islam et al. (2014) aggregated the water utility indices based on the available water volume, pressure and quality to compute the overall reliability under uncertainties. Ermini and Ataoui (2014) employed fuzzy set to combine three indicators of reliability, resiliency, and vulnerability into a single indicator reflecting the WDS performance (good, poor or somewhere in between). They employed analytic hierarchy process to assign weight to each indicator. Neither Shafiqul Islam et al. (2014) nor Ermini and Ataoui (2014) did not study various states of reliability by considering different combination of pipe failures.

Failure can occur at different states (Gheisi and Naser, 2014a, b and c) and each state of failure can affect WDS performance in various aspects simultaneously (e.g. quantity, quality, equity of delivered water, and water leakage). This includes quantitative as well as qualitative aspects. For instance a pipe breakage in a WDS can reduce the amount of deliverable water to consumers. At the same time, the breakage can undermine the equity and uniformity in supplied water, change water loss due to leakage, lead to pressure reduction (back-siphonage), and increase the chance of back flow and water contamination through unprotected cross-connections (Boulos et al., 2005; Gottipati and Nanduri, 2014). On 24/June/1987, construction crew at Fair Lawn and Hawthorne of New Jersey (Unites States) broke a water main accidentally while widening a bridge. The pipe breakage resulted in a sudden pressure reduction and back-siphonage at the water main. Potable water system of a pest control local company was affected by the backflow incident. Noticeable amount of pesticides entered the public WDS and contaminated the potable water. In an immediate reaction, the water department stopped supplying water to consumers after receiving numerous complaints. Totally 63 residences did not have potable water for several days and several pipes were replaced since pesticides stuck to them. The pest control company was also sued for $21,000,000 (AWWA PNWS, 1995). Schneider et al. (2010) analyzed more than 42,000 field testing data of backflow sensing meters installed at four different water systems at Pennsylvania, New Jersey and West Virginia (United States). Results showed that backflow can be a serious issue for water industry and it was more widespread than previously believed. Readings with backflow consist of 1.6% of all measured data occurring at 5% of all the residences where sensing meters were installed.

WDS performance can be viewed and assessed from suppliers and consumers perspectives. Water consumers' focuses are mainly on water delivery cut-offs, deficiencies and duration of interruptions in continuous water supply. Suppliers' and water authorities' concerns are more extensive and deal with various states of failures in WDS at design, operation and maintenance level (Kwietniewski, 2004 and 2006). They are chiefly curious to know the effect of failures on quantity, quality, uniformity and efficiency of water delivery as well as the energy variations in WDS (Gargano and Pianese, 2000; Bertola and Nicolini, 2006; Gupta et al. 2009, Zhuang et al., 2012; Shuang et al., 2014; Gottipati and Nanduri 2014; Dziedzic and Karney, 2015). Authorities employ various indicators and tools to assess WDS performance (Cardoso et al., 2004). Using/defining several indicators, systems of performance indicators evaluate/monitor the efficiency/effectiveness of a water supply system from various aspects including natural resources, operational, services, financial, physical assets, personnel, water quality, public health, and environmental (Haider et al., 2013). Over the past decade, water agencies proposed several performance indicators to assess sustainability of water supply systems (Haider et al., 2013). Haider et al. (2013) conducted a comprehensive review to evaluate understandability, measurability, and comparability of the proposed performance indices in literature to find suitable indicators for small- and medium-sized water supply systems. The performance indicators are powerful tools to monitor all sectors in an in-practice water supply system at management level to eventually identify the sectors with poor performances. Managers also need a tool to enhance the performance of sectors with poor performances. In such situations, technical assessment tools can be employed to evaluate and enhance WDS performance using simulation models (Cardoso et al., 2004; Muranho et al., 2014b). Traditionally, designers/researchers study

WDS performance in one aspect or two aspects separately. Techniques, which evaluate the performance of WDS in multiple aspects separately, are not able to demonstrate the interaction that may exist among various aspects. A multiple aspects and states analysis of a WDS is required to have a more realistic estimate of the system's reliability. Figure 2.5 shows a general framework for a multiple states and aspects WDS reliability analysis.

2.6 Summary

This chapter made an in-depth review of literature on WDS reliability analysis. The aim was to classify the relevant literature and differentiates types of failure from the techniques of reliability analysis. Failure in a WDS was classified into mechanical/physical, hydraulic and water quality failures. Occurrence probability or rates of failure in pipes, pipes failure combinations, and criteria to measure reliability were the key factors that affect the WDS reliability. Pipes failure combinations can determine the exactness of WDS reliability results and also the state of reliability analysis. WDS reliability analysis was divided into analytic, system-holistic and heuristic approaches. Subsequently, system-holistic approach was subcategorized into hydraulic-simulation and water quality based WDS reliability analysis. Heuristic approach was subcategorized into entropy-based, power/energy-based and hybrid surrogate measure. Entropy-based surrogate reliability measure was based on the concept of information entropy. Heuristic power/energy-based techniques included resilience index, modified resilience index, network resilience index, minimum surplus head index and energy efficiency index. Hybrid surrogate measure takes the advantage of combining the reliability surrogate measures. While WDS failure has been studied for many decades, very little attention has been paid to how the system respond to failures. Incorporating a multiple aspects performance response index in WDS reliability analysis can lead to more informative and realistic outcomes. The most commonly applied performance index in simulation-based WDS reliability technique is the single-aspect performance response index of supply ratio. This research highlighted the need for multiple aspects and states performance analysis, which has largely been neglected in the literature.

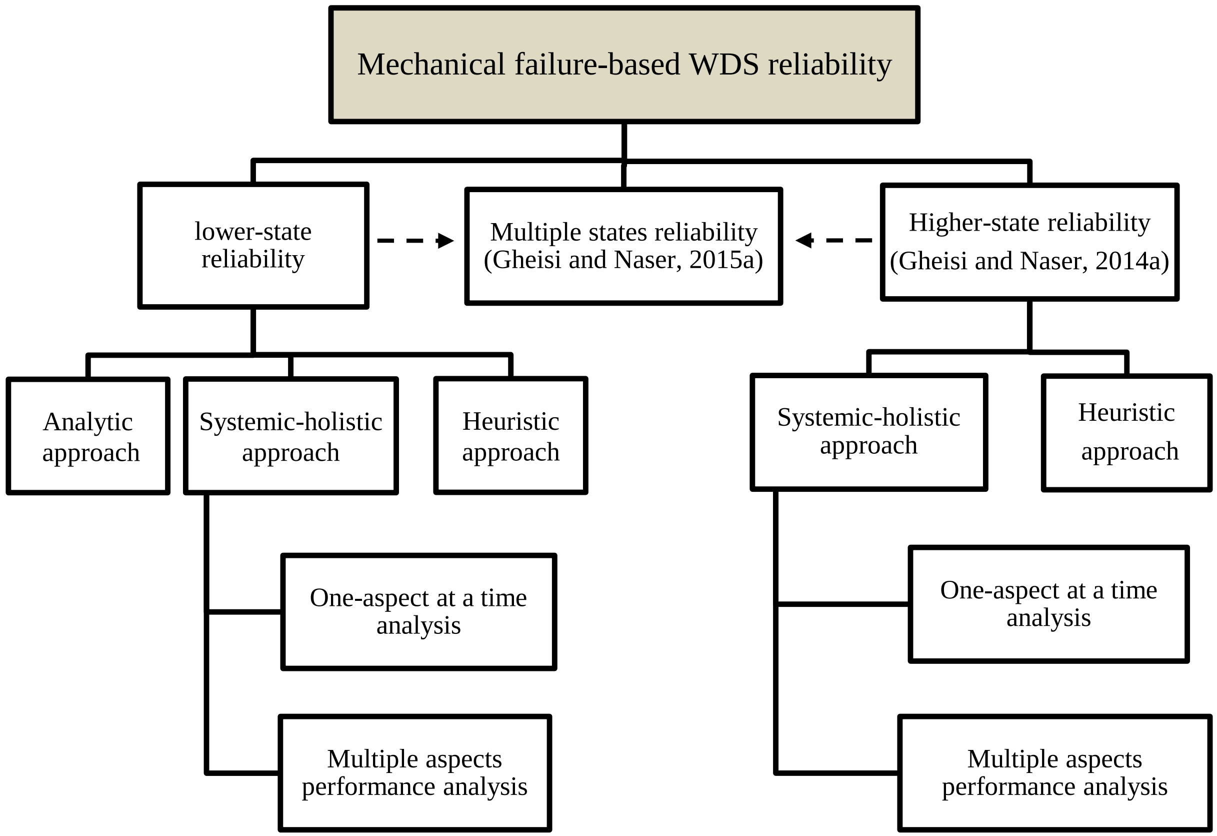

Figure 2.5 Comprehensive mechanical failure-based WDS reliability analysis (the contribution of multiple states and aspects performance analysis)

Chapter 3:Higher-State Water Distribution System Reliability Analysis[2]

> "*India's energy crisis cascaded over half the country Tuesday when three of its regional grids collapsed, leaving hundreds of millions of people without government-supplied electricity in one of the world's biggest-ever blackouts.*"
> (CBC News, "India blackouts affect half the country", 31 July 2012)

As indicated in the above quotation, the most catastrophic blackout occurred in India on July 31th 2012 due to simultaneous failure of three power lines. The electricity outage spread across twenty states of India and hundreds of millions of people were affected. As it can be seen some failure scenarios such as the simultaneous failure of several components of a system may not happen frequently, but they can have huge catastrophic aftermaths. Simultaneous multiple components failure scenario can occur for every system comprised of several components such a WDS. A WDS is a complex network of various mechanical and electromechanical components, which is expected to continuously deliver demanded water with acceptable pressure and quality to consumers. Occurrence of a break and/or failure in a pipe may interrupt service, undermine system performance, and ultimately lead to consumer dissatisfaction. Some customers (e.g., hospitals, industrial centers, and governmental buildings) can be critically affected by a failure (Tabesh et al., 2009). Therefore, it is essential to have a way of predicting the performance of a WDS should the system fail, which is known as WDS reliability analysis. A deep insight into the relevant literature revealed that WDS reliability studies have primarily considered one failure at a time, and little attention has been paid to situations in which several pipes fail simultaneously. This limited approach may inaccurately provide a high level of confidence about system performance and eventually lead to severe consequences. This chapter aims to evaluate WDS reliability when several pipes fail simultaneously.

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[2] A version of chapter three has been published in the journal of American Water Work Association. Gheisi, A., and Naser, G. (2014). "Water Distribution Systems Reliability under Simultaneous Multicomponent Failure Scenario." *Journal of American Water Work Association*, AWWA, 106 (7), E319-E327.

3.1 Need for Simultaneous Multiple Pipes Failure Based Reliability Analysis

According to Gheisi and Naser (2013), key factors that significantly influence WDS reliability include reliability assessment techniques, the criterion used to measure system reliability, the number of components involved in failure combinations, and failure probabilities or frequencies. With regard to the first item, researchers have approached WDS reliability assessment from the standpoint that only a single pipe is likely to fail at a time (Su et al., 1987; Cullinane et al., 1992; Gupta and Bhave, 1994; Ostfeld et al., 2002). When a pipe fails, it can only be isolated by closing cutoff valves located on the pipe, and this closure scenario may result in the shutoff of several pipes, depending on the valve locations (Walski, 1993). As a consequence, the failure of a single pipe can lead to simultaneous closure of several pipes. Although ignoring simultaneous multiple pipes failures may significantly reduce the computational workload in reliability analysis (Gargano and Pianese, 2000), it may also lead to inaccurate estimates of level of confidence.

Simultaneous multiple pipes failures may occur in systems located in harsh climates. Water main failures in the city of Winnipeg, Manitoba, for a 10-year period from 1975 to 1984 were studied by various researchers (Kettler and Goulter, 1985; Goulter and Kazemi, 1988, 1989; Jacobs and Goulter, 1991). Figure 3.1 profiles the occurrences of the Winnipeg water main failures. Although more than 20,200 failures were reported to have occurred in 2,230 km of distribution pipes and 106.2 km of transmission mains, the records did not differentiate between failures that occurred in distribution and those that occurred during transmission. Further details of the failure scenarios in Winnipeg were discussed by Kettler and Goulter (1985) and Goulter and Kazemi (1988, 1989). Goulter and Kazemi (1989) indicated several types of failures occurred in Winnipeg, including joint, sleeve, corporation cock, circular crack, longitudinal split, hole, old clamp leaking, as well as unknown types. Although no specific causes for the failures were discussed, it is likely that the majority of these failures occurred randomly at the same time. At different parts of the Winnipeg WDS, maximum number and various levels of simultaneous pipe failures were analyzed. The maximum number of simultaneous pipe failures (failures occurring in the same calendar day) recorded in the city was more than 80 breaks (Jacobs and Goulter, 1991). In the current research, analysis of the data reported by Jacobs and Goulter found that number of days in which 2–6, 7–8, and 9–20 pipes failed simultaneously was more than 300, 200, and 100, respectively. Moreover, results indicated that during the study period, the system was in multiple pipes failure, one-pipe failure, and no-failure situations on average 78.5, 9, and 12.5% of the time, respectively. Jacobs and Goulter (1991) showed that, as expected, the maximum number of simultaneous failures occurring in the same calendar day increased with the size of a system.

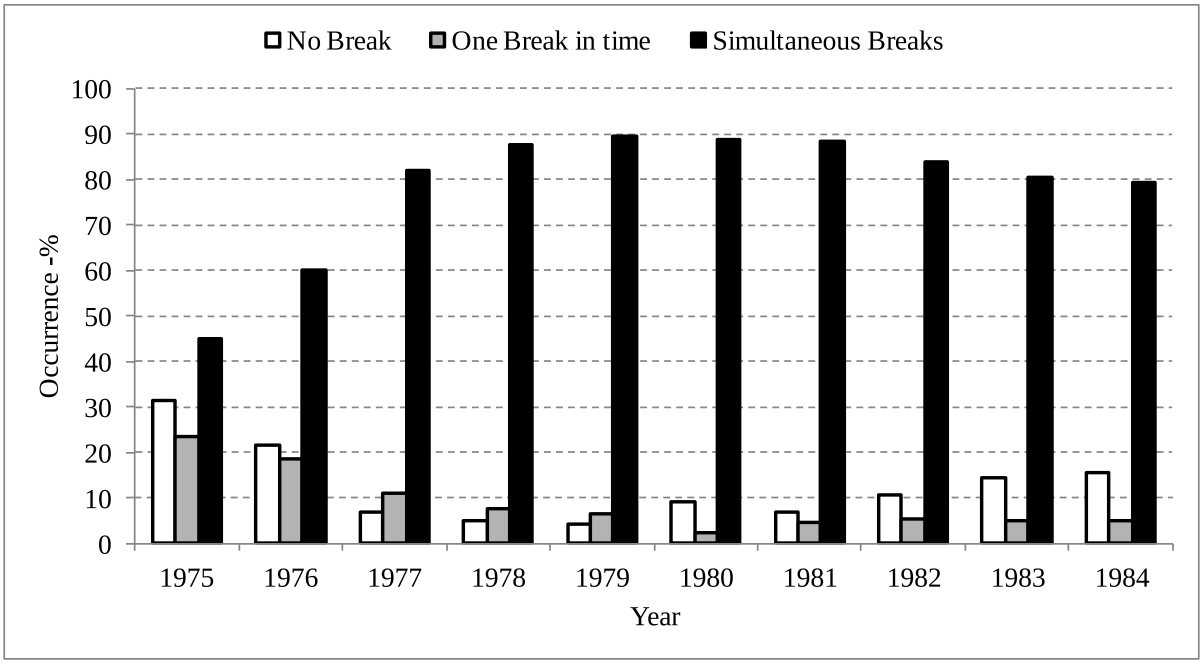


Figure 3.1 Records of water main pipe failures in the city of Winnipeg, Manitoba (data derived from Jacobs and Goulter, 1991)

3.2 Higher-State Reliability Analysis Technique

To evaluate higher states of WDS reliability when a system experiences simultaneous pipe failures, this study applied the technique initially proposed by Gargano and Pianese (1998, 2000) and Tanyimboh et al., (2001) and recently modified by Gheisi and Naser (2013). The technique considers all possible pipe-failure combinations as well as spatiotemporal changes in demand. Moreover, the technique is capable of handling partial failure conditions when the pressure is inadequate to fully satisfy the consumer demand (Gargano and Pianese, 2000; Tanyimboh et al., 2001; Kalungi and Tanyimboh, 2003; Surendran et al., 2005).

Reliability of a WDS is generally defined as the system's ability to continuously meet the nodal demands with acceptable quality and pressure. Following Gheisi and Naser (2013), the current research measured the reliability (*R*) as a weighted mean of performance indexes of the system:

$$R = PI(0)P(0) + \sum_{a=1}^{N} PI(a_1)\, P(a_1) + \sum_{a=1}^{N-1}\sum_{b=a+1}^{N} PI(a_1,a_2)\, P(a_1,a_2) + \sum_{a=1}^{N-2}\sum_{b=a+1}^{N-1}\sum_{c=b+1}^{N} PI(a_1,a_2,a_3)\, P(a_1,a_2,a_3) + \cdots \quad (3.1)$$

in which *N* is the number of pipes (measured from one node to the next) in the system and $PI(0)$, $PI(a_1)$, $PI(a_1,a_2)$, $PI(a_1,a_2,a_3)$, and $PI(a_1,a_2,a_3,\ldots)$ correspond to the system performance indexes when zero, one, two, three, and more pipes are unavailable simultaneously. $P(0)$, $P(a_1)$, $P(a_1,a_2)$, $P(a_1,a_2,a_3)$ and $P(a_1,a_2,a_3,\ldots)$ are the weighting coefficients, defined as the probability that a WDS may end up in a specific failure combination. $P(0)$ is the probability of no failure, and $P(a_1)$, $P(a_1,a_2)$, $P(a_1,a_2,a_3)$, and $P(a_1,a_2,a_3,\ldots)$ are the probabilities of one, two, three, and more than three simultaneous failures, respectively.

Tanyimboh et al., (2001) and Martínez-Rodríguez et al., (2011) noted that the concept of tolerance to failure (the first state of reliability, R^1) provides a better measure of WDS performance and redundancy than of WDS hydraulic reliability. Using Equation (3.2), the tolerance to failure (TF) for a WDS was estimated (Tanyimboh et al., 2001; Kalungi and Tanyimboh, 2003):

$$TF = \frac{R - P(0)PI(0)}{1 - P(0)} \quad (3.2)$$

Using the weighted mean of a system's performance indexes (*PI*) for typical failure combinations of a_1, a_2, and a_3, the higher states (R^k = k^{th} state of reliability with $k = 2$ to N) of reliability were developed:

$$R^k = \frac{\sum_{j=k}^{F}\left[\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j)\, P(a_1,\ldots,a_j)\right]}{1 - P(0) - \sum_{j=1}^{k-1}\left(\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} P(a_1,\ldots,a_j)\right)} \quad (3.3)$$

in which *F* is the number of component failure combinations considered in the reliability analysis in each state. The k^{th} states of reliability measure the probability that a WDS meets customers' demands when at least k pipes of the system fail simultaneously.

An actual WDS may have pipes with different spatial characteristics, and two or more pipes in close proximity may be more likely to fail simultaneously. Moreover, the failure of some pipes may have more consequences than if other pipes fail. For example, a pipe serving a large demand area or critical users may be considered more vital to operation than a pipe serving a small demand area or noncritical users. In this research, all pipes were treated similarly.

Fujiwara and De Silva (1990) and Fujiwara and Tung (1991) applied the concept of availability (*A*) and unavailability (*U*) of a pipe i (A_i and $U_i = 1 - A_i$), to define the weighting coefficient of each performance index as

$$P(0) = \prod_{i=1}^{N} A_i \quad , \quad P(a_1) = P(0)\frac{U_{a1}}{A_{a_1}} \quad , \qquad (3.4)$$

$$P(a_1, a_2) = P(0)\frac{U_{a_1}U_{a_2}}{A_{a_1}A_{a_2}} \quad , \quad P(a_1, a_2, a_3) = P(0)\frac{U_{a_1}U_{a_2}U_{a_3}}{A_{a_1}A_{a_2}A_{a_3}} \quad \text{and } ...$$

in which Π is the product operator, index *i* refers to pipe number, and A_{a1} , A_{a2} , A_{a3} ,… and U_{a1} , U_{a2} , U_{a3} ,… represent the availability and unavailability of pipes a_1, a_2, a_3,…, respectively. Replacing Equation (3.4) in Equation (3.3), the higher states of reliability are as shown in Equation (3.5):

$$R^k = \frac{\prod_{i=1}^{N} A_i \left(\sum_{j=k}^{F} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1}U_{a_2}.....U_{a_j}}{A_{a_1}A_{a_2}.....A_{a_j}} PI(a_1,...,a_j) \right) \right)}{1 - \prod_{i=1}^{N} A_i - \sum_{j=1}^{k-1} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1}U_{a_2}.....U_{a_j}}{A_{a_1}A_{a_2}.....A_{a_j}} \prod_{i=1}^{N} A_i \right)} \qquad (3.5)$$

It is computationally demanding to include all possible combinations of unavailable pipes in a reliability assessment. Therefore, Tanyimboh and Sheahan (2002) proposed a methodology to reduce errors in reliability analysis caused by neglecting number of pipe-failure subsets. Initially these researchers estimated the unreliability of the system and then defined one minus the unreliability as an upper bound for reliability. No value greater than this bound is conceivable even if all pipe-failure subsets are considered. Similar to Tanyimboh and Sheahan (2002), the current research added half of the difference between the computed reliability and its upper bound to the calculated reliability in order to compensate for the error in the analysis attributable to ignored pipe-failure subsets. *F* number of failure combinations is considered in the reliability analysis for each state. R^k is then calculated as

$$R^k = \frac{\prod_{i=1}^{N} A_i \left(\sum_{j=k}^{F} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1} U_{a_2} \ldots U_{a_j}}{A_{a_1} A_{a_2} \ldots A_{a_j}} PI\,(a_1,\ldots,a_j) \right) \right)}{1 - \prod_{i=1}^{N} A_i - \sum_{j=1}^{k-1} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1} U_{a_2} \ldots U_{a_j}}{A_{a_1} A_{a_2} \ldots A_{a_j}} \prod_{i=1}^{N} A_i \right)}$$

$$+ \frac{1}{2} - \left[\frac{\prod_{i=1}^{N} A_i \left[\sum_{j=k}^{F} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1} U_{a_2} \ldots U_{a_j}}{A_{a_1} A_{a_2} \ldots\ldots A_{a_j}} \right) \right]}{2 \left(1 - \prod_{i=1}^{N} A_i - \sum_{j=1}^{k-1} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a1} U_{a_2} \ldots U_{a_j}}{A_{a_1} A_{a_2} \ldots A_{a_j}} \prod_{i=1}^{N} A_i \right) \right)} \right] \quad (3.6)$$

The right side of Equation (3.6) has two terms. The first corresponds to the k^{th} state of reliability. The second term, followed by the constant ½, is half of the difference between the computed reliability and its upper bound. It is an approximation of the amount by which the first term underestimates the different states of reliability.

Unfortunately, analysis of higher states of reliability is complex and computationally demanding. Following Gheisi and Naser (2013), the current researchers, in order to simplify calculations and increase computational efficiency, assumed the geometric mean of pipes availabilities, A_{mean}, to be equal to the availability of each pipe. Equation (3.6) can then be replaced by Equation (3.7):

$$R^k = \frac{\prod_{i=1}^{N} A_i \left(\sum_{j=k}^{F} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1} U_{a_2} \ldots U_{a_j}}{A_{a_1} A_{a_2} \ldots A_{a_j}} PI\,(a_1,\ldots,a_j) \right) \right)}{1 - \prod_{i=1}^{N} A_i - \sum_{j=1}^{k-1} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} \frac{U_{a_1} U_{a_2} \ldots U_{a_j}}{A_{a_1} A_{a_2} \ldots A_{a_j}} \prod_{i=1}^{N} A_i \right)}$$

$$+ \frac{1}{2} - \left[\frac{\sum_{f=k}^{F} \binom{N}{f} A_{mean}^{N-f} (1 - A_{mean})^{f}}{2 - 2 A_{mean}^{N} \left[1 + \sum_{j=1}^{k-1} \frac{(N - j + 1)(1 - A_{mean})^{j}}{A_{mean}^{j}} \right]} \right] \quad (3.7)$$

in which f is the number of pipe-failure subsets.

3.2.1 Error in Reliability Assessment

Following the methodology initially introduced by Fujiware and Tung (1991) and later applied by others (Tanyimboh et al., 2001; Gheisi and Naser, 2013), this research estimated the maximum errors in different states of reliability attributable to the number of failure subsets using Equation (3.8):

$$E(R^k) = 1 - \frac{\sum_{f=k}^{F} \binom{N}{f} A_{mean}^{N-f} (1 - A_{mean})^f}{1 - A_{mean}^N \left[1 + \sum_{j=1}^{k-1} \frac{(N - j + 1) \cdot (1 - A_{mean})^j}{A_{mean}^j} \right]} \tag{3.8}$$

3.2.2 Pipe Availability

Similar to Cullinane et al., (1992), the current research considered the availability of pipe *i* as the ratio of the mean time between the failures to the sum of the mean time between the failures and the mean failure duration. With D_i as the diameter (in.) of a pipe *i*, the pipe availability was determined as in Equation (3.9) (Cullinane et al., 1992):

$$A_i = \frac{0.21218 D_i^{1.462131}}{0.00074 D_i^{0.285} + 0.21218 D_i^{1.462131}} \qquad i = 1, 2, \ldots, N \tag{3.9}$$

in which $i = 1, 2, \ldots, N$.

3.3 Case Studies

The developed model was applied to two case studies. Case 1 was a hypothetical small system with few redundancies that was considered representative of water transmission systems. Case 2, an actual WDS that consisted of transmission mains and a low redundancy distribution network, was a relatively small system selected to reduce the computational burden. In practice, multiple failures of transmission pipes are unlikely, and if they should happen, they typically are localized and caused by the same phenomenon (such as a cascading surge failure). The objective of conducting these case studies was not to elucidate the causes of failure but rather to study the system reliability when such failures do occur (even though they may be rare in practice) and to demonstrate deficiencies of the reliability assessment techniques currently available in the literature in providing realistic level of confidence.

3.3.1 Case 1

This hypothetical water supply system delivers water from a reservoir to five consumers. To find the most reliable design, six different layouts (including branched and looped systems) were studied. Figure 3.2 shows schematics of the layouts and nodal demands in L/s (cfs). A 42-m (138-ft) constant-head reservoir is located at node 1. All pipes are 1 km (3,280 ft) in length and 250 mm (10 in.) in diameter with constant Hazen–Williams coefficient of 100. All nodes are at the same elevation. This research applied a minimum residual head of 20 m (66 ft) at each demand node. This case studied multiple simultaneous pipe failures randomly occurring in the system.

3.3.2 Case 2

The second case study focused on the WDS in the city of Hanoi, Vietnam, which has been studied by other researchers (Fujiwara and Khang, 1990; Savic and Walters, 1997; Cunha and Sousa, 1999; Vairavamoorthy and Ali, 2000; Rossmann, 2000). The system consists of 34 pipes, 32 nodes, and 3 loops, with all nodes at the same elevation. A single reservoir located at an elevation of 100 m (328 ft) provides water for the system. Figure 3.3 shows a schematic view of the Hanoi WDS. Nodal demands, lengths and diameters of pipes for the Hanoi WDS are shown in Appendix A, Table A.1 and A.2, respectively. Pipe diameters were chosen using the cross entropy optimization approach (Shibu and Reddy, 2011). In the current research, a minimum residual head of 30 m (98 ft) was applied at each demand node. For this research random and uncorrelated failures for transmission and distribution lines were assumed to be occurring at the same time.

For both cases studies, the modified version of EPANET2 (Pathirana, 2010), was used to simulate system hydraulics. EPANET2, copyright-free software developed by the US Environmental Protection Agency, can be used to determine the hydraulic and water quality conditions in a pressurized WDS. As a demand-driven-based model, EPANET2 determines the nodal pressures by considering the demand at nodal points to be constant. EPANET2, in its original form, is not able to correctly simulate a WDS with low operating pressures. It also provides emitter elements with a pressure-driven model to estimate flow through sprinkler systems and irrigation networks on the basis of pressure. The emitter formula assumes that demand is proportional to the fractional power of the pressure. The modified version of EPANET2 uses the emitter element to estimate the flow at each node on the basis of available pressure. The software then estimates the demands at each node in the next step on the basis of the estimated nodal pressure. This process continues until the point at which no significant changes in demand or nodal pressure are observed (Pathirana, 2010).

3.4 Results and Discussion

3.4.1 Case 1 Results

Equation (3.1) was used to compute system reliability for each design layout of the WDS. Results indicated that all design layouts (even branched systems) proved highly reliable (Figure 3.4). Design 5 was the most reliable (99.99%) and design 3 the least reliable (99.95%). From a practical standpoint, both systems were highly reliable with only a 0.04% difference in reliability. Therefore, in the case of a failure, there is a 99.95% chance that the system would still be able satisfy all consumers, a promising result that offers engineers a high level of confidence. Equation (3.2) was used to compute the tolerance to failure of each design. As shown in Figure 3.5, results indicated that the average tolerance of the system to failure is approximately 76%, with the highest and lowest tolerances at 98% and 54% for designs 5 and 3, respectively. Therefore, in case of at least one failure, on average there is a 76% chance that the system would still be able to satisfy all consumers. Figures 3.4 and 3.5 indicate that all six designs would perform acceptably should failure occur, but the best-performing layout would be design 5.

The effect of simultaneous multiple pipes failures on system reliability was addressed by studying the higher states of reliability (R^2, R^3, R^4, and R^5). Figures 3.6 – 3.9 show results for the second, third, fourth, and fifth state of reliability analyses for all design layouts, with average percentages of 0.03, 4.9×10^{-6}, 3.9×10^{-10}, and 1.3×10^{-14}, respectively. Results indicated that all design layouts would perform poorly in the event of simultaneous multiple pipes failures. In these analyses, design 4 performed more reliably than the other designs, which contrasted with the results of the reliability and failure tolerance analyses that found design 5 to be the best layout.

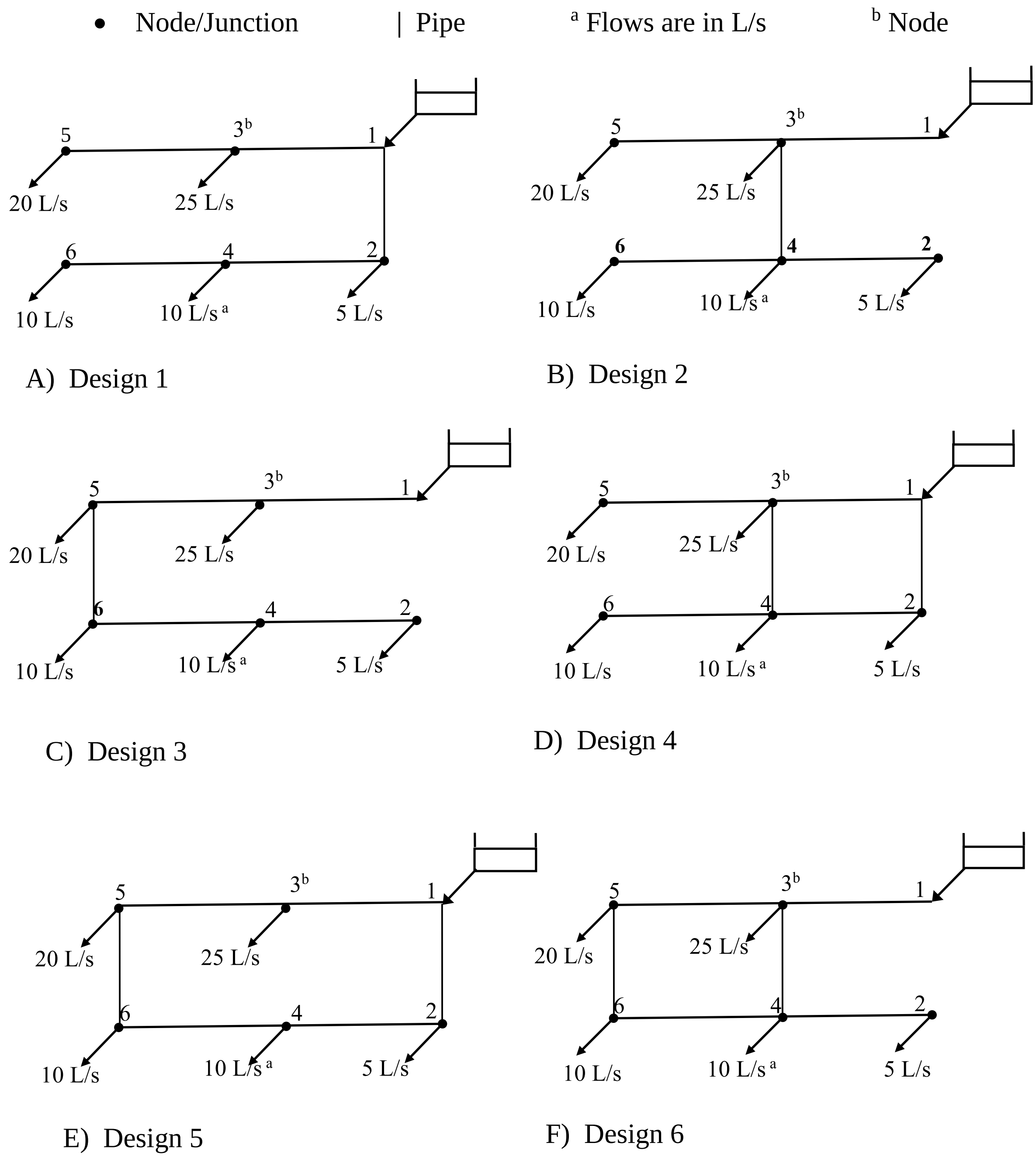


Figure 3.2 Schematic view of six designs for the hypothetical WDS (case 1)

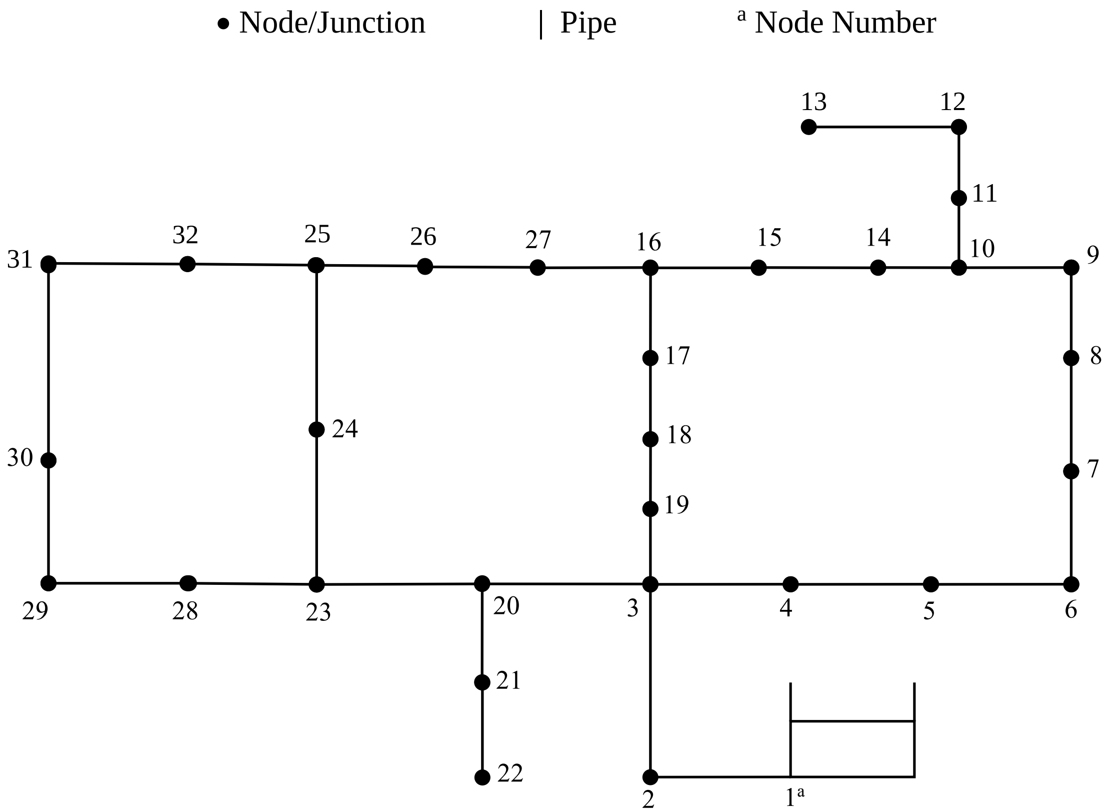


Figure 3.3 Schematic view of the WDS of the city of Hanoi (case 2)

A total of 852 hydraulic simulations were performed to compute various states of reliability for case 1 (Table 3.3). For an actual WDS, the analysis of higher states of reliability is expected to be computationally demanding because of the large computational burden and simulation time. Despite the computational challenges this may cause for an actual WDS, such simulations may prove necessary. Comparing the various states of reliability provides researchers with essential information about the sensitivity of systems to simultaneous multiple pipes failures. A system that may be reliable when a single failure occurs may see its functionality impaired by simultaneous multiple pipes failures. The technique developed in this dissertation can be applied to analyze reliability of an in-practice and full-scale WDS, regardless of system size.

3.4.2 Case 2 Results

Equations (3.1, 3.2, and 3.7) were used to compute reliability, tolerance to failure, and the second and third states of reliability (R^2 and R^3), respectively, for the Hanoi WDS of case 2. Results showed that the tolerance of the system to pipe failure was > 90% and the reliability of the system was > 99.97% (Figure 3.10). Therefore, even in the event of a pipe failure, the damaged system would likely still be able to provide sufficient water to satisfy consumer demand. In contrast, results of the higher states of reliability analysis were not as promising; in the case of three simultaneous failures, system reliability dropped to nearly 75%. In other words, system reliability remains quite high should one pipe fail at a time but decreases noticeably in the case of simultaneous pipe failures. Given that 6,580 simulations were required to perform the second and third states of reliability for this system's hydraulics, the fourth and fifth states of reliability were not determined because of the additional computational burden they would entail.

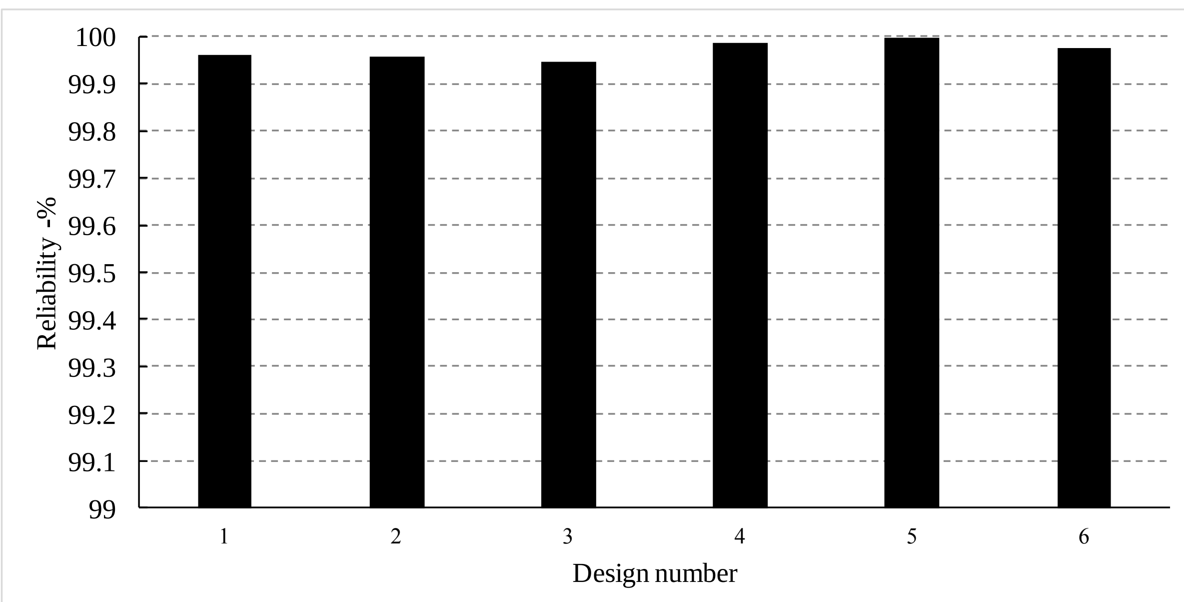


Figure 3.4 Reliability analysis of six designs for the hypothetical WDS (case 1)

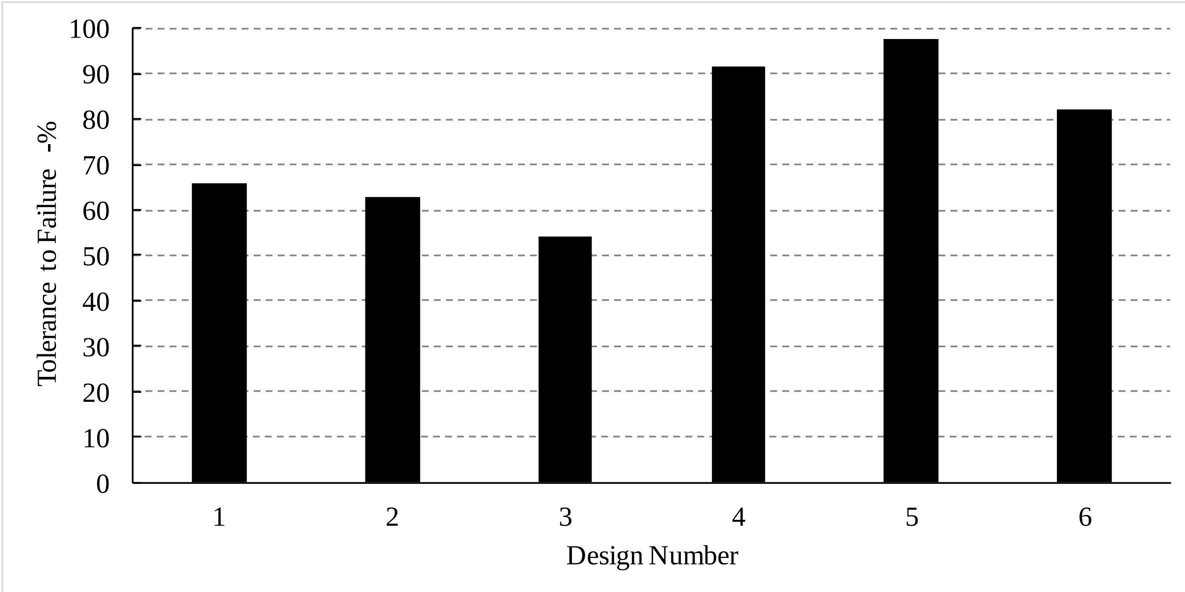


Figure 3.5 Tolerance to failure or first state of reliability (R^1) analysis of six designs for the hypothetical WDS (case 1)

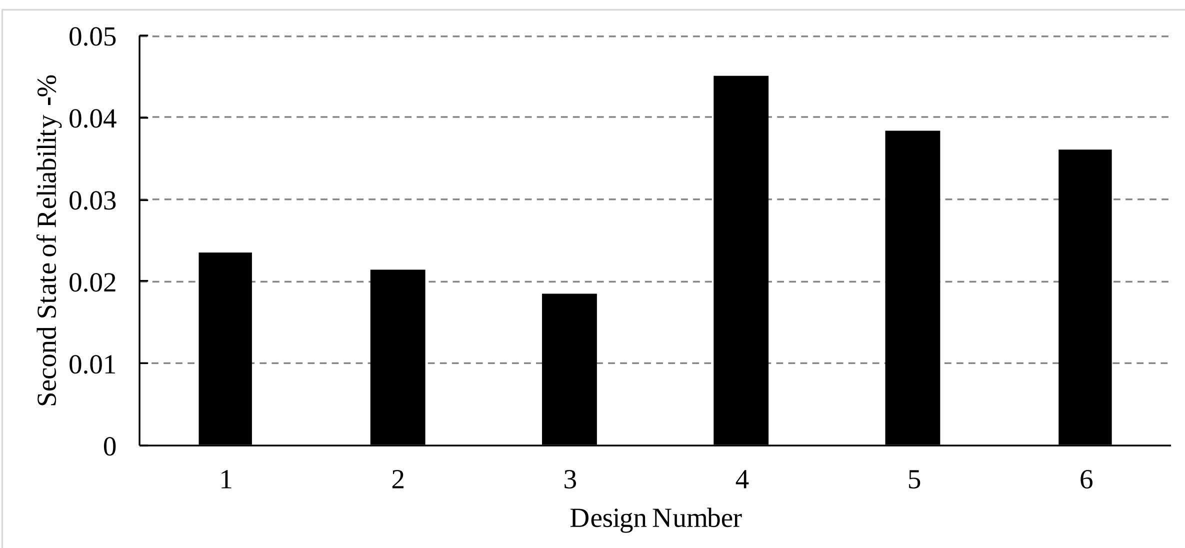


Figure 3.6 Second state of reliability (R^2) analysis of six designs for the hypothetical WDS (case 1)

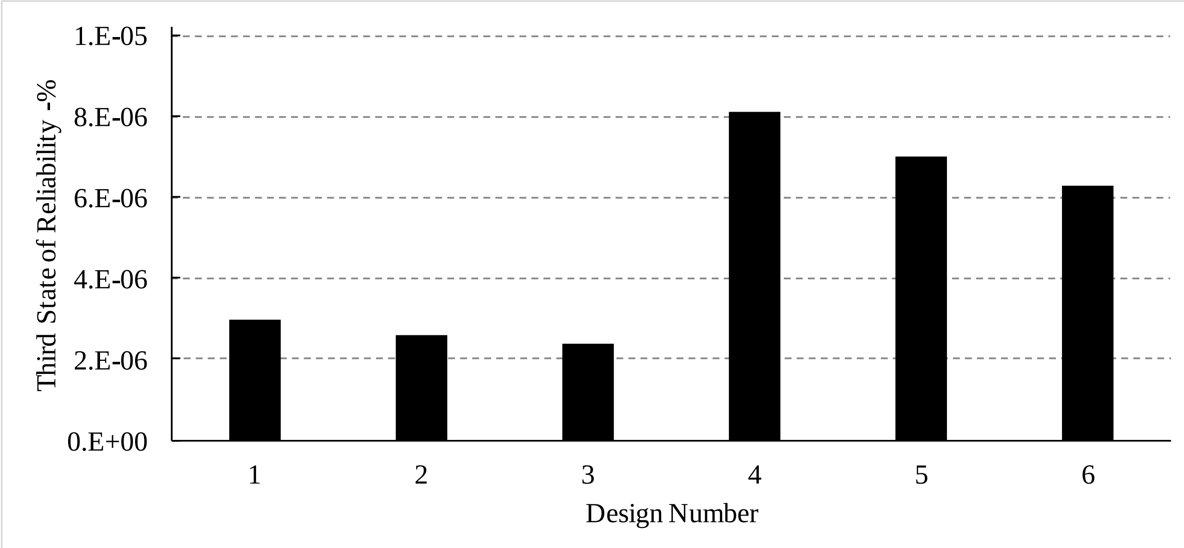


Figure 3.7 Third state of reliability (R^3) analysis of six designs for the hypothetical WDS (case 1)

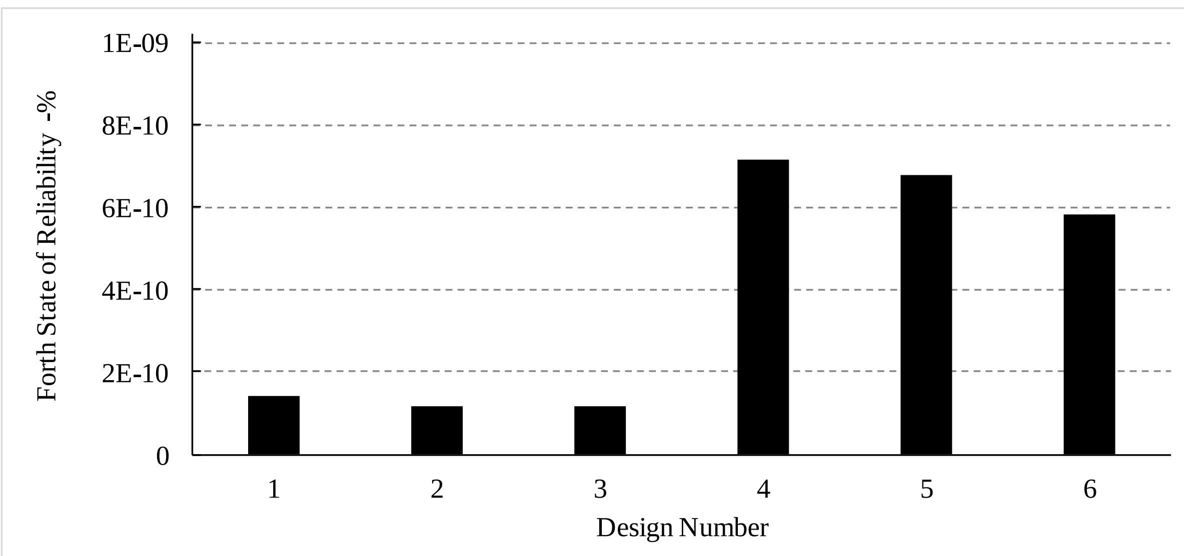


Figure 3.8 Fourth state of reliability (R^4) analysis of six designs for the hypothetical WDS (case 1)

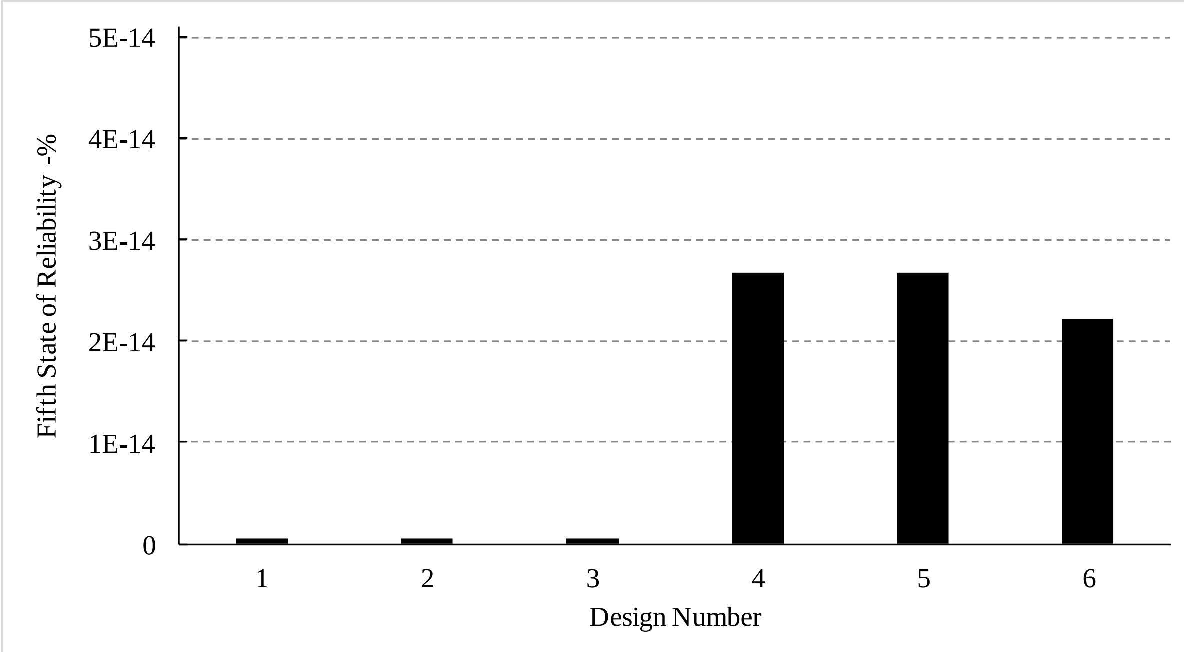


Figure 3.9 Fifth state of reliability (R^5) analysis of six designs for the hypothetical WDS (case 1)

Table 3.1 Number of hydraulic simulations performed for different layouts of the hypothetical WDS (case 1).

Number of Hydraulic Simulations						
Analysis	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Reliability	32	32	32	64	64	64
Tolerance to failure	27	27	27	58	58	58
Second state of reliability	17	17	17	43	43	43
Third state of reliability	7	7	7	23	23	23
Forth state of reliability	2	2	2	8	8	8
Fifth state of reliability	1	1	1	2	2	2

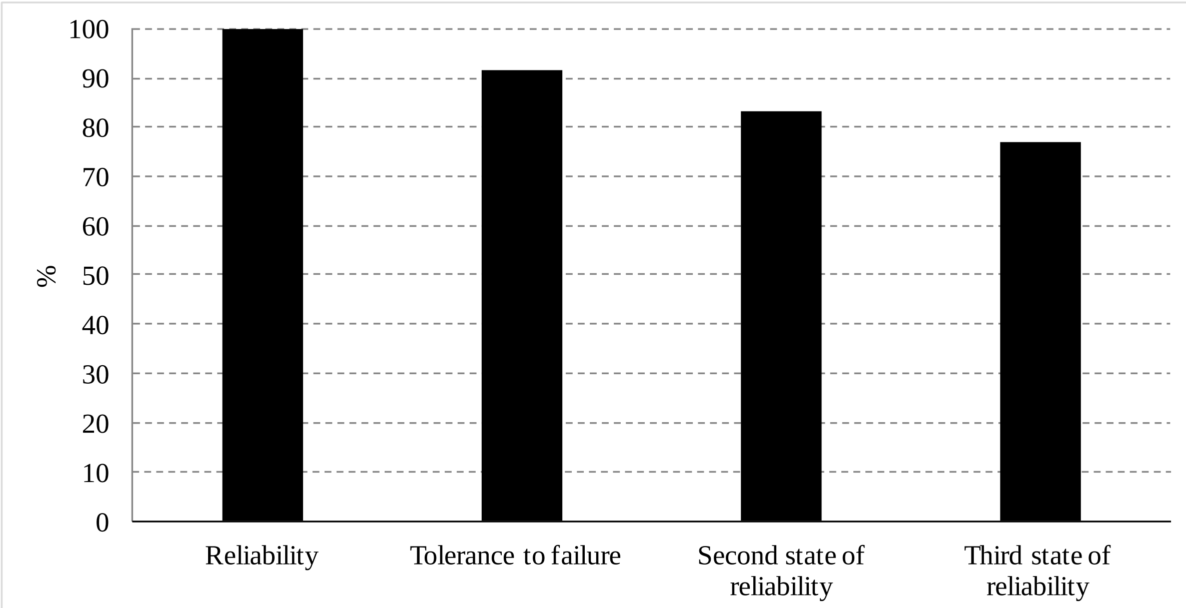


Figure 3.10 Combined analytical results for the WDS of the city of Hanoi (case 2).

3.5 Summary

Multiple pipes failure (i.e., failure that requires repair and closing of cutoff valves) is a phenomenon that has greater likelihood in an older WDS or one located in harsh climatic conditions. Existing reliability assessment techniques are not able to properly analyze the vulnerability of a WDS to simultaneous multiple pipes failures. As a result, use of these assessment techniques can lead researchers to predict an unrealistically higher level of confidence for the system. The current research defined the higher states of WDS reliability, and a set of governing equations was derived. The developed model was used to study the reliability of two cases that included at least some simultaneous multiple pipes failures. The case studies represented transmission as well as distribution parts of a typical water supply system.

Comparing the various states of reliability provided valuable information about the sensitivity of the systems to simultaneous multiple pipes failures. Results for case 1, a hypothetical small system, showed that transmission pipes were reliable when a single failure occurred but were quite sensitive to simultaneous multiple pipes failures. Although the probability of multiple failures of transmission pipes is low, the consequences of any such occurrence could be catastrophic and significantly reduce system reliability. Results for case 2, the Hanoi WDS, indicated that although the reliability of the distribution network did not decline significantly in the event of simultaneous multiple pipes failures, service could be noticeably reduced.

In general, researchers can apply the developed methodology as a complementary approach to check the performance of a WDS in the event of simultaneous multiple pipes failures. Furthermore, analysis of the higher states of reliability for a WDS can be coupled with optimization as a complementary criterion to enhance system design, including such considerations as pipe placement, size, and service area. Unfortunately, the computational workload involved in such analyses can be significant, even for a very small system, and may limit the application of this methodology to simple systems. However, when it is necessary to assess the reliability of a larger WDS in the event of simultaneous multiple pipes failures, the number of computations can be minimized by first evaluating the system for its sensitivity to lower levels of simultaneous pipe failures. If significant decrement in system reliability is observed, then the higher states of reliability should be studied. The current study focused only on pipe failures; further research is needed to analyze WDS reliability when other system components (such as pumps) fail.

Chapter 4: Multiple States Water Distribution System Reliability Analysis[3]

A WDS is a network of various interconnected elements such as tanks, pipes, pumps, joints, and valves comprising a vast variety of mechanical, hydraulic, and electromechanical components. While a WDS is often designed to continuously deliver a demanded amount of water with acceptable quality and adequate pressure to various consumers, it may also have subsidiary intents such as firefighting (Ang and Jowitt 2005). The continuous delivery of water to consumers may be interrupted in some circumstances (i.e., harsh climatic conditions, natural disasters, corrosion, and hydraulic pressures) due to occurrence of a component failure. A failure may undermine the hydraulic integrity of a WDS and drop the pressure at demand nodes. Consequently, consumers may be supplied partially (if not at all). The research reported in this chapter focused on different states of pipe failure based mechanical failure based reliability (subsequently referred to simply as reliability).

4.1 Need for Multiple State Reliability Analysis

While the authorities of a WDS constantly monitor major components such as pumps and storage tanks, other components (pipes, joints, valves, and so on) have more chance of unplanned failure (Perelman and Amin 2014). Interruptions for repair due to unexpected pipe failures is more prevalent in a WDS at advanced state of corrosion, and larger systems with more components are more prone to simultaneous pipe failures (Jacobs and Goulter 1991; Gargano and Pianese 2000). Traditionally, researchers believe that the chance of failure of more than one pipe at a time in a WDS is very little; and therefore, they often consider one

[3] A version of chapter four has been published as a journal article and two conference proceedings. Gheisi, A., and Naser, G. (2015). "Multistate Reliability of Water-Distribution Systems: Comparison of Surrogate Measures." *Journal of Water Resources Planning and Management*, ASCE, 04015018; Gheisi, A., and Naser, G. (2014). "Simultaneous multi-pipe failure impact on reliability of water distribution systems." *Procedia Engineering*, 89, 326-332. *In Proceedings of 16th Conference on Water Distribution System Analysis,* WDSA, Bari, Italy. 14 – 17 July, 2014; Gheisi, A., and Naser, G. (2014). "A surrogate measure for multi-component failure based reliability analysis of water distribution systems." *Procedia Engineering*, 89, 333-338. *In Proceedings of 16th Conference on Water Distribution System Analysis,* WDSA, Bari, Italy. 14 – 17 July, 2014.

pipe failure at a time (Su et al., 1987; Cullinane et al., 1992; Gupta and Bhave 1994; Ostfeld et al., 2002). A pipe failure may lead to simultaneous closure of several pipes due to the location and installation of the cutoff valves in a WDS (Walski 1993). Thus, multi-component failure should be studied carefully.

Jacobs and Goulter (1991) investigated water main failures in the WDS of the city of Winnipeg (Manitoba, Canada) occurred from 1975 to 1984. In the previous chapter, Gheisi and Naser (2014a) analyzed the failure data for the city of Winnipeg and classified the pipe failure combinations into three categories [(1) multiple pipes failure, (2) one pipe failure, and (3) no failure]. They indicated that the WDS was mostly in multiple pipes failure situation when several pipes fail simultaneously in the same calendar day. From 1975 to 1984 the system was in multiple pipes, one-pipe, and no-failure situations at 78.5, 9, and 12.5% of the time, respectively. The research reported in this chapter applied a test case WDS. Knowing the tolerance of WDS to different component failure combinations, the question is how one can judge different states of reliability or identify the most reliable layout for a system. Therefore, multiple criteria decision analysis (MCDA) was applied in this chapter to rank a set of WDS layouts (alternatives) using various states of reliability (criteria). The multiple states reliability assessment considers the relative importance of each state of reliability in finding the most reliable system by applying subjective, objective, and dependency weights.

4.2 A Surrogate Measure for Higher-State Reliability Analysis

Reliability of an urban drinking water sector is highly dependent on vulnerability of distribution section. Other parts of an urban drinking water sector such as treatment and transmission sections commonly receive daily monitoring and are physically/mechanically more secure (Perelman and Amin 2014). Gheisi and Naser (2014a) recently studied WDS reliability under simultaneous multiple pipes failure operating scenario. They showed that the response of a WDS to simultaneous multiple pipes failures cannot be faithfully studied using the currently available reliability assessment techniques as they provide researchers with an erroneous level of confidence. They proposed the higher states of WDS reliability should be considered in design. Despite their usefulness, assessing the higher-states reliability of an in-practice WDS is computationally demanding. Reliability surrogate measures are new techniques to lessen the associated computational burden and assess the reliability of a WDS based on both mechanical and hydraulic uncertainties more easily. Table 4.1 compares commonly used surrogate measures. There are few attempts to find a proper surrogate measure for mechanical and hydraulic failure based reliability assessment (Ang and Jowitt 2005; Raad et al., 2010; Tanyimboh et al., 2011). However, no attention has been paid to higher states of reliability. Relevant literature (Tanyimboh and Templeman 1993, 2000; Tanyimboh and Setiadi 2008; Di Nardo et al., 2010; Tanyimboh et al., 2011) revealed entropy as a better surrogate measure for mechanical failure based reliability assessment of a WDS. However, after more than one decade of research it is not yet clear what the entropy shows in the concept of reliability and how entropy and mechanical uncertainties are related (Ostfeld 2004; Setiadi et al., 2005). Recently, Tanyimboh and Templeman (2000) and Tanyimboh et al., (2011) argued that a design of a WDS with higher amount of statistical entropy is less restricted to any relevant but uncertain information. Recent research (Farmani et al., 2005; Di Nardo et al., 2010; Raad et al., 2010; Baños et al., 2011; Atkinson et al., 2014) showed that a WDS with higher resilience index could deal better with wide range of future hydraulic uncertainties such as demand variation. Atkinson et al., (2014) optimized the total cost of Anytown WDS against the flow entropy and resilience index. They found that the optimized systems with entropy as a surrogate reliability indicator were mechanically more reliable, but they were more expensive and had poor hydraulic and water quality reliabilities. In contrast, optimized systems (considering resilience index as a surrogate reliability indicator) were cheaper and hydraulically more reliable but with limited mechanical reliability. Atkinson et al. (2014) encountered a tradeoff while optimizing the system by simultaneous consideration of entropy and resilience index. They indicated that such optimization for a specific layout is almost impossible. Twort et al. (1994) and Walski (1995) indicated that design of a WDS involves significant hydraulic and mechanical uncertainties including (but not limited to) spatiotemporal variation of nodal demands, random bursts and component failures, and changes in characteristics and performance of components with age. Consequently to have a more flexible design, a WDS should be studied for various future uncertainties and operating conditions. Flexible designs function under a wide range of future uncertainties (De Neufville and Scholtes, 2011). The objectives of this chapter were: 1) to set flow entropy using the concept of higher states of reliabilities, and (2) to find a proper surrogate measure to study the higher states of reliability.

Table 4.1 Summary of surrogate reliability measurement techniques

Technique	Author	Explanation	Strengths/weakness
Statistical Flow Entropy	Awumah et al. (1991) Tanyimboh and Templeman (1993)	Degree of flow uniformity and redundancy in a WDS.	Can be estimated easily by knowing the pipe flow rates.
Resilience Index	Todini (2000)	Surplus power available at demand nodes as a percentage of net input power.	It cannot be applied for a WDS with multiple sources and does not consider redundancy. A WDS with plenty of surplus power may show a low resilience index due to high input power.
Modified Resilience Index	Jayaram and Srinivasan (2008)	Surplus power available at demand nodes as a percentage of required power.	A resilience index independent of input power.
Network Resilience Index	Prasad and Park (2004)	Surplus power available at demand nodes as a percentage of net input power considering reliable loops and redundancy.	A resilience index which consider the effect of redundancy.
A Mixed Reliability Surrogate	Raad et al. (2011)	Mixture of statistical flow entropy approach and resilience index	Consider both flow uniformity and excess power available at demand nodes.

4.3 Methodology

The research reported in this chapter investigated the correlation between the surrogate reliability measures and higher states of reliability of a WDS. Tanyimboh and Templeman (2000) observed a linear relationship between zero state of reliability and entropy of WDS. Following Tanyimboh and Templeman (2000), this study applied Pearson's linear correlation coefficient to investigate the possible linear correlation between the higher states of reliability and flow entropy. Literature provides various applications of statistical flow entropy, resilience index (RI), and network resilience (NR) as reliability surrogate measures (Raad et al., 2010; Tanyimboh et al., 2011). Other measures such as modified resilience index (Jayaram and Srinivasan 2008) and mixed reliability surrogate measure (Raad et al., 2010) can be derived by these measures. Thus, the research reported in this chapter focused on statistical flow entropy, resilience index, network resilience, and various states of reliability as surrogate measures.

4.3.1 Statistical Flow Entropy

While Shannon (1948) introduced the concept of informational entropy as a measure of uncertainty, Awumah et al., (1991) applied the concept to entropic measure of redundancy and flexibility of a WDS. Results indicated that the developed entropic model was capable of recognizing flexible layouts with more redundancy very easily with the least amount of computations. Using Shannon's informational entropy function, Tanyimboh and Templeman (1993a) introduced a methodology to estimate the flow entropy for a single-source WDS. Flow entropy represents pipe flow uniformity in a WDS. A system with higher uniformity is expected to cope better with uncertainties. Knowing the discharge and direction of flow in each pipe, the flow entropy of a single-source WDS was (Tanyimboh and Templeman 1993)

$$\frac{S}{K} = -\sum_{j \in I} \left(\frac{Q_j}{T}\right) \ln \left(\frac{Q_j}{T}\right) - \frac{1}{T} \sum_{j=1}^{J} T_j \left[\left(\frac{Q_j}{T_j}\right) \ln \left(\frac{Q_j}{T_j}\right) + \sum_{i \in N_j} \left(\frac{q_{ij}}{T_j}\right) \ln \left(\frac{q_{ij}}{T_j}\right) \right] \qquad (4.1)$$

where S = entropy; K = positive constant commonly taken as 1 (Ang and Jowitt 2003; Tanyimboh and Templeman 2000); T = amount of water supplied by reservoir (m^3/s); T_j = total incoming discharge to Node j (m^3/s); Q_j = demand or supply at Node j (m^3/s); q_{ij} =

discharge (m^3/s) in Pipe ij; I = set of source nodes; J = number of nodes; and N_j refers to upstream nodes directly connected to Node j. Equation (4.1) is derived for a single-source WDS. When multiple sources feed a system, the proportion of the nodal demand supplied by each reservoir is unknown. Yassin- Kassab et al., (1999) introduced the concept of path probability to estimate the entropy of a WDS while multiple sources exist in the system.

4.3.2 Resilience Index

Todini (2000) divided the total power dissipated in a WDS into the power dissipated in the pipes plus the power delivered to the nodes. When a hydraulic or mechanical failure happens in a WDS, the amount of internal energy losses in the system may increase dramatically depending on the type and position of failure. A WDS with higher surplus power energy is expected to compromise the failures more readily. The resilience index is the ratio of the excess power available in a WDS to the power that should be dissipated in the system to meet the demands (Todini 2000)

$$RI = \frac{\sum_{i=1}^{n_n} Q_i^{req}(H_i - H_i^{req})}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} \frac{P_j}{\gamma} - \sum_{i=1}^{n_n} Q_i^{req} H_i^{req}} \tag{4.2}$$

where Q_i^{req} is the water demand (m^3/s) at node i; H_i is the pressure head at node i (m); H_i^{req} is the minimum head (m) required at node i; Q_k is the flow (m^3/s) provided by reservoir k (Q_k is equal to T when there is just one reservoir in the system); H_k is head (m) at reservoir k; P_j is the power (N.m/s) of the pump j; γ is the specific weight (N/m^3) of water; n_n, n_r and n_p are the number of demand nodes, reservoirs and pumps, respectively.

4.3.3 Network Resilience

Degree of redundancy in a WDS is a significant parameter, and sufficient head at demand nodes cannot always guarantee a reliable system. A pipe outage in a branched WDS with sufficient surplus power energy could leave several downstream consumers without water (Prasad and Park 2004). To consider redundancy, Prasad and Park (2004) incorporated the concept of diameter uniformity of pipes ending at the same node and reliable loops into the

Todini (2000) concept of resilience index. Calculated for each node, the index shows the ratio of pipes diameter connected to a node to the maximum diameter ending at that node. Higher uniformity index UN_i (with respect to Node i; dimensionless) shows that the pipes connected to a node are not widely dispersed in diameter, and that may guarantee the higher redundancy and existence of reliable loops in the system (Todini 2000). The network resilience was formulated as (Prasad and Park 2004)

$$NR = \frac{\sum_{i=1}^{n_n} UN_i Q_i^{req}(H_i - H_i^{req})}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} \frac{P_j}{\gamma} - \sum_{i=1}^{n_n} Q_i^{req} H_i^{req}} \tag{4.3}$$

4.3.4 Water Distribution System Reliability

The research reported in this chapter applied the technique initially proposed by Gargano and Pianese (1998) for reliability assessment of a WDS. The technique has several advantages. It considers all possible pipe-failure combinations, temporal and spatial variations of demands, as well as estimating the reliability of a system when the pressure is insufficient to thoroughly satisfy the consumer demands. The technique was employed subsequently (Gargano and Pianese 2000; Tanyimboh et al., 2001; Kalungi and Tanyimboh 2003; Surendran et al., 2005; Gheisi and Naser 2013) to address different states of reliability as discussed next.

Zeroth-state reliability, $R^{(0)}$, of a WDS was estimated as a weighted mean of performance indices of the system (Gheisi and Naser 2013)

$$R^{(0)} = PI(0)\cdot P(0) + \sum_{a=1}^{N} PI(a_1)\cdot P(a_1) + \sum_{a=1}^{N-1}\sum_{b=a+1}^{N} PI(a_1,a_2)\cdot P(a_1,a_2) + \frac{1}{2}\left(1 - P(0) + \sum_{a=1}^{N} P(a_1) + \sum_{a=1}^{N-1}\sum_{b=a+1}^{N} P(a_1,a_2)\right) \tag{4.4}$$

where N = the number of pipes in the WDS; PI(0), $PI(a_1)$, $PI(a_1,a_2)$, and $PI(a_1,a_2,\ldots)$ = WDS performance indices when zero, one, two, and more than two pipes are unavailable at the same time; and P(0), $P(a_1)$, $P(a_1,a_2)$, and $P(a_1,a_2,\ldots)$ are the weighting coefficients defined as the probability of a WDS with zero, one, two, and more than two simultaneous pipe failure(s), respectively.

First-state reliability, $R^{(1)}$, measures the capability of a WDS to do its task when at least one component is out of service (Tanyimboh and Templeman, 1998). Tanyimboh et al.

(2001) and Martínez-Rodríguez et al. (2011) noted that $R^{(1)}$ can provide a better measure for performance and redundancy of a WDS than $R^{(0)}$, particularly when the WDS is very reliable. Using Equation (4.4), $R^{(1)}$ was (Tanyimboh et al., 2001; Kalungi and Tanyimboh, 2003):

$$R^{(1)} = \frac{R^{(0)} - P(0) \cdot PI(0)}{1 - P(0)} \tag{4.5}$$

Higher-state reliabilities were determined using weighted mean of the system's performance indices for typical pipe failure combinations (Gargano and Pianese 2000; Tanyimboh et al., 2001; Gheisi and Naser 2013). As shown in the previous chapter, Gheisi and Naser (2014a) combined the reliability assessment techniques proposed by Gargano and Pianese (2000) and Tanyimboh et al. (2001) to derive higher-state reliabilities. In accordance with Gheisi and Naser (2014a), the k^{th} state reliability, $R^{(k)}$, was

$$R^{(k)} = \frac{\sum_{j=k}^{F}\left[\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j)\cdot P(a_1,\ldots,a_j)\right]}{1-P(0)-\sum_{j=1}^{k-1}\left(\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} P(a_1,\ldots,a_j)\right)} + \frac{1}{2} - \left[\frac{\sum_{j=k}^{F}\left[\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j)\right]}{2\left(1-P(0)-\sum_{j=1}^{k-1}\left(\sum_{a_1=1}^{N-j+1}\sum_{a_2=a_1+1}^{N-j+2}\cdots\sum_{a_j=a_{j-1}+1}^{N} P(a_1,\ldots,a_j)\right)\right)}\right] \tag{4.6}$$

where $R^{(k)}$ = probability of delivering demands when at least k (>2) number of pipes fails simultaneously; and F = number of component failure combinations.

The availability (A) and unavailability (U) of Pipe i (A_i; $U_i = 1 - A_i$) were applied to estimate probability of different pipe failure combinations (Fujiwara and De Silva 1990; Fujiwara and Tung 1991)

$$P(0) = \prod_{i=1}^{N} A_i \tag{4.7a}$$

$$P(a_1) = P(0)\frac{U_{a_1}}{A_{a_1}} \tag{4.7b}$$

$$P(a_1, a_2) = P(0)\frac{U_{a_1}U_{a_2}}{A_{a_1}A_{a_2}} \tag{4.7c}$$

and so on, where A_{a1} , A_{a2} (and so on), and U_{a1} , U_{a2} (and so on) = availability and unavailability of Pipes a_1; a_2, … , and so on; and Π is the product operator; and i = pipe number. Cullinane et al. (1992) divided the whole lifetime of a pipe into two parts, as follows: (1) time when the pipe is in operation (time between the failures), and (2) time when the pipe is failed and need to be replaced or fixed. They defined the availability of Pipe i as the ratio of the time when the pipe is in operation to the whole lifetime of the pipe. Given D_i as the diameter (in meters) of Pipe i, the research reported in this dissertation determined the availability of Pipe i as (Cullinane et al., 1992)

$$A_i = \frac{45.60858\, D_i^{1.462131}}{0.00211\, D_i^{0.285} + 45.60858\, D_i^{1.462131}} \qquad i = 1, 2, \ldots, N \qquad (4.8)$$

4.3.5 Multiple Criteria Decision Analysis

Engineers and researchers require various states of reliabilities for designing the most reliable layout of a WDS. A multiple criteria decision analysis can assist them with ranking a set of distribution layouts (alternatives) using various states of reliabilities (criteria). To rank the layouts, the research reported in this study applied three MCDA methods including (1) weighted sum model (WSM; Fishburn 1967), (2) weighted product model (WPM; Bridgman 1922; Miller and Starr 1969), and (3) technique for order of preference by similarity to ideal solution (TOPSIS; Hwang and Yoon 1981). MCDA methods of WSM, WPM and TOPSIS were employed in this study due to their computational simplicity and the robustness of their results (Jiang et al., 2011).

A MCDA requires assigning a proper weight to each decision criterion. Weights demonstrate significance of each criterion and its contribution in final decision. Assigned weights are subjective, objective, independency and combinative weights. Subjective weights are chosen based on the judgment and expertise of the decision makers. Objective weights are determined without considering preference of decision makers. Relative literature provides various techniques to model objective weights. The list includes (but not limited to) mean weight method (Deng et al., 2000), SD method (Diakoulaki et al., 1995), preference selection index method (Maniya and Bhatt 2010), and entropy approach (Hwang and Yoon 1981). Initially introduced by Shannon (1948) and subsequently developed by Hwang and Yoon (1981), the research reported in this study applied entropy concept to assign the objective weights. This was mainly because of the following: (1) it is not affected by the scales and dimensions of criteria, (2) it has strong structure for weight assignment, (3) it computes weights based on degree of dispersion or scattering in rating each criterion, (4) it may not end up with negative meaningless weights, and (5) it measures the amount of information content and uncertainties in each normalized criterion (Jahan et al., 2012). To compute objective weights, initially each state of reliability (criteria) of layouts (alternative) was normalized. Normalization eliminated any inconsistencies in alternatives due to different probable scales or units and made them comparable. In the next step, the amount of entropy in each alternative was computed using Shannon's entropy function and then summed up for each criterion to calculate the amount of entropy for each criterion. The amount of dispersion or scattering in each criterion was then computed by decreasing one from the amount of entropy computed in previous step for each criterion. Then, the objective weight for a criterion was defined as the ratio of the amount of dispersion for that specific criterion to the total dispersion for all criteria (Hwang and Yoon 1981).

Jahan et al. (2012) applied independency weights to lessen the effect of possible correlation among criteria. A criterion with higher correlation should contribute less in decision making process and receive less independency weight. To compute the independency weights, initially the inter-correlation for each pair of criteria was computed. Then, the disassociation between each two criteria was estimated as correlations minus 1. The disassociation values were then summed up for the alternatives of each criterion and normalized to compute independency weigh for the criterion (Jahan et al., 2012).

Combinative weights consider all subjective, objective, and independency weights simultaneously. The research reported in this study applied the combinative weighting approach by Jahan et al. (2012). Thus, the normalized geometric mean of all weights was assigned as the combinative weight to each criterion.

4.4 Test Case

In accordance with the relevant literature (Awumah et al., 1991; Tanyimboh and Templeman, 2000; Tanyimboh et al., 2011), the research reported in this chapter tested the hypothetical WDS of Figure 4.1. In Figure 4.1, dashed line indicates the link between two nodes. All the nodes have identical elevation of 0 m. Each pipe is 1-km long with a Hazen–Williams coefficient of 130. Pipe diameters vary from 100–405 mm. Table B.1 in Appendix B provides further information. The piezometric head at the source (Node 1) is 100 m. However, to prevent redundancy in the form of surplus pressures at demand nodes oversized pipes were avoided (Tanyimboh and Templeman, 2000). To meet the nodal demands, the minimum residual head was set at 30 m. To supply demands to hypothetical consumers, a set of 22 looped layouts with maximum flow entropy and minimum cost was studied (Figure 4.2).

Hydraulic simulation of the layouts was performed using the modified version of EPANET2 developed by Pathirana (2010). Failure may drop the pressure less than the minimum required residual head, and the original version of EPANET2 is not able to simulate a system in pressure-deficient conditions. The modified version of EPANET2 is a pressure-driven model that estimates the deliverable flow by using the available pressure at each node and the emitter function (Pathirana 2010).

The same performance indices were applied for all layouts to measure the performance of the layouts under different pipe failure scenarios. A performance index (PI) quantifies the fraction of demand supplied to users. Thus, it was computed as the ratio of volumes of water supplied by the WDS to the actual required demand thorough different pipe failure combinations when zero, one, two, and more than two pipes are unavailable at the same time (Wagner et al., 1988; Gupta and Bhave 1994; Gargano and Pianese 2000).

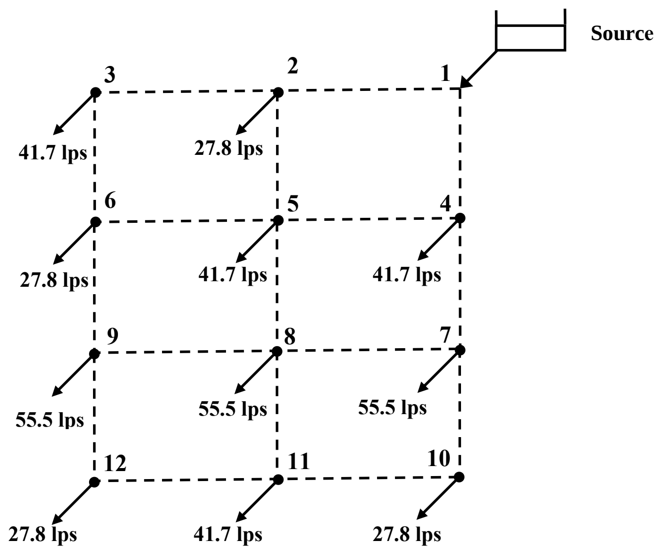


Figure 4.1 Schematic view of the hypothetical WDS from © Tanyimboh, T. T., and Templeman A. B. (2000). "A quantified assessment of the relationship between the reliability and entropy of water distribution systems." *Engineering Optimization*, *33*(2), 179-199. Page 187. Adapted with permission from publisher Taylor & Francis Ltd.

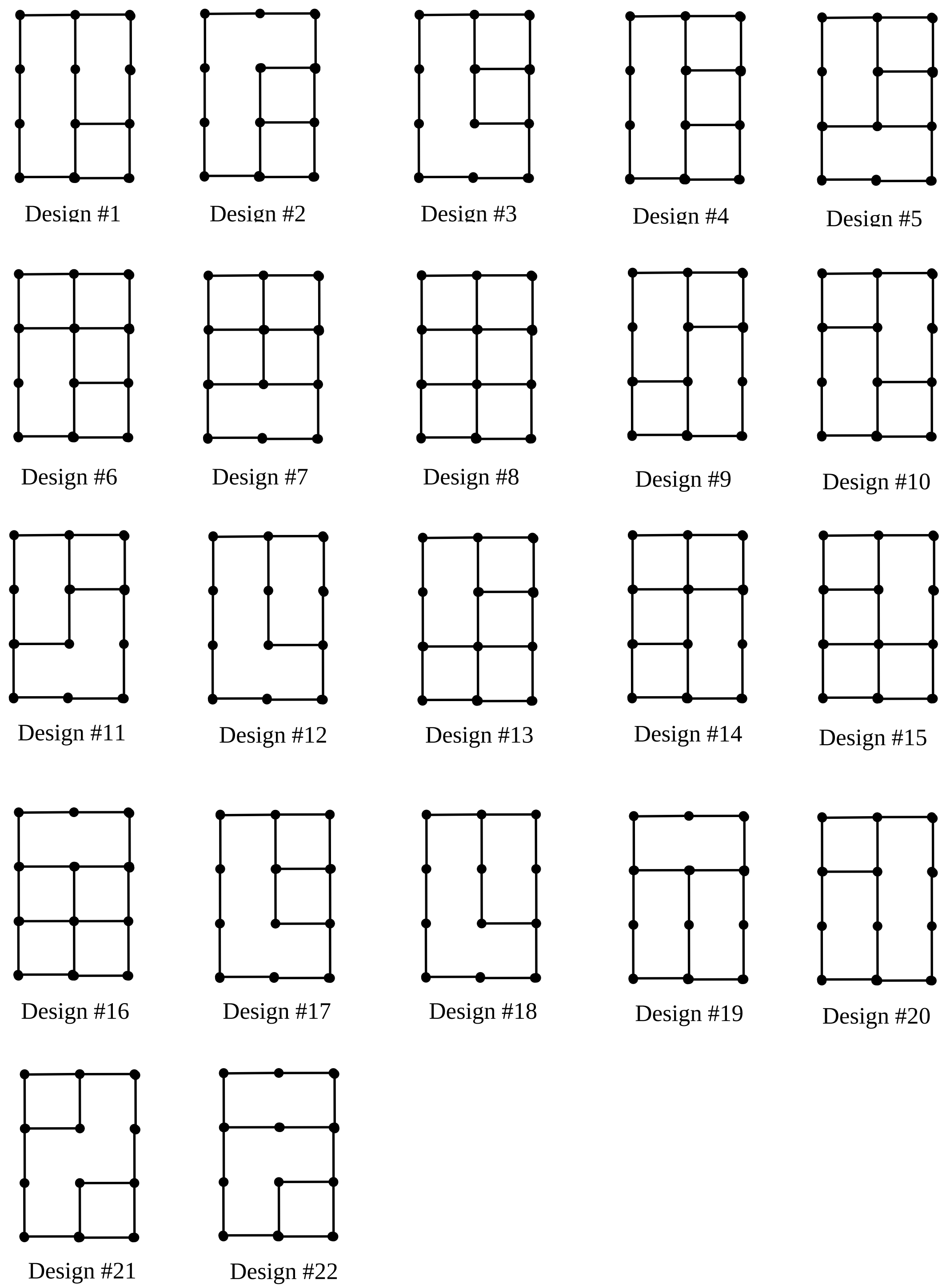


Figure 4.2 Set of 22 designs for the hypothetical WDS from © Tanyimboh, T. T., and Templeman A. B. (2000). "A quantified assessment of the relationship between the reliability and entropy of water distribution systems." *Engineering Optimization*, *33*(2), 179-199. Pages 188 to 190. Adapted with permission from publisher Taylor & Francis Ltd.

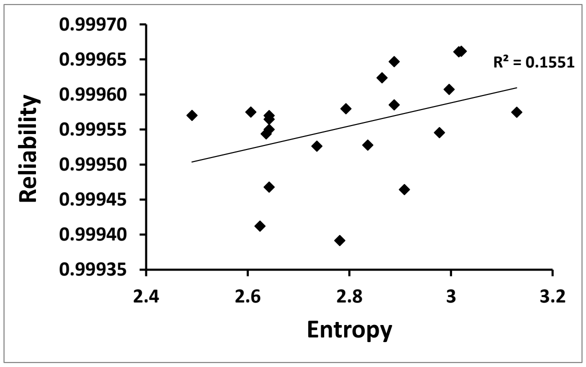
4.5 Results and Discussion

Surrogate reliability measures (flow entropy, resilience, and network resilience indices) and zeroth, first, and second states of reliability were calculated for each design layout (Figure 4.2). Boxplot test was used to detect the possible outliers in the calculated data (Dawson, 2011). Moreover, Anderson–Darling (AD) test (Anderson and Darling, 1952) was employed to test how well the data follow the normal distribution. AD test is a powerful statistical tool to check the normality of any given sample of data (Stephens, 1974). Figures C.1 to C.6 in Appendix C show the result of AD normality test. Higher probability value (P-value) obtained for each AD normality test provides weaker evidence against the null hypothesis of data following a normal distribution. Results of AD tests of normality (Figures C.1 to C.6 in Appendix C) reveal that all measured data are normally distributed with P-value more than 0.05. Figures 4.3(a–i) compare surrogate reliability measures against zeroth, first, and second states of reliability. Figures 4.3(a–i) also indicate the best fit to the data along with coefficient of determination (R^2). The linear correlation coefficient (R) was also computed and the results are provided in Table 4.2. Table 4.3 indicates P-values, which test the null hypothesis of no correlation (R=0). A low p-value (< 0.05) shows that the null hypothesis can be rejected and the relationship is statistically significant (Draper and Smith, 1998). As Figure 4.3, Table 4.2 and Table 4.3 indicate, entropy demonstrates a more convincing correlation with different states of reliability than resilience and network resilience indices. While this finding is in harmony with the literature (Tanyimboh and Templeman 2000; Tanymboh et al., 2011), the correlation is dramatically growing by increasing the state of reliability. This is a fact that has not been observed in the literature. The higher states of reliability show stronger positive correlation with statistical flow entropy. This implies that entropy is a better representative for higher states of reliability. A WDS with higher entropy is expected to cope better with higher states of mechanical uncertainties such as simultaneous failure of several pipes in the system. This might explain why it is not yet clear how entropy and mechanical reliability are related as no attention has been paid to higher states of reliability. The weak negative correlation (Figure 4.3; Table 4.2; Table 4.2) between higher states of reliability and network resiliency of the systems is also surprising. There is no specific correlation between reliability and resilience or network resilience indices. As the state of reliability increases a negative correlation appears which is more evident and statistically significant for network resilience index. This negative correlation becomes stronger for the higher states of reliability. This may explain the tradeoff that Atkinson et al. (2014) faced with while optimizing their systems by considering entropy and resiliency simultaneously. Entropy has a positive correlation with reliability but network resiliency demonstrates a negative tendency. Therefore, optimizing a WDS considering simultaneously entropy and network resiliency indicators is almost impossible.

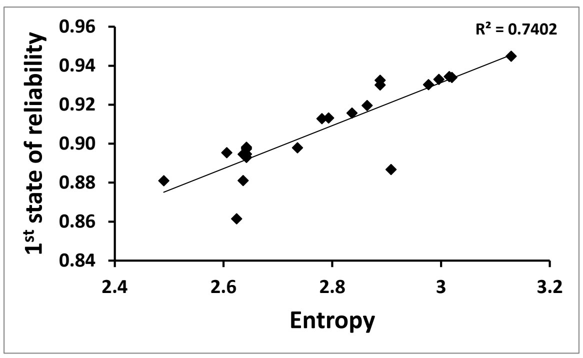
The research reported in this study employed MCDA to rank a set of WDS layouts and to find the most reliable layout. The objective weight to each criterion was computed and the results are shown in Table 4.4. As the table indicates, the minimum weight is associated with the zeroth state of reliability. The weights increased by increasing the state of mechanical reliability with the highest weight for flow entropy. Results of assigning objective weights to criteria using entropy approach revealed that higher states of reliabilities had more contribution in reliability ranking than the lower states. This happened since the amount of dispersion in higher states of reliability was more than that in the lower states. In case of higher states reliability, any small modification in WDS layouts could lead to significant changes in system reliability. In contrast, in lower states reliability, any significant modification in WDS layouts might lead to very small changes in reliability of the system. Therefore, higher states of reliability are more important and should receive higher objective weight in MCDA.

Subjective weights were not studied due to lack of information about type and number of failure for the test case. However, this can be easily adjusted if such information exists for an in-practice WDS. In accordance with Jahan et al. (2012), the independency weights were also computed based on the amount of correlation that exists among the criteria and the results are given in Table 4.4. The zeroth-state reliability had the highest independency weight. The zeroth-reliability received the least amount of correlation or the highest amount of disassociation with other criteria. Criterion with less correlation with the other criteria is more important and should receive higher independency weight in MCDA. The independency weights were smaller for entropy, second, and first states of reliability. Table 4.4 also reveals the overall weights computed by combining assigned weights. The higher overall weights were assigned to higher states of reliabilities. This implies that the higher state of reliability should have more contribution in decision-making process when system reliability is a concern. This is important as researchers often consider one pipe failure at a time when assessing WDS reliability.

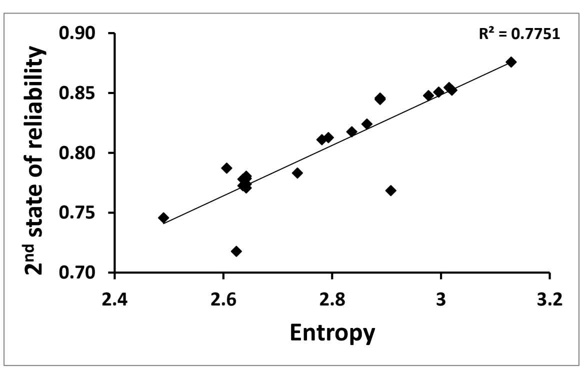
Using the three MCDA methods [(1) WSM, (2) WPM, and (3) TOPSIS], the layouts for the test case were scored and ranked. Table 4.5 compares the results of MCDA with those for reliability or entropy techniques. Table 4.5 indicates fairly identical results for the three MCDA techniques. While the ranking outcomes of MCDA techniques were comparable to higher-state reliability-based rankings, they were very different from the results for the zeroth-state reliability. Discrepancies were more noticeable in less reliable layouts with less number of pipe connections. Table 4.5 also reveals that while entropy was incapable of properly differentiate layouts with low-order reliability, it could fairly identify layouts when several pipes of the system fail at the same time.


Reliability
Entropy
R² = 0.1551
0.99970
0.99965
0.99960
0.99955
0.99950
0.99945
0.99940
0.99935
2.4
2.6
2.8
3
3.2

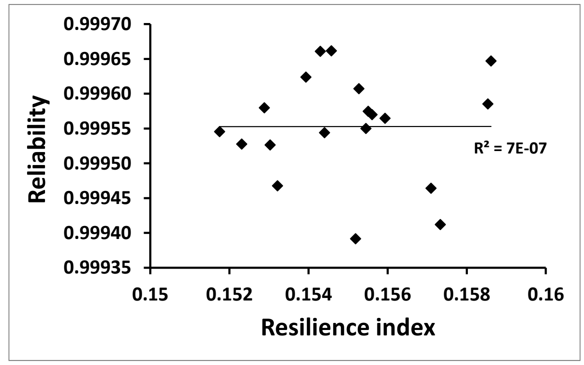
a)


1st state of reliability
Entropy
R² = 0.7402
0.96
0.94
0.92
0.90
0.88
0.86
0.84
2.4
2.6
2.8
3
3.2

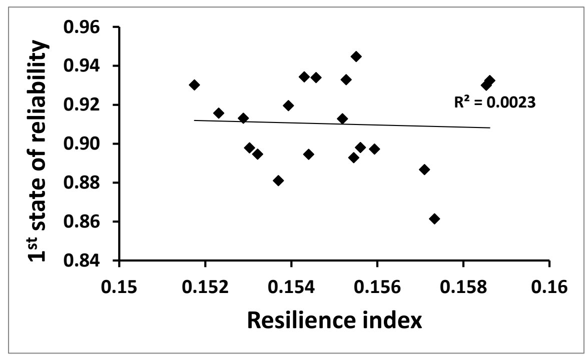
b)


2nd state of reliability
Entropy
R² = 0.7751
0.90
0.85
0.80
0.75
0.70
2.4
2.6
2.8
3
3.2

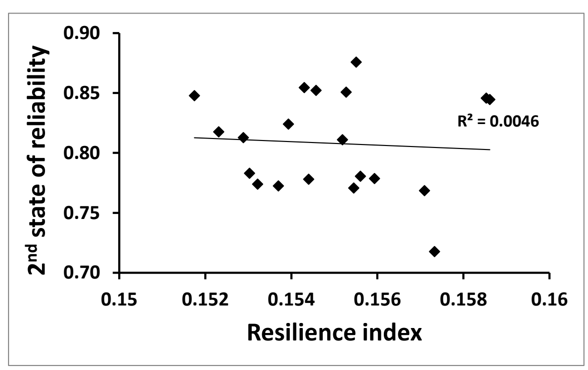
c)


Reliability
Resilience index
R² = 7E-07
0.99970
0.99965
0.99960
0.99955
0.99950
0.99945
0.99940
0.99935
0.15
0.152
0.154
0.156
0.158
0.16

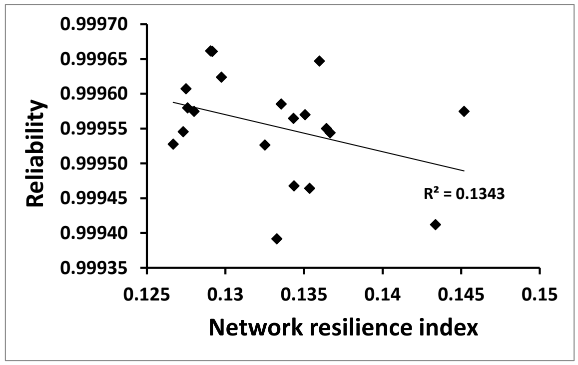
d)


1st state of reliability
Resilience index
R² = 0.0023
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.15
0.152
0.154
0.156
0.158
0.16

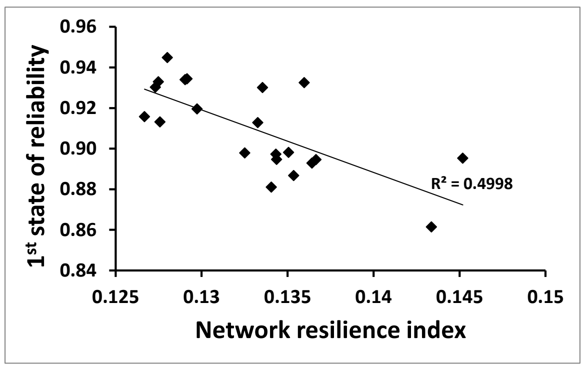
e)


2nd state of reliability
Resilience index
R² = 0.0046
0.90
0.85
0.80
0.75
0.70
0.15
0.152
0.154
0.156
0.158
0.16

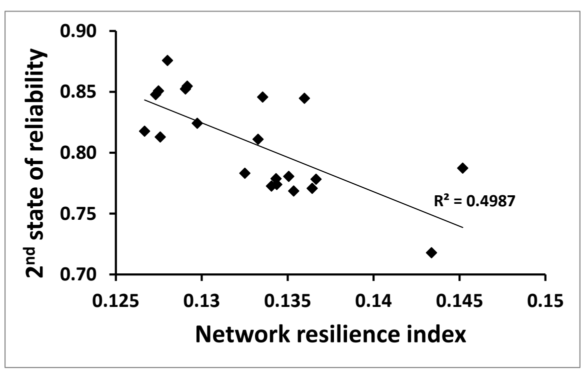
f)



g)



h)



i)

Figure 4.3 Plots of surrogate reliability measures against different states of reliability

Table 4.2 Correlation among surrogate reliability measures and different states of reliability

Surrogate Measures	Zeroth Reliability	First Reliability	Second Reliability
Entropy	0.39	0.86	0.88
Resilience Index	0.00	-0.05	-0.07
Network Resilience Index	-0.37	-0.71	-0.71

Table 4.3 P-values to test the null hypothesis of no correlation (R=0)

Surrogate Measures	Zeroth Reliability	First Reliability	Second Reliability
Entropy	0.077	0.000	0.000
Resilience Index	0.997	0.840	0.776
Network Resilience Index	0.112	0.000	0.000

Table 4.4 Assigned weight to each criterion

Assigned Weight	Zeroth Reliability	First Reliability	Second Reliability	Entropy
Dependency Weights	0.423	0.158	0.174	0.246
Objective Weights	1.564×10^{-6}	0.084	0.375	0.540
Overall Weights	0.001	0.157	0.347	0.495

Table 4.5 Ranking WDS layouts based on higher states of reliability, entropy and MCDA

Design Number	Rank Number						
	Zeroth Reliability	First Reliability	Second Reliability	Entropy	WSM	WPM	TOPSIS
1	15	17	16	14	16	16	16
2	22	20	18	14	20	20	20
3	8	15	12	16	18	18	19
4	7	10	10	10	10	10	11
5	16	9	9	9	9	9	9
6	1	3	3	2	3	3	2
7	14	6	5	5	5	5	5
8	9	1	1	1	1	1	1
9	4	8	8	8	8	8	8
10	21	11	11	11	11	11	12
11	17	13	13	12	13	13	13
12	10	21	21	17	22	22	22
13	5	4	4	4	4	4	4
14	2	2	2	3	2	2	3
15	3	5	7	7	7	7	7
16	6	7	6	7	6	6	6
17	19	19	20	6	12	12	10
18	20	22	22	15	21	21	21
19	11	12	14	13	14	14	14
20	18	16	17	13	17	17	17
21	13	18	19	13	19	19	18
22	12	14	15	13	15	15	15

4.6 Summary

This chapter compared various reliability measures and ultimately proposed a proper surrogate measure to study the higher states of reliability when there were at least some simultaneous multiple pipes failures in the system. The results revealed that statistical entropy had a stronger correlation with higher states of reliability. Therefore, a system with higher entropy could cope better with higher states of uncertainties such as simultaneous failure of several pipes in the system.

Knowing the tolerance of WDS to different component failure combinations, the question is how one can judge different states of reliability or identify the most reliable layout for a system. MCDA was applied to rank a set of distribution layouts using various states of reliabilities. Subjective and objective weights of criteria were applied reflecting the relative importance of each criterion in the decision making process. Results of assigning objective weights to criteria using entropy approach revealed that higher states of reliabilities had more contribution in reliability ranking of WDS when compared with the lower states of reliabilities. Additionally, the zeroth state of reliability had the highest independency weight with the least correlation with other criteria. Subsequently, entropy, first, and second states of reliability obtained less independency weights. Results of weighting assignment to criteria showed that the higher overall weights were related to higher states of reliabilities. As such, higher state of reliability should receive more attention by decision makers.

In practice, MCDA can provide more convincing results as it considered various states of reliability and flow entropy at the same time. Moreover, it is capable of incorporating the judgment and expertise of the designers/engineers in choosing more reliable layouts using the subjective weights when there is sufficient information about the type and number of failures. In order to obtain an optimal layout, the tradeoff between WDS reliability and cost should be taken into consideration. Moreover, the test case in the research reported in this study was highly simplistic and it could be very informative to demonstrate the robustness of the developed approach by its application to an in-practice WDS.

Chapter 5: Multiple Aspect/Multiple States Water Distribution System Reliability Analysis[4]

A municipal water supply system is responsible for supplying residential and nonresidential water demands. It is typically comprised of infrastructures for collection, treatment, transmission, storage, and distribution of water. Among these, a water distribution system (WDS) is the most vulnerable with the least amount of protection. Being laid out over vast areas with a large number of exposed components, it is difficult (if not impossible) to regularly monitor a WDS. Other infrastructures such as treatment plants, transmission mains and storage tanks are more secure due to regular monitoring (Fragiadakis et al., 2013; Perelman and Amin, 2014). A WDS is a complex network with vast variety of mechanical, hydraulic and electromechanical interconnected components. Key components of an urban WDS are distribution pipes, pumping stations, and storage tanks (Cullinane et al., 1992). Pumping stations often include back-up pumps that provide more security to the system in emergency situations when regular pumps fail to operate. Storage tanks and pumping stations receive regular monitoring, while distribution pipes do not (Watson et al., 2001; Perelman and Amin, 2014). This makes distribution pipes be the most vulnerable part of an urban WDS, while they constitute the major portion of capital cost of a WDS. Focusing on pipe failure, this chapter studied WDS reliability when failure/break occurs at pipes.

5.1 Need for Multiple Aspects Reliability Analysis

Pipe failure in a WDS may happen at different states with one failure, two simultaneous failures, three simultaneous failures and so on known as failures of state one, two, three and

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[4] A small version of chapter five has been published in a conference proceeding. A more thorough version submitted for publication in the journal of Reliability Engineering and System Safety. It is currently under review. Gheisi, A., and Naser, G. (2015). "Multi-aspect Performance Analysis of Water Distribution Systems under Pipe Failure." *Procedia Engineering*, 119, 158-167. *In Proceedings of 13th Computer Control for Water Industry Conference*, CCWI 2015, Leicester, UK. 2 – 4 September, 2015; Gheisi, A., Lê, C., and Naser, G. (2015). "Water Distribution System Reliability – Multiaspect/Multistate Analyses." *Reliability Engineering & System Safety*, Manuscript No. RESS-D-15-00791.

so on (Soltanjalili et al., 2011; Gheisi and Naser, 2014a, b and c). A specific state of pipe failure in a WDS could have several simultaneous impacts on the performance of the system from different aspects (e.g. quantity and/or quality of delivered water, water leakage, etc.). Accordingly, the reliability of a WDS can be evaluated in various aspects. Existing techniques for reliability analysis are unable to demonstrate these simultaneous impacts. Tanymboh et al. (2001) indicated that a comprehensive WDS reliability analysis should be able to study the variation in flow, pressure, leakage, and other relevant factors caused by a failure. Appling a specific performance index, engineers used to evaluate the performance of a WDS in one aspect or two aspects separately (Ostfeld et al., 2002, 2004; Kansal et al., 2004). Such techniques are unable to demonstrate the interactions that may exist among various aspects. Bertola and Nicolini (2006) proposed a WDS reliability analysis considering flow and leakage variations. They conducted reliability and efficiency analysis separately and estimated the overall performance of WDS as the product of reliability and water-leakage-based efficiency. They concluded that applying a single performance index in reliability analysis did not guarantee the long-term reliable operation of the system. For example, a WDS with low efficiency suffers from high amount of water leakage, which could not be distinguished in a single-aspect reliability analysis. Gupta et al. (2009) employed a single performance index representing the hydraulic and water quality condition of a WDS. They defined the performance index as the ratio of total delivered to total demanded water with acceptable quality at demand nodes. Using fuzzy sets to aggregate the level of service received by consumers from different aspects, Shafiqul Islam et al. (2014) developed a novel technique to determine overall reliability of a WDS. They aggregated the water utilities' indices representing the volume, pressure and quality of deliverable water and estimated the overall reliability of the system in three aspects under uncertainties. Defining an index representing the overall hydraulic performance of a WDS, Ermini and Ataoui (2014) employed fuzzy sets to integrate reliability, resiliency, and vulnerability into a unique index. They expressed the WDS performance as good, poor or somewhere in between. Using theory of fuzzy sets, Shafiqul Islam et al. (2014) and Ermini and Ataoui (2014) conducted a multiple aspects performance analysis. However, the multiple aspects analysis was conducted under uncertainties based on vague and fuzzy numbers without considering various states of failure. A multiple aspects approach is necessary for comprehensive reliability analyses of a WDS under various failure conditions. Multiple aspects/states analyses allow engineers to have a more realistic understanding of WDS vulnerability when failures occur simultaneously. While this has received no attention in the literature; and it is the prime objective of this chapter.

5.2 Aspect of WDS Reliability Analysis

Performance analysis for a WDS can be conducted from two major perspectives of consumers and suppliers. Any interruptions/disruptions in continuous delivery of water to consumers such as water cut-offs, water deficiencies and duration of such disruptions are highly distressing for consumers. Water suppliers, however, are keen to know types and combinations of failures in a WDS (Kwietniewski, 2004 and 2006). Furthermore, the effect of such failures on quantity, quality, equity and efficiency of water delivery to consumers as well as the energy balance of the whole system are the major concerns of water suppliers (Gargano and Pianese, 2000; Bertola and Nicolini, 2006; Gupta et al., 2009, Zhuang et al., 2012; Shuang et al., 2014; Gottipati and Nanduri 2014; Dziedzic and Karney, 2015). This research focused on the three aspects of quantity of delivered water, equity in water delivery and efficiency of the WDS due to leakage. However, the developed technique in this research can be easily modified/employed to study other aspects of a WDS as well. The research conducted two- and three-aspect analyses for each state of pipe failure and the corresponding system's reliabilities were determined. Adopting a test case reported in the literature (Gheisi and Naser, 2015a), the research compared the results of two- and three-aspect analyses with those of single-aspect and multiple states analysis.

The quadrant and octant analyses are useful tools to study the interactions among various aspects when multiple states failures occur simultaneously. The quadrant analysis has been applied widely in marketing (Martilla and James, 1977) to manage the customer satisfaction, sports (Scanlan and Lewthwaite, 1986) to study enjoyment experienced by athletics, and engineering (Willmarth and Lu, 1972; Grass, 1971; Gheisi et al., 2006; Keshavarzi and Gheisi, 2006 and 2007) to study the coherent near-bed turbulent flow structures (bursting events) in two dimensions. Gheisi et al. (2006) and Keshavarzi and

Gheisi (2006 and 2007) extended the quadrant analysis to octant analysis to study bursting events in three dimensions.

5.3 Methodology

This section describes: 1) performance indices to measure WDS reliability, 2) the techniques of quadrant and octant analyses, 3) reliability analysis of WDS, and 4) multiple criteria decision analysis (MCDA) for ranking a WDS layouts.

5.3.1 Performance Indices

This research applied three performance indices for adequacy, equity and efficiency of water delivery.

5.3.1.1 Adequacy of Water Delivery

Water utility index (defined as the ratio of supplied water to demand) is the most commonly practiced performance index that reflects the level of agreement between supply and demand (Wagner et al., 1988; Gupta and Bhave, 1994; Gargano and Pianese, 2000; Zhuang et al., 2012; Shuang et al., 2014). This study employed the index of supply ratio between 0 and 1 to check the adequacy of water delivery to consumers as (Gargano and Pianese, 2000; Zhuang et al., 2012; Shuang et al., 2014):

$$PI_j^{ad} = \frac{Q_j^{su}}{Q_j^{re}} \tag{5.1}$$

$$PI_{sys}^{ad} = \frac{\sum_{j=1}^{n_n} Q_j^{su}}{\sum_{j=1}^{n_n} Q_j^{re}} \tag{5.2}$$

where PI^{ad} is the performance index for the adequacy of water delivery; n_n is the number of nodes; Q^{su} is the supplied water (L/s); and Q^{re} is the demanded or required water (L/s). The subscripts "*j*" and "*sys*" refer to node number and system, respectively.

5.3.1.2 Equity of Water Delivery

Index of supply ratio reveals how much water is available at demand nodes, while it provides no information on how fair the available water is distributed among consumers. Equity index can address this by revealing how uniformly and equally the water shortage is shared among different users in pressure deficient conditions. Performance index of equity has been widely employed in irrigation as well as distribution systems (Bos, 1997; Fujiwara and Li, 1998; Gorantiwar and Smout, 2005; Gottipati and Nanduri, 2014). The coefficient of uniformity (Christiansen, 1942) is a global scale to measure uniformity. It has been widely applied in field of irrigation water management as a proven criterion to clearly demonstrate uniformity of distributed water (Karmeli, 1978; Topak et al., 2005). Using the coefficient of uniformity and knowing the supply ratio for each demand node, the equity index between 0 and 1 can be obtained. Initially, the average of supply ratios is computed then the deviation of each nodal ratio from the average is obtained. Average of deviations over the average of supply ratios represents the amount of variations in the WDS. The uniformity or equity index is one minus the variations (Gottipati and Nanduri, 2014):

$$PI_{sys}^{eq} = 1 - \left[\frac{\sum_{j=1}^{n_n} \left| PI_j^{ad} - \frac{1}{n_n} \sum_{j=1}^{n_n} PI_j^{ad} \right|}{\sum_{j=1}^{n_n} PI_j^{ad}} \right] \tag{5.3}$$

where PI^{eq} is equity performance index. Gottipati and Nanduri (2014) discussed many factors that may influence the equity results. They indicated that location of supply tanks and WDS layouts have significant impact. Increasing water level in supply tanks (to some level), decreasing demand at nodes very close or far away from the tanks, increasing the diameter or eliminating some key linking pipes in a WDS can significantly improve the equity in water delivery.

5.3.1.3 Efficiency of Water Delivery

As a WDS ages the loss of water due to leakage increases and becomes a more controversial issue. A large proportion of supplied water in WDS is wasted daily due to leakage and is gradually reaching alarming level (Van Zyl and Clayton, 2007). Twort et al. (1974) reported the global average of 5 to 55% of total supply as the water lost from different parts of a WDS depending on the available residual pressure inside the system. Water leakage has significant effect on the operation of an aged WDS due to huge wastes of supplied water (Germanopoulos, 1985). Leakage rate depends on many factors including available pressure in WDS, shape and hydraulics of the leak opening, material properties of pipes, hydraulic characteristics of the surrounding soil and also the pressure-dependent water discharge at demand nodes (Van Zyl and Clayton, 2007). To consider leakage in reliability analysis, this research proposed and applied the performance index of efficiency. Literature lists a number of relationships to estimate the leakage (Germanopoulos, 1985; Vela et al., 1991; Pudar and Ligget, 1992; Lambert, 1997; Ainola et al., 2000; Araujo et al., 2003; Burrows et al., 2003; Giustolisi and Laucelli, 2007; Tabesh et al., 2009). The technique proposed by Germanopoulos [1985] has been applied widely due to its simplicity (Martinez et al., 1999; Nazif et al., 2010; Jun and Guoping, 2012; Tabesh et al., 2014). Assuming leakage to be uniformly distributed along a pipe, this research found the leak by (Germanopoulos, 1985):

$$Q_i^{leak} = C\, L_i\, (P_i^{ave})^{1.18} \tag{5.4}$$

where Q^{leak} is the leak (L/s) from a pipe, L is the pipe's length (m), P^{ave} is the average residual pressure in the pipe, and the subscript i is the pipe number. Note that P^{ave} can be estimated by pressure averaging at the beginning and ending nodes of a pipe. The coefficient C depends on the pipe's material and its age and number of leakage points per unit length of pipe (Giustolisi et al., 2008c). This research used C = 0.0001, which gives efficiency of 0.7 when all pipes are in operation. Efficiency of 0.7 means 30% of total supply is lost due to leak. This is, indeed, in the middle of the global average water losses for a WDS reported by Twort et al. (1974). The WDS performance index of efficiency (PI^{ef}) due to leakage was obtained by (Bertola and Nicolini, 2006):

$$PI_{sys}^{ef} = \frac{\sum_{j=1}^{n_n} Q_j^{su}}{\sum_{j=1}^{n_n} Q_j^{su} + \sum_{n=1}^{N} Q_n^{leak}} \tag{5.5}$$

where N is number of pipes in the system.

5.3.1.4 Overall Performance of WDS

Following Bertola and Nicolini (2006), the overall performance of WDS for each state of failure was determined by:

$$PI_{sys} = PI_{sys}^{ad} \cdot PI_{sys}^{eq} \cdot PI_{sys}^{ef} \tag{5.6}$$

5.3.2 Quadrant/Octant Analysis

This research applied quadrant and octant analyses for two- and three-aspect analyses, respectively. In two-aspect analysis, the x- and y-axes of a Cartesian system divide the plane surface into four separate zones known as quadrant I, II, III and IV (Figure 5.1).

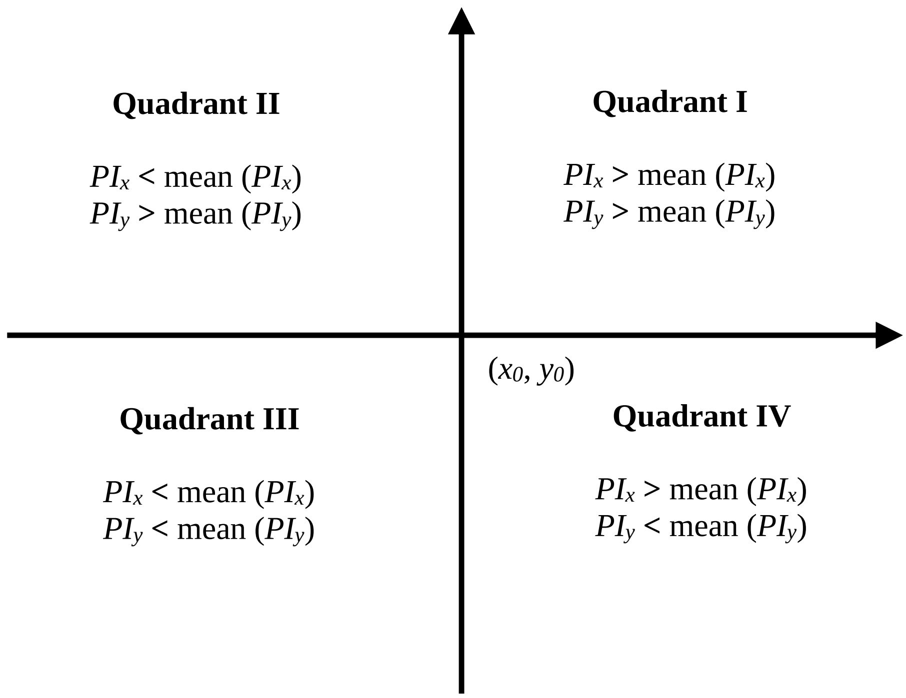


Figure 5.1 Four quadrant zones of the two-aspect performance analysis

Each quadrant is restricted by two half-axes, which reflect the performance of WDS in two aspects simultaneously (e.g. water adequacy and efficiency). The point where the *x*- and *y*-axes meet (x_o, y_o) represents the mean performance of the system in both aspects; x_o = mean (PI_x) and y_o = mean (PI_y). The response of WDS to different states of pipe failure was defined as:

- **Quadrant Zone I:** Performances of the system in *x* and *y* directions are higher than the mean condition; PI_x > mean (PI_x) and PI_y > mean (PI_y).
- **Quadrant Zone II:** Performance of the system in *x* direction is less than the mean condition in that direction, but it is higher than the corresponding mean in *y* direction; PI_x < mean (PI_x) and PI_y > mean (PI_y).
- **Quadrant Zone III:** Performances of the system in *x* and *y* directions are less than the corresponding mean conditions; PI_x < mean (PI_x) and PI_y < mean (PI_y).
- **Quadrant Zone IV:** Performances of the system in *x* and *y* directions are higher and lower than the corresponding mean conditions; PI_x > mean (PI_x) and PI_y < mean (PI_y).

In three-aspect analysis, the *x*-, *y*- and *z*-axes of a Cartesian system divide the space into eight zones known as octant I, II, III, IV, V, VI, VII and VIII (Figure 5.2).

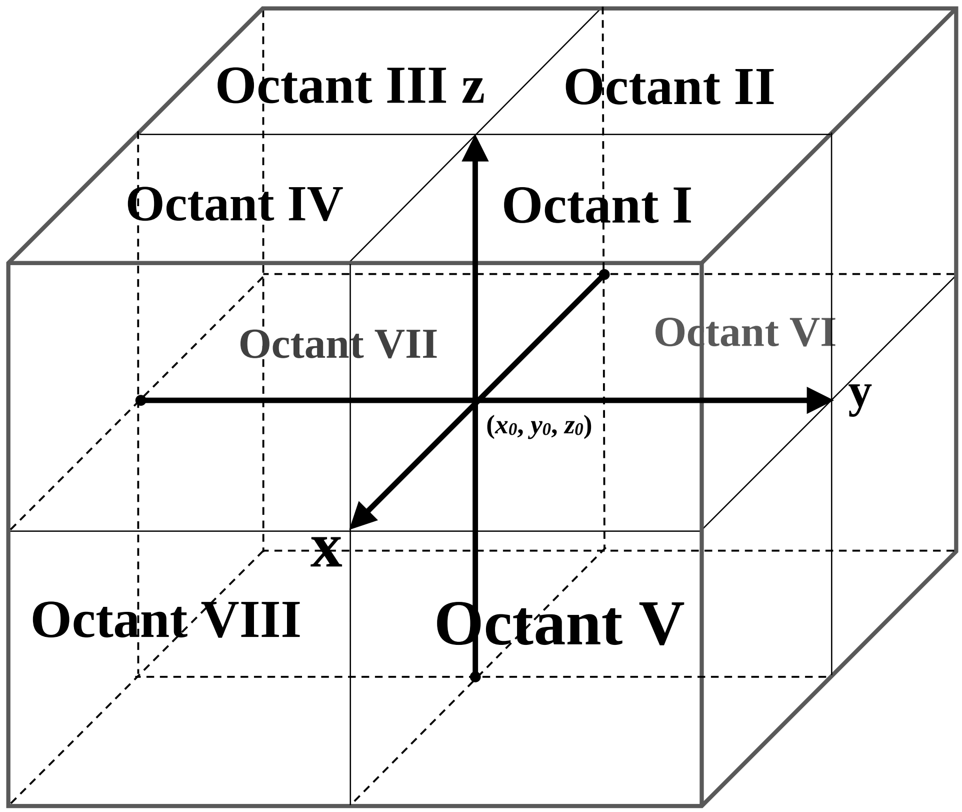


Figure 5.2 Eight octant zones of the three-aspect performance analysis

Each octant is restricted by three half-axes, which reflect the performance of the system in three aspects simultaneously (water adequacy, equity and efficiency). The point where the *x*-, *y*- and *z*-axes meet represents the mean performance of the system in all three aspects (mean operating condition). Thus, x_o = mean (PI_x), y_o = mean (PI_y), and z_o = mean (PI_z). In octant analysis the response of WDS to different state of pipe failure was defined as:

- **Octant Zone I:** Performance of the system in *x*, *y* and *z* directions are higher than the corresponding mean conditions; PI_x > mean (PI_x); PI_y > mean (PI_y); and PI_z > mean (PI_z).

- **Octant Zone II:** Performance of the system in *x* direction is less than the mean condition in that direction, but they are higher than the mean conditions in *y* and *z* directions; PI_x < mean (PI_x); PI_y > mean (PI_y); and PI_z > mean (PI_z).
- **Octant Zone III:** Performances of the system in *x* and *y* directions (PI_x, PI_y) are less than the mean conditions in those directions, but it is higher than the mean condition in *z* direction. Thus, PI_x < mean (PI_x); PI_y < mean (PI_y); and PI_z > mean (PI_z).
- **Octant Zone IV:** Performances of the system in *x* and *z* directions are higher than the corresponding mean conditions, but in *y* direction it is less than the mean condition. Thus, PI_x > mean (PI_x); PI_y < mean (PI_y) and PI_z > mean (PI_z).
- **Octant Zone V:** Performances of the system in *x* and *y* directions are higher than the mean conditions in those directions, but in *z* direction it is less than the mean condition. Thus, PI_x > mean (PI_x); PI_y > mean (PI_y); and PI_z < mean (PI_z).
- **Octant Zone VI:** Performances of the system in *x* and *z* directions are less than the corresponding mean conditions, but in *y* direction it is higher than the mean condition. Thus, PI_x < mean (PI_x); PI_y > mean (PI_y); and PI_z < mean (PI_z).
- **Octant Zone VII:** Performances of the system in *x*, *y* and *z* directions are less than the corresponding mean conditions; PI_x < mean (PI_x); PI_y < mean (PI_y) and PI_z < mean (PI_z).
- **Octant Zone VIII:** Performance of the system in *x* direction is higher than the mean condition in that direction, but in *y* and *z* directions they are less than the corresponding mean conditions. Thus, PI_x > mean (PI_x); PI_y < mean (PI_y) and PI_z < mean (PI_z).

5.3.3 WDS Reliability

This study applied the technique developed by Gheisi and Naser (2013, 2014a, 2014b, 2014c, 2015a) to determine the overall reliability of a WDS under different states of pipe failure. The research measures reliability as a probability-weighted average of performance indices. Assigned weight to each performance index was defined as the probability of occurrence of a specific combination of pipe failure. Probability of occurrence was obtained using the concept of components availability. This technique has several advantages and was employed frequently to estimate lower states of reliability (Gargano and Pianese, 1998; Gargano and Pianese, 2000; Tanyimboh et al., 2001; Kalungi and Tanyimboh, 2003; Surendran et al., 2005). This research applied a systemic-holistic (or system-performance or simulation-based) approach for reliability analysis (Gheisi et al., 2015). The technique has the capability of incorporating all potential combinations of pipe failures, spatiotemporal variations in demands and also dealing with pressure deficient conditions due to inadequate residual pressure at nodes.

Following Gheisi and Naser (2014a and 2015a), zeroth state reliability (R^0) for a WDS was estimated by equation (4.4). This research applied the concept of availability (A) and unavailability (U=1-A) of a pipe (Equations 4.7a to 4.7c) to determine the probability of failure for different pipe combinations (Fujiwara and De Silva, 1990; Fujiwara and Tung, 1991). Following Cullinane et al. (1992), the availability of pipe i with diameter D_i (in meter) was estimated by using equation (4.8). Given that a pipe is in operation or failure condition, Cullinane et al. (1992) defined pipe availability as the ratio of the time when the pipe is in operation or it is between two sequential failures to the pipe lifetime. Pipe lifetime comprises the time between two sequential failures and the time required to repair or replace the pipe. Following the literature (Tanyimboh et al., 2001; Kalungi and Tanyimboh, 2003), Gheisi and Naser (2014a) derived the governing equations for the first and k^{th} state of reliability (R^1 and R^k) as equations (4.5) and (4.6) which were employed in this study.

5.3.4 Multiple Criteria Decision Analysis (MCDA)

To find the most reliable layout of a WDS, this research applied MCDA to rank the WDS layouts (alternatives). Multiple states/aspects overall reliabilities were employed as the criteria to rank the layouts. The research applied and compared three methods of MCDA including Weighted Sum Model (WSM) (Fishburn, 1967), Weighted Product Model (WPM) (Bridgman, 1922; Miller and Starr, 1969) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981). MCDA computes a score for each alternative by assigning a proper weight to every criterion involved in decision-making. The weights can be subjective, objective, and independency weights. They represent the significance of each criterion in decision-making and determine the percentage of contribution of each criterion in the final scores. Final scores for every layouts were eventually ranked to conduct a comprehensive reliability ranking.

This research adopted the combinative weighting approach (Jahan et al., 2012), which estimates the overall weights as the normalized geometric mean of subjective, objective and independency weights. Based on the available history of pipe failures, decision makers can judge about the appropriate subjective weights using her/his engineering judgment or expertise. In contrary to subjective weights, personal judgment and expertise of the decision makers do not play any role in the objective weights assignment. In each state of overall reliability analysis (criterion) the results may vary from one layout (alternative) to another. Objective weights determine which state of overall reliability should have more contribution in the final decision. The state of overall reliability varies (in various layouts) more than other applied criterion. Thus, it should have more contribution in the final decision and receives a larger objective weight. Using the concept of Shannon's information entropy (Shannon, 1948), this research computed the objective weights as the ratio of the amount of scattering in reliability results for each state to the total scattering estimated for all states of reliabilities (Hwang and Yoon, 1981). Gheisi and Naser (2015a) showed that the statistical flow entropy is a proper surrogate measure for higher states of reliabilities. Therefore, this study employed flow entropy as the representative of higher states of overall reliability in MCDA. Using the discharge and direction of flow in pipes, the amount of flow entropy (S) for a single-source WDS was obtained by equation (4.1) (Tanymboh and Templeman, 1993).

The last weight employed in the combinative weighting approach was the independency weight proposed by Jahan et al. (2012). This weight can diminish the effect of correlation, which may exist among the applied criteria in MCDA. Independency weight can be estimated based on the inter-correlation or the relative disassociation between each pair of criteria in MCDA. A criterion, which is highly correlated with the other criteria in MCDA, is less significant and should have less contribution in the final decision. Therefore, the lowest independency weight goes to a criterion, which has the highest correlation with other criteria.

5.4 Test Case

Following the literature (Tanymboh and Templeman, 2000; Tanyimboh and Sheahan, 2002; Tanymboh et al., 2011; Gheisi and Naser, 2015a), this research tested a hypothetical WDS (Figure 4.1) with a set of 22 layouts (alternatives) as of Figure 4.2. Elevation of all the demand nodes is 0 m. The pipes are 1 km long with a Hazen-Williams coefficient of 130. Table B.1 in Appendix B shows the diameter of the pipes for each layout. The pressure head at source node 1 is 100 m. Minimum required residual head at each node is 30 m. Failure of a pipe may cause a sudden pressure drop in the system.

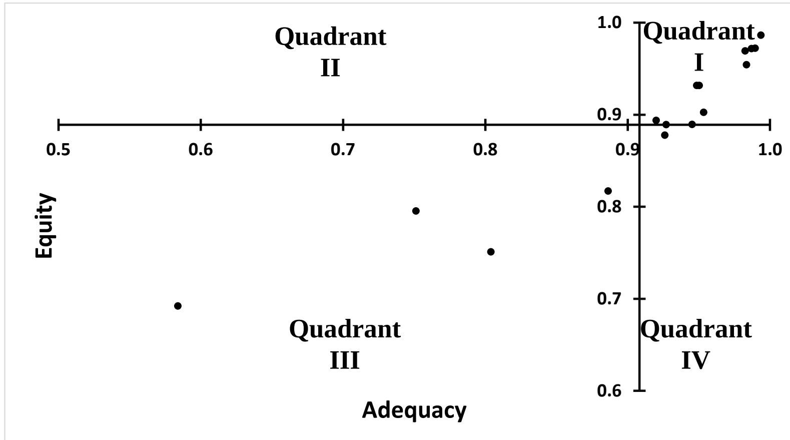
The original version of EPANET2 (Rossman, 2000) is unable to study the pressure deficient conditions when the residual pressure head at a node is not enough to fully satisfy the demand. Therefore, this research applied the modified version of EPANET2 known as EPANET-Emitter (Pathirana, 2010) to perform the hydraulic simulations in pressure-deficient conditions.

5.5 Results and Discussion

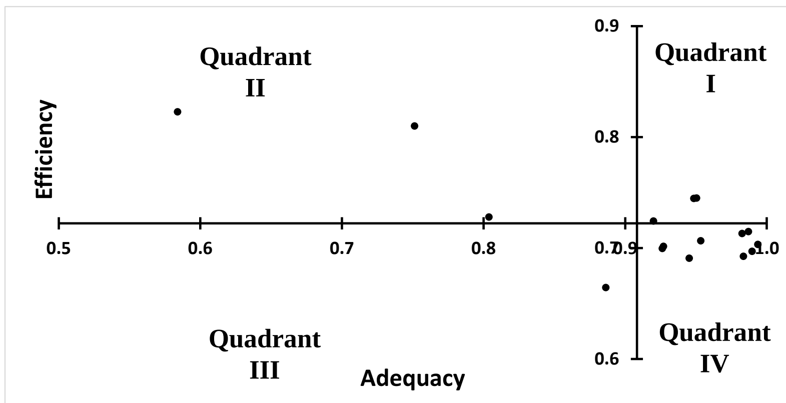
The 22 layouts were studied under two scenarios of when 1) one pipe failed and 2) two pipes failed simultaneously. Mean and deviations from the mean of the responses were evaluated in two or three aspects using the quadrant and octant analyses.

Figures 5.3 and 5.4 show the results of quadrant analyses for every two aspects (of adequacy-equity, adequacy-efficiency, and equity-efficiency) for the Layout 6 during one-and two-pipe failure scenarios, respectively. Results of quadrant analysis are shown for Layout 6 due the high amount of variation seen in the results.

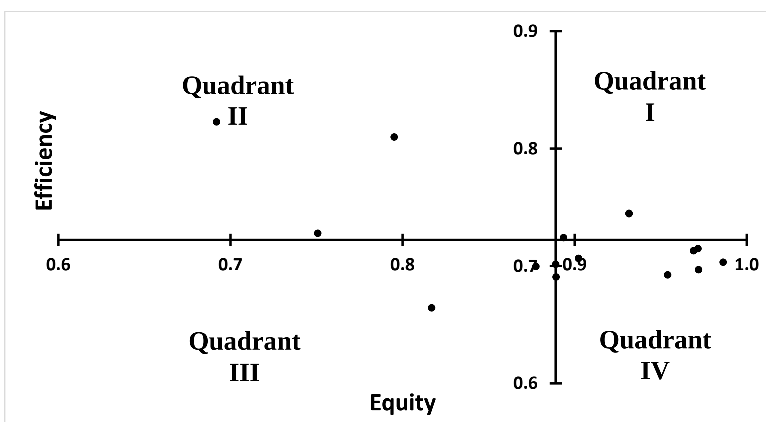
Each point represents the performance of WDS in two-aspect. While each individual point on the Figures 5.3 and 5.4 show the impact of failure on each aspect, the figures do not reveal the degree of impact. The contribution of WDS performances to each quadrant/octant zone was determined by counting the number of points in each zone. Tables 5.1 to 5.8 indicate contribution probabilities of WDS performances. Contribution probability revealed that what portion of the failure events had caused the WDS to perform in a certain way, which falls into a particular quadrant/octant zone.



a)

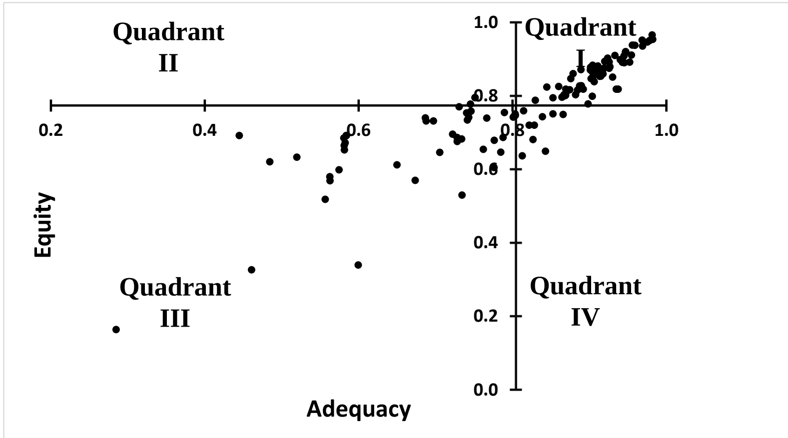


b)

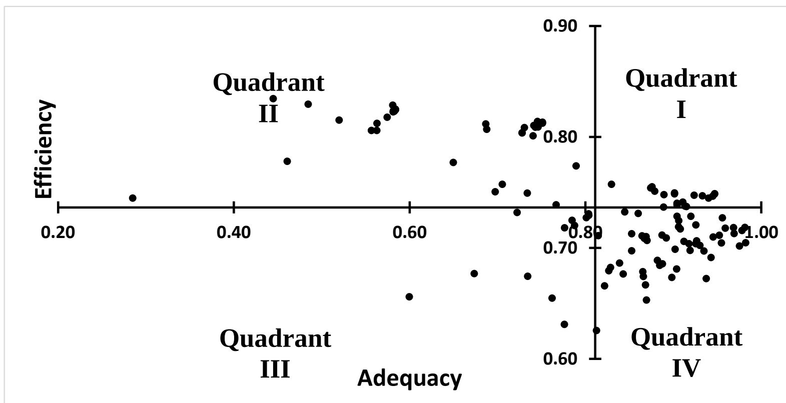


c)

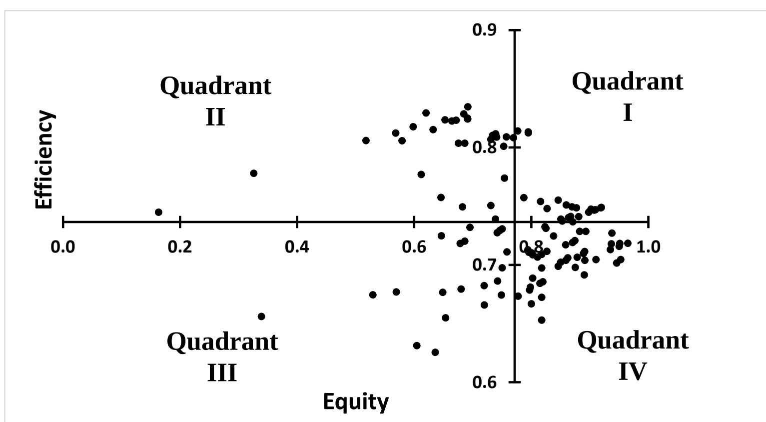
Figure 5.3 One pipe failure at a time quadrant performance response analysis of the WDS layout 6 in: a) adequacy vs. equity; b) adequacy vs. efficiency; c) equity vs. efficiency



a)



b)



c)

Figure 5.4 Two pipes failure at a time quadrant performance response analysis of the WDS layout 6 in: a) adequacy vs. equity; b) adequacy vs. efficiency; c) equity vs. efficiency

Table 5.1 Contribution probability of WDS performances regarding one-pipe failure at a time events to each quadrant zone in adequacy and equity aspects

Layout No.	Quadrant I (%)	Quadrant II (%)	Quadrant III (%)	Quadrant IV (%)
1	64.29	0.00	35.71	0.00
2	64.29	0.00	35.71	0.00
3	57.14	0.00	42.86	0.00
4	66.67	0.00	33.33	0.00
5	60.00	0.00	33.33	6.67
6	68.75	0.00	25.00	6.25
7	68.75	0.00	25.00	6.25
8	64.71	0.00	23.53	11.76
9	66.67	0.00	33.33	0.00
10	66.67	0.00	26.67	6.67
11	57.14	0.00	42.86	0.00
12	53.85	0.00	46.15	0.00
13	68.75	0.00	31.25	0.00
14	68.75	0.00	25.00	6.25
15	75.00	0.00	25.00	0.00
16	75.00	0.00	25.00	0.00
17	42.86	7.14	35.71	14.29
18	53.85	7.69	30.77	7.69
19	64.29	0.00	28.57	7.14
20	71.43	0.00	28.57	0.00
21	78.57	0.00	21.43	0.00
22	78.57	0.00	21.43	0.00

Table 5.2 Contribution probability of WDS performances regarding two-pipe failure at a time events to each quadrant zone in adequacy and equity aspects

Layout No.	Quadrant I (%)	Quadrant II (%)	Quadrant III (%)	Quadrant IV (%)
1	50.55	1.10	39.56	8.79
2	56.04	2.20	38.46	3.30
3	46.15	3.30	47.25	3.30
4	48.57	0.95	42.86	7.62
5	47.62	5.71	35.24	11.43
6	53.33	2.50	36.67	7.50
7	50.83	6.67	30.83	11.67
8	57.35	2.94	34.56	5.15
9	46.67	5.71	40.95	6.67
10	55.24	1.90	40.00	2.86
11	46.15	5.49	40.66	7.69
12	46.15	2.56	43.59	7.69
13	51.67	5.00	34.17	9.17
14	50.83	5.00	35.00	9.17
15	60.00	1.67	36.67	1.67
16	67.50	7.50	24.17	0.83
17	43.96	9.89	32.97	13.19
18	50.00	5.13	37.18	7.69
19	59.34	10.99	25.27	4.40
20	58.24	4.40	34.07	3.30
21	56.04	1.10	39.56	3.30
22	63.74	2.20	29.67	4.40

Table 5.3 Contribution probability of WDS performances regarding one-pipe failure at a time events to each quadrant zone in adequacy and efficiency aspects

Layout No.	**Quadrant I (%)**	**Quadrant II (%)**	**Quadrant III (%)**	**Quadrant IV (%)**
1	21.43	21.43	14.29	42.86
2	28.57	21.43	14.29	35.71
3	21.43	21.43	21.43	35.71
4	20.00	20.00	13.33	46.67
5	13.33	20.00	13.33	53.33
6	18.75	18.75	6.25	56.25
7	18.75	12.50	12.50	56.25
8	11.76	17.65	5.88	64.71
9	13.33	13.33	20.00	53.33
10	6.67	26.67	0.00	66.67
11	14.29	21.43	21.43	42.86
12	15.38	23.08	23.08	38.46
13	12.50	18.75	12.50	56.25
14	18.75	12.50	12.50	56.25
15	6.25	25.00	0.00	68.75
16	18.75	25.00	0.00	56.25
17	21.43	14.29	28.57	35.71
18	15.38	23.08	15.38	46.15
19	7.14	21.43	7.14	64.29
20	42.86	21.43	7.14	28.57
21	35.71	7.14	14.29	42.86
22	28.57	14.29	7.14	50.00

Table 5.4 Contribution probability of WDS performances regarding two-pipe failure at a time events to each quadrant zone in adequacy and efficiency aspects

Layout No.	Quadrant I (%)	Quadrant II (%)	Quadrant III (%)	Quadrant IV (%)
1	20.88	25.27	15.38	38.46
2	29.67	26.37	14.29	29.67
3	16.48	30.77	19.78	32.97
4	20.95	27.62	16.19	35.24
5	15.24	26.67	14.29	43.81
6	16.67	28.33	10.83	44.17
7	15.83	25.83	11.67	46.67
8	11.03	27.94	9.56	51.47
9	15.24	28.57	18.10	38.10
10	13.33	34.29	7.62	44.76
11	16.48	27.47	18.68	37.36
12	24.36	24.36	21.79	29.49
13	12.50	31.67	7.50	48.33
14	15.83	25.83	14.17	44.17
15	8.33	30.83	7.50	53.33
16	21.67	25.83	5.83	46.67
17	25.27	21.98	20.88	31.87
18	25.64	21.79	20.51	32.05
19	25.27	27.47	8.79	38.46
20	29.67	24.18	14.29	31.87
21	32.97	23.08	17.58	26.37
22	35.16	17.58	14.29	32.97

Table 5.5 Contribution probability of WDS performances regarding one-pipe failure at a time events to each quadrant zone in equity and efficiency aspects

Layout No.	Quadrant I (%)	Quadrant II (%)	Quadrant III (%)	Quadrant IV (%)
1	21.43	21.43	14.29	42.86
2	28.57	21.43	14.29	35.71
3	21.43	21.43	21.43	35.71
4	20.00	20.00	13.33	46.67
5	13.33	20.00	20.00	46.67
6	18.75	18.75	12.50	50.00
7	18.75	12.50	18.75	50.00
8	11.76	17.65	17.65	52.94
9	13.33	13.33	20.00	53.33
10	6.67	26.67	6.67	60.00
11	14.29	21.43	21.43	42.86
12	15.38	23.08	23.08	38.46
13	12.50	18.75	12.50	56.25
14	18.75	12.50	18.75	50.00
15	6.25	25.00	0.00	68.75
16	18.75	25.00	0.00	56.25
17	28.57	7.14	42.86	21.43
18	23.08	15.38	23.08	38.46
19	7.14	21.43	14.29	57.14
20	42.86	21.43	7.14	28.57
21	35.71	7.14	14.29	42.86
22	28.57	14.29	7.14	50.00

Table 5.6 Contribution probability of WDS performances regarding two-pipe failure at a time events to each quadrant zone in equity and efficiency aspects

Layout No.	Quadrant I (%)	Quadrant II (%)	Quadrant III (%)	Quadrant IV (%)
1	20.88	25.27	23.08	30.77
2	31.87	24.18	17.58	26.37
3	19.78	27.47	23.08	29.67
4	20.00	28.57	21.90	29.52
5	20.00	21.90	24.76	33.33
6	19.17	25.83	18.33	36.67
7	21.67	20.00	22.50	35.83
8	13.97	25.00	14.71	46.32
9	20.95	22.86	24.76	31.43
10	15.24	32.38	10.48	41.90
11	21.98	21.98	26.37	29.67
12	15.38	23.08	23.08	38.46
13	15.83	28.33	15.00	40.83
14	20.00	21.67	22.50	35.83
15	10.00	29.17	9.17	51.67
16	28.33	19.17	5.83	46.67
17	34.07	13.19	32.97	19.78
18	29.49	17.95	26.92	25.64
19	36.26	16.48	13.19	34.07
20	34.07	19.78	17.58	28.57
21	34.07	21.98	20.88	23.08
22	37.36	15.38	18.68	28.57

Table 5.7 Contribution probability of WDS performances regarding one-pipe failure at a time events to each octant zone in adequacy, equity and efficiency aspects

Layout No.	Octant I (%)	Octant II (%)	Octant III (%)	Octant IV (%)	Octant V (%)	Octant VI (%)	Octant VII (%)	Octant VIII (%)
1	21.43	0.00	21.43	0.00	42.86	0.00	14.29	0.00
2	28.57	0.00	21.43	0.00	35.71	0.00	14.29	0.00
3	21.43	0.00	21.43	0.00	35.71	0.00	21.43	0.00
4	20.00	0.00	20.00	0.00	46.67	0.00	13.33	0.00
5	13.33	0.00	20.00	0.00	46.67	0.00	13.33	6.67
6	18.75	0.00	18.75	0.00	50.00	0.00	6.25	6.25
7	18.75	0.00	12.50	0.00	50.00	0.00	12.50	6.25
8	11.76	0.00	17.65	0.00	52.94	0.00	5.88	11.76
9	13.33	0.00	13.33	0.00	53.33	0.00	20.00	0.00
10	6.67	0.00	26.67	0.00	60.00	0.00	0.00	6.67
11	14.29	0.00	21.43	0.00	42.86	0.00	21.43	0.00
12	15.38	0.00	23.08	0.00	38.46	0.00	23.08	0.00
13	12.50	0.00	18.75	0.00	56.25	0.00	12.50	0.00
14	18.75	0.00	12.50	0.00	50.00	0.00	12.50	6.25
15	6.25	0.00	25.00	0.00	68.75	0.00	0.00	0.00
16	18.75	0.00	25.00	0.00	56.25	0.00	0.00	0.00
17	21.43	7.14	7.14	0.00	21.43	0.00	28.57	14.29
18	15.38	7.69	15.38	0.00	38.46	0.00	15.38	7.69
19	7.14	0.00	21.43	0.00	57.14	0.00	7.14	7.14
20	42.86	0.00	21.43	0.00	28.57	0.00	7.14	0.00
21	35.71	0.00	7.14	0.00	42.86	0.00	14.29	0.00
22	28.57	0.00	14.29	0.00	50.00	0.00	7.14	0.00

Table 5.8 Contribution probability of WDS performances regarding two-pipe failure at a time events to each octant zone in adequacy, equity and efficiency aspects

Layout No.	Octant I (%)	Octant II (%)	Octant III (%)	Octant IV (%)	Octant V (%)	Octant VI (%)	Octant VII (%)	Octant VIII (%)
1	19.78	1.10	24.18	1.10	30.77	0.00	15.38	7.69
2	29.67	2.20	24.18	0.00	26.37	0.00	14.29	3.30
3	16.48	3.30	27.47	0.00	29.67	0.00	19.78	3.30
4	19.05	0.95	26.67	1.90	29.52	0.00	16.19	5.71
5	14.29	5.71	20.95	0.95	33.33	0.00	14.29	10.48
6	16.67	2.50	25.83	0.00	36.67	0.00	10.83	7.50
7	15.83	6.67	19.17	0.00	35.83	0.00	11.67	10.83
8	11.03	2.94	25.00	0.00	46.32	0.00	9.56	5.15
9	15.24	5.71	22.86	0.00	31.43	0.00	18.10	6.67
10	13.33	1.90	32.38	0.00	41.90	0.00	7.62	2.86
11	16.48	5.49	21.98	0.00	29.67	0.00	18.68	7.69
12	23.08	2.56	21.79	1.28	23.08	0.00	21.79	6.41
13	10.83	5.00	26.67	1.67	40.83	0.00	7.50	7.50
14	15.00	5.00	20.83	0.83	35.83	0.00	14.17	8.33
15	8.33	1.67	29.17	0.00	51.67	0.00	7.50	1.67
16	20.83	7.50	18.33	0.83	46.67	0.00	5.83	0.00
17	24.18	9.89	12.09	1.10	19.78	0.00	20.88	12.09
18	25.64	3.85	17.95	0.00	24.36	1.28	19.23	7.69
19	25.27	10.99	16.48	0.00	34.07	0.00	8.79	4.40
20	29.67	4.40	19.78	0.00	28.57	0.00	14.29	3.30
21	32.97	1.10	21.98	0.00	23.08	0.00	17.58	3.30
22	35.16	2.20	15.38	0.00	28.57	0.00	14.29	4.40

Mean performance responses of the layouts to one- and two-pipe failure events in adequacy, equity and efficiency aspects were shown in Tables 5.9 and 5.10. Mean performance showed the average operational performance of a WDS in every aspects of adequacy, equity or efficiency when a state of pipe failure occurs in the system.

Table 5.9 Mean performance responses of WDS layouts to one-pipe failure at a time events in adequacy, equity and efficiency aspects

Layout No.	Adequacy	Equity	Efficiency
1	0.852	0.778	0.742
2	0.845	0.748	0.735
3	0.864	0.790	0.729
4	0.875	0.817	0.727
5	0.880	0.836	0.730
6	0.908	0.889	0.722
7	0.900	0.874	0.721
8	0.920	0.909	0.720
9	0.890	0.859	0.737
10	0.877	0.832	0.734
11	0.865	0.806	0.740
12	0.842	0.747	0.744
13	0.904	0.881	0.726
14	0.909	0.892	0.727
15	0.895	0.873	0.730
16	0.891	0.853	0.725
17	0.856	0.790	0.732
18	0.822	0.755	0.750
19	0.858	0.803	0.744
20	0.855	0.781	0.728
21	0.850	0.754	0.736
22	0.854	0.789	0.741

Table 5.10 Mean performance responses of WDS layouts to two-pipe failure at a time events in adequacy, equity and efficiency aspects

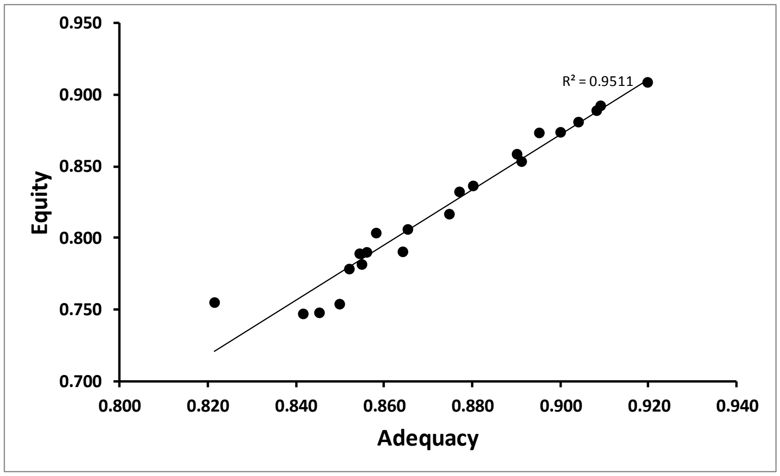
Layout No.	Adequacy	Equity	Efficiency
1	0.704	0.565	0.744
2	0.694	0.498	0.732
3	0.723	0.576	0.734
4	0.747	0.648	0.736
5	0.756	0.674	0.740
6	0.811	0.772	0.737
7	0.793	0.747	0.737
8	0.827	0.809	0.739
9	0.770	0.705	0.748
10	0.747	0.665	0.743
11	0.727	0.617	0.745
12	0.680	0.482	0.743
13	0.796	0.754	0.742
14	0.806	0.771	0.743
15	0.779	0.731	0.744
16	0.773	0.699	0.736
17	0.721	0.595	0.738
18	0.656	0.512	0.750
19	0.710	0.597	0.745
20	0.704	0.559	0.742
21	0.697	0.520	0.734
22	0.705	0.574	0.741

Compared to the quadrant analysis, the octant analysis is more comprehensive as it considers three aspects simultaneously. Octant analysis demonstrated the performance of each layout to pipe failure events in three aspects of adequacy, equity and efficiency, simultaneously. Among the eight-octant zones (Figure 5.2), Zones 1 and 7 are the most critical. The octant zone 1 demonstrates the events, which can cause the WDS layouts to perform better than the mean operating condition in all the three aspects of adequacy, equity and efficiency. On contrary, zone 7 demonstrates the failure events, which can cause WDS layouts to operate worse than the mean operating situation in all the three aspects of adequacy, equity and efficiency. Moreover, results of one-failure scenario (Table 5.7) revealed that among the 22 layouts, pipe failure events relative to the layouts 20, 21, 22 and 2 had the largest contribution probability in octant zone 1. However, the highest contribution probability in octant zone 7 occurred for the failure events at layouts 17, 12, 11 and 3.

Similarly, the results of two-failure scenario (Table 5.8) showed that the two-failure events occurring at the layouts 22, 21, 20 and 2 had the highest contribution probability in octant zone 1, but the highest contribution probability in octant zone 7 was related to the pipe failures happening at the layouts 12, 17, 3 and 18. Furthermore, Tables 5.7 and 5.8 revealed that among the 22 layouts studied, the water consumers of layouts 22, 21, 20 and 2 had the highest chance of receiving more water in a fairly manner compared to the mean operating condition. Consumers of layouts 17, 12 and 3 had more chance of receiving less water in a fairly manner compared to the mean operating condition during the pipe failures.

Tables 5.9 and 5.10 showed mean of performance responses of the 22 layouts to one- and two-failure scenarios, respectively. As the tables revealed, layouts 8, 14 and 6 had high water adequacy and equity responses to pipe failures, while layout 18 had the worst adequacy response. Interestingly, Tables 5.9 and 5.10 revealed that the layouts with the highest adequacy and equity had the lowest efficiency (due to the water leakage losses) when one pipe failed at a time. When two pipes failed simultaneously the variations in efficiency of layouts were trivial without any noticeable correlation with the two indices of water adequacy and equity. Compared to one-failure scenario, different combination of simultaneous failure of two pipes caused less variation in pressure and velocity among the layouts.

Figures 5.5 and 5.6 demonstrated the mean responses of the layouts to different states of pipe failure in terms of water adequacy against water equity and efficiency. Additionally, Figure 5.7 showed the equity in water delivery to consumers versus efficiency of the layouts.



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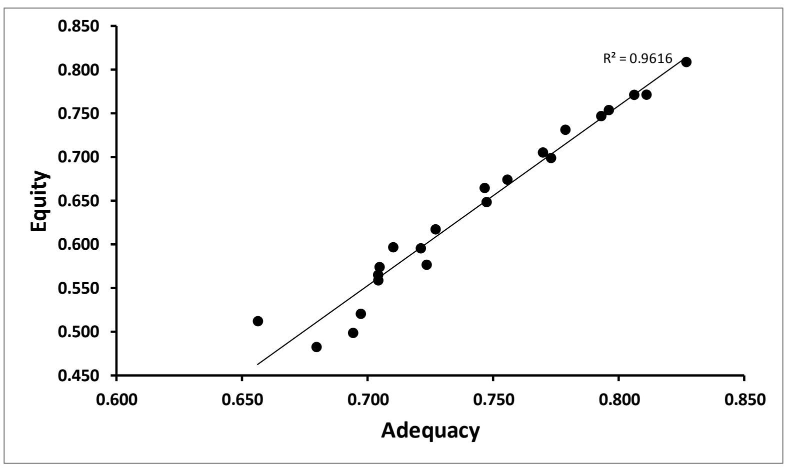

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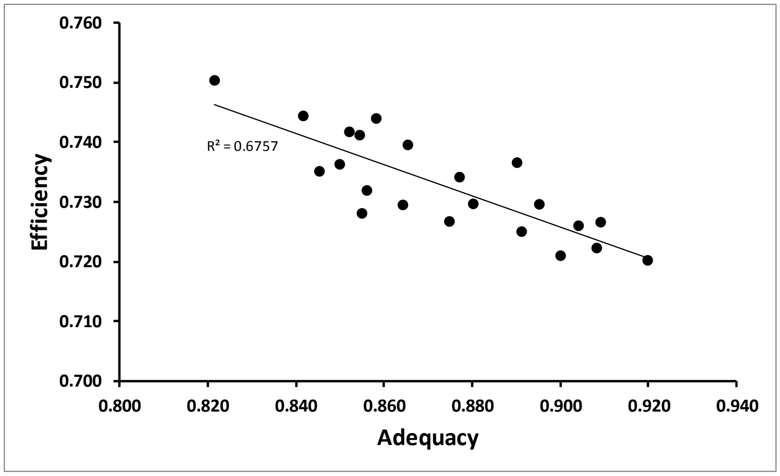
Figure 5.5 Mean responses of the WDS layouts in term of water adequacy against water equity: a) one pipe failure at a time; b) two pipes failure at a time



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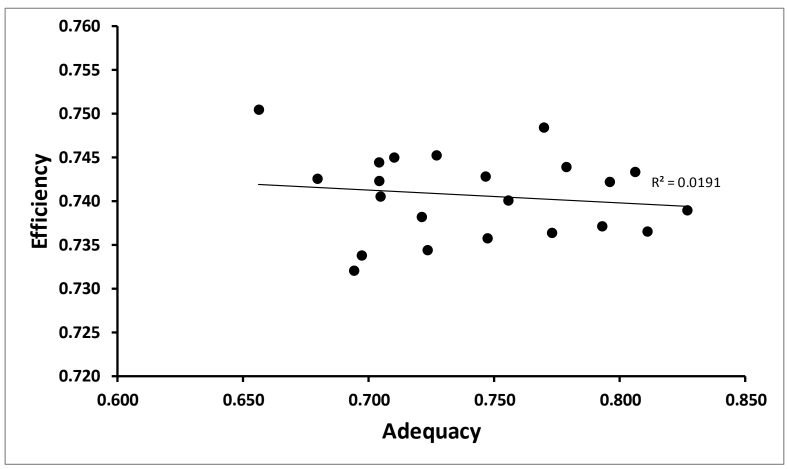

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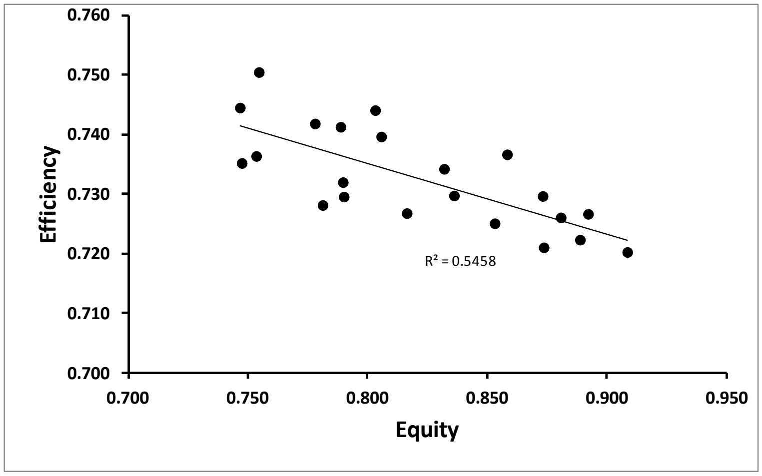
Figure 5.6 Mean responses of the WDS layouts in term of water adequacy against efficiency: a) one pipe failure at a time; b) two pipes failure at a time



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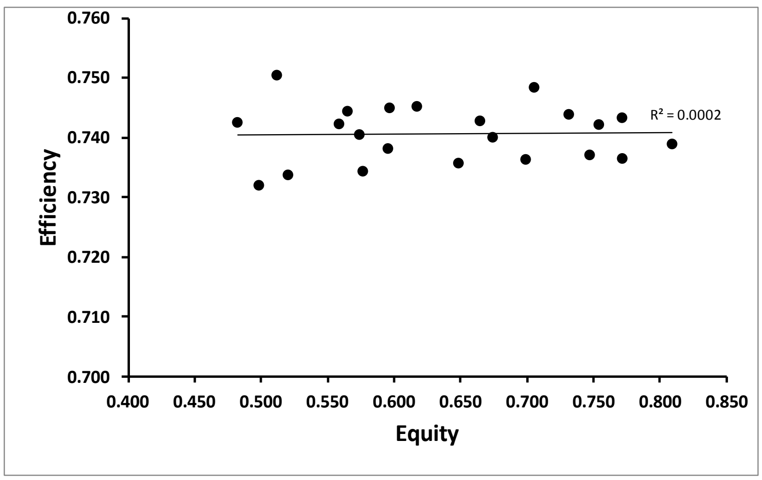


b)

Figure 5.7 Mean responses of the layouts in term of equity in water delivery against efficiency: a) one pipe failure at a time; b) two pipes failure at a time

Figure 5.5 showed a decrease in equity as the number of simultaneous pipe failure increased; but there was always a strong positive correlation between adequacy and equity in water delivery. This indicated that the layouts, which can provide more water for consumers during different combinations of pipe failure, were also able to distribute the water among the consumers more fairly. Figures 5.6 and 5.7 revealed a negative correlation between efficiency of the layouts and water adequacy and equity when one pipe fails at a time.

Interestingly, no negative correlation was observed for two-pipe failure scenarios. Indeed, unlike the case of two-failure scenarios, layouts with high water delivery to consumers suffered from low efficiency and higher amount of leakage when one pipe fails. This highlights the necessity for multiple aspects overall performance analysis of WDS, which has been largely neglected in the literature. Indeed, evaluating the performance of a WDS in just one aspect cannot always guaranty an ideal performance of the system.

Using the results of performance analysis in three aspects, the overall multiple aspects reliability of the layouts under different states of pipe failures was studied. Reliability was computed as a probability-weighted average of the overall performance indices of the WDS in different aspects. The overall performance of WDS was determined as the product of the performance indices in various aspects. The results of zeroth, first and second state overall reliability in every single, double, and triple aspects were computed and shown in Tables 5.11, 5.12 and 5.13, respectively.

Table 5.11 Results of zeroth state reliability in every single, double, and triple aspects

Layout No.	Adequacy	Equity	Efficiency	Adequacy & Equity	Adequacy & Efficiency	Equity & Efficiency	Adequacy & Equity & Efficiency
1	0.99954	0.99929	0.72378	0.99899	0.72343	0.72325	0.72303
2	0.99953	0.99921	0.72439	0.99895	0.72404	0.72381	0.72362
3	0.99960	0.99936	0.70907	0.99911	0.70877	0.70860	0.70842
4	0.99958	0.99935	0.70712	0.99906	0.70681	0.70664	0.70643
5	0.99959	0.99940	0.70765	0.99910	0.70735	0.70721	0.70699
6	0.99966	0.99954	0.69340	0.99926	0.69315	0.69307	0.69286
7	0.99963	0.99949	0.69536	0.99921	0.69509	0.69499	0.69478
8	0.99969	0.99959	0.69075	0.99933	0.69052	0.69046	0.69026
9	0.99962	0.99947	0.70986	0.99918	0.70958	0.70947	0.70925
10	0.99959	0.99942	0.71002	0.99913	0.70971	0.70958	0.70937
11	0.99957	0.99934	0.71992	0.99903	0.71960	0.71944	0.71920
12	0.99957	0.99929	0.72440	0.99904	0.72408	0.72387	0.72368
13	0.99965	0.99952	0.69672	0.99925	0.69646	0.69637	0.69617
14	0.99966	0.99955	0.69674	0.99927	0.69648	0.69641	0.69620
15	0.99963	0.99952	0.69888	0.99924	0.69860	0.69852	0.69831
16	0.99963	0.99947	0.69918	0.99924	0.69890	0.69879	0.69862
17	0.99958	0.99934	0.71386	0.99904	0.71354	0.71339	0.71316
18	0.99952	0.99930	0.73307	0.99897	0.73271	0.73255	0.73230
19	0.99957	0.99937	0.72311	0.99908	0.72278	0.72263	0.72242
20	0.99956	0.99931	0.72353	0.99904	0.72322	0.72304	0.72284
21	0.99955	0.99926	0.72351	0.99902	0.72317	0.72296	0.72278
22	0.99956	0.99934	0.72338	0.99907	0.72305	0.72288	0.72268

Table 5.12 Results of first state reliability in every single, double, and triple aspects

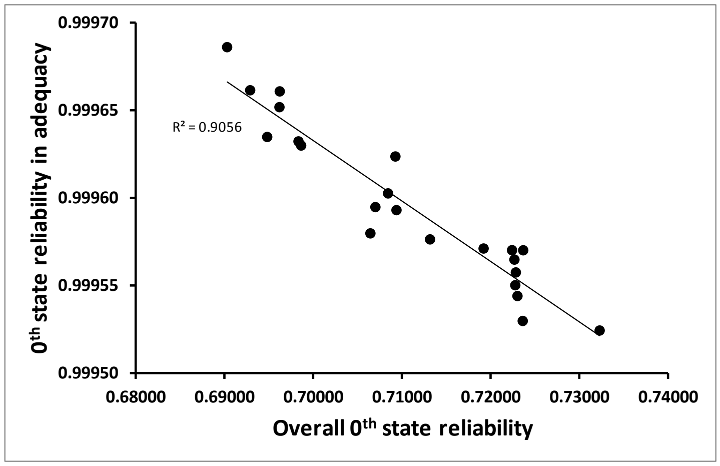
Layout No.	Adequacy	Equity	Efficiency	Adequacy & Equity	Adequacy & Efficiency	Equity & Efficiency	Adequacy & Equity & Efficiency
1	0.89453	0.83535	0.73707	0.76727	0.65756	0.61389	0.56300
2	0.89175	0.81915	0.73383	0.75922	0.65396	0.60065	0.55662
3	0.90214	0.84298	0.72609	0.78139	0.65376	0.61149	0.56625
4	0.91311	0.86547	0.72210	0.80527	0.65800	0.62411	0.57995
5	0.91567	0.87562	0.72388	0.81358	0.66106	0.63266	0.58678
6	0.93397	0.91076	0.71466	0.85636	0.66551	0.64978	0.60950
7	0.93019	0.90303	0.71407	0.84870	0.66240	0.64392	0.60394
8	0.94477	0.92866	0.71138	0.88235	0.66998	0.65916	0.62470
9	0.91956	0.88735	0.72939	0.82461	0.66884	0.64605	0.59892
10	0.91282	0.87505	0.72820	0.81444	0.66256	0.63476	0.58966
11	0.89786	0.84348	0.73433	0.76988	0.65774	0.61866	0.56360
12	0.88090	0.80425	0.74023	0.73297	0.65019	0.59345	0.54007
13	0.93291	0.90796	0.71806	0.85476	0.66775	0.65026	0.61066
14	0.93436	0.91329	0.71818	0.85876	0.66910	0.65482	0.61417
15	0.92967	0.90811	0.72116	0.85515	0.66783	0.65233	0.61257
16	0.93003	0.90045	0.71925	0.85587	0.66713	0.64552	0.61280
17	0.88671	0.82469	0.72735	0.74306	0.64419	0.60173	0.54146
18	0.86143	0.79504	0.74540	0.70092	0.63960	0.59192	0.52044
19	0.89815	0.85008	0.73945	0.78269	0.66227	0.62652	0.57604
20	0.89464	0.83679	0.73131	0.77219	0.65593	0.61477	0.56724
21	0.89286	0.82302	0.73526	0.76604	0.65613	0.60450	0.56257
22	0.89728	0.84351	0.73821	0.78027	0.66112	0.62145	0.57434

Table 5.13 Results of second state reliability in every single, double, and triple aspects

Layout No.	Adequacy	Equity	Efficiency	Adequacy & Equity	Adequacy & Efficiency	Equity & Efficiency	Adequacy & Equity & Efficiency
1	0.77737	0.65322	0.73886	0.54251	0.57157	0.48185	0.39851
2	0.77256	0.61523	0.73090	0.52795	0.56522	0.45280	0.38707
3	0.78724	0.65328	0.72907	0.54986	0.57250	0.47856	0.40148
4	0.81285	0.71746	0.72655	0.60806	0.58911	0.52195	0.44089
5	0.81765	0.73301	0.72936	0.62062	0.59438	0.53497	0.45107
6	0.85228	0.80583	0.72241	0.70093	0.61529	0.58364	0.50573
7	0.84773	0.79262	0.72432	0.68855	0.61186	0.57441	0.49683
8	0.87577	0.84418	0.72333	0.75091	0.63092	0.61003	0.53989
9	0.82412	0.75520	0.73624	0.64084	0.60493	0.55704	0.47038
10	0.81100	0.73621	0.73326	0.62748	0.59255	0.53892	0.45732
11	0.78312	0.67054	0.73699	0.54606	0.57423	0.49486	0.40116
12	0.74579	0.56851	0.73902	0.46677	0.54834	0.42093	0.34393
13	0.85075	0.79922	0.72854	0.69603	0.61732	0.58171	0.50410
14	0.85460	0.81024	0.72886	0.70557	0.62081	0.59096	0.51215
15	0.84464	0.79926	0.73167	0.69953	0.61530	0.58339	0.50782
16	0.84573	0.78520	0.72783	0.70169	0.61431	0.57163	0.50874
17	0.76853	0.63988	0.73205	0.50972	0.55986	0.47312	0.37523
18	0.71776	0.56907	0.74358	0.43901	0.52926	0.42576	0.32563
19	0.78053	0.67754	0.73939	0.56677	0.57570	0.50225	0.41785
20	0.77391	0.64806	0.73842	0.41114	0.45188	0.37129	0.30292
21	0.77069	0.62526	0.73284	0.53550	0.56444	0.46028	0.39302
22	0.77865	0.66483	0.73683	0.56162	0.57326	0.49256	0.41401

The results of zeroth state of reliability (Table 5.11) revealed that the layouts were highly reliable in adequacy (99.9% reliable). However, the overall triple-aspects zeroth state reliability dramatically decreased to 71% when considering various aspects. In case of higher states reliabilities (Tables 5.12 and 5.13), the decrease in reliability was from 90% and 80% for first and second states in adequacy to 58% and 43% for the first and second states of overall triple-aspect reliability, respectively. This indicated noticeable differences among the results of reliability in one aspect comparing to those for multiple aspects. This confirmed that evaluating the reliability of a WDS in one aspect without incorporating the other important aspects could lead to unrealistic and misleading results.

Figures 5.8, 5.9 and 5.10 compared the overall multiple aspects zeroth, first and second state reliabilities in three aspects of adequacy, equity and efficiency with their corresponding results in one aspect.



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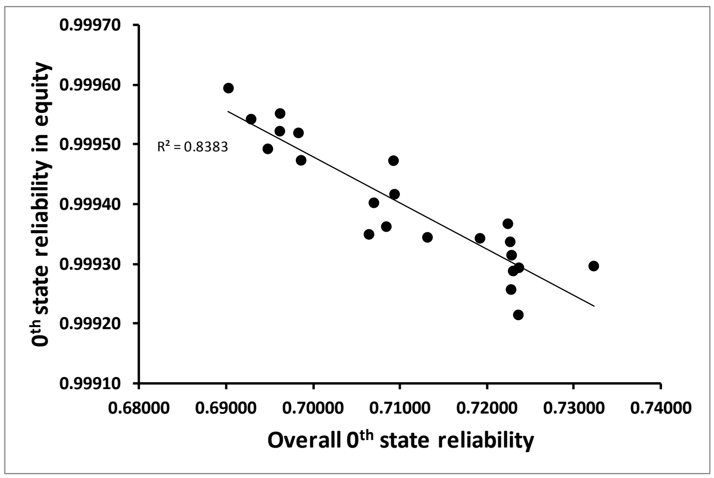

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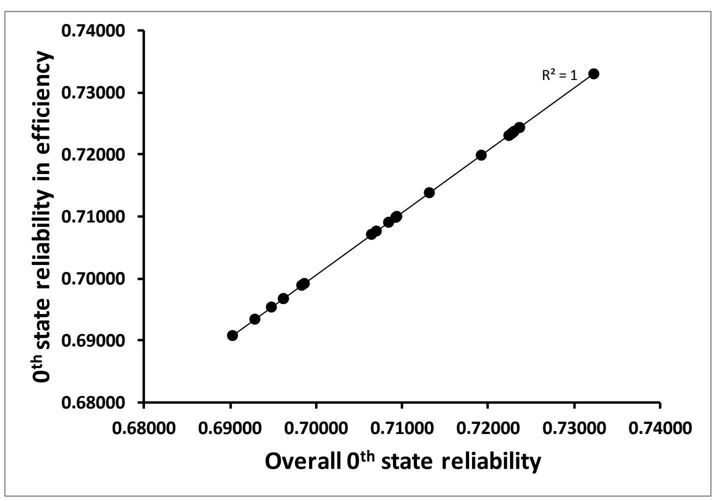

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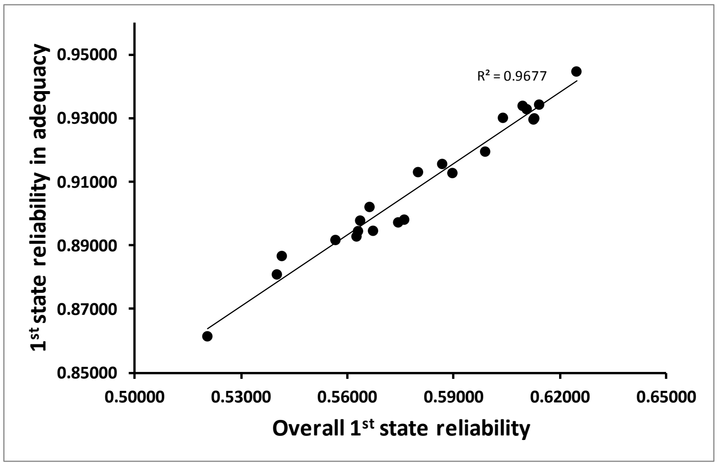
Figure 5.8 Overall multiple aspects zeroth state reliability outcomes against: a) adequacy-based reliability results; b) equity-based reliability results; c) efficiency-based reliability results



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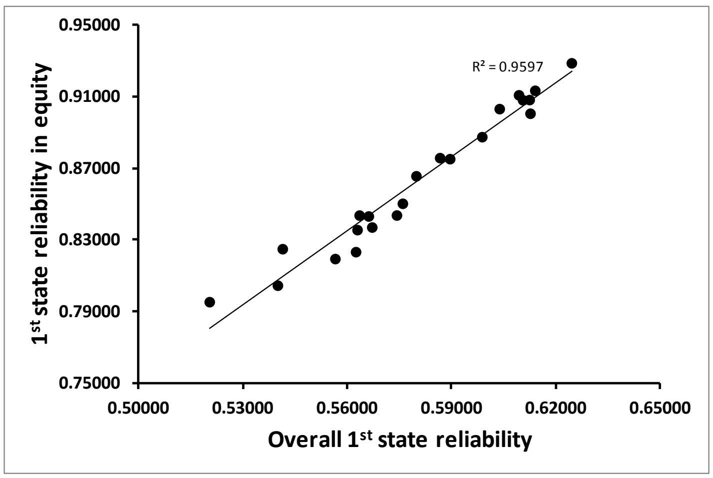

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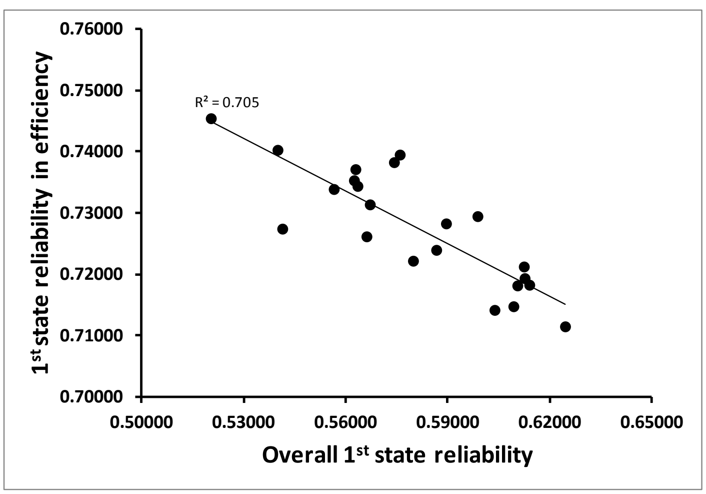

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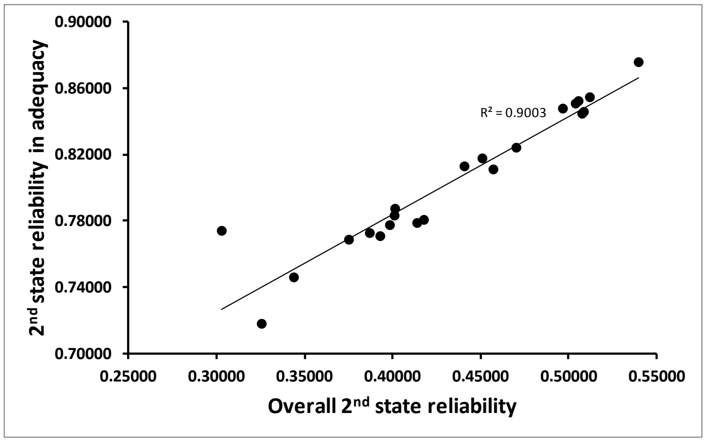
Figure 5.9 Overall multiple aspects first state reliability outcomes against: a) adequacy-based reliability results; b) equity-based reliability results; c) efficiency-based reliability results



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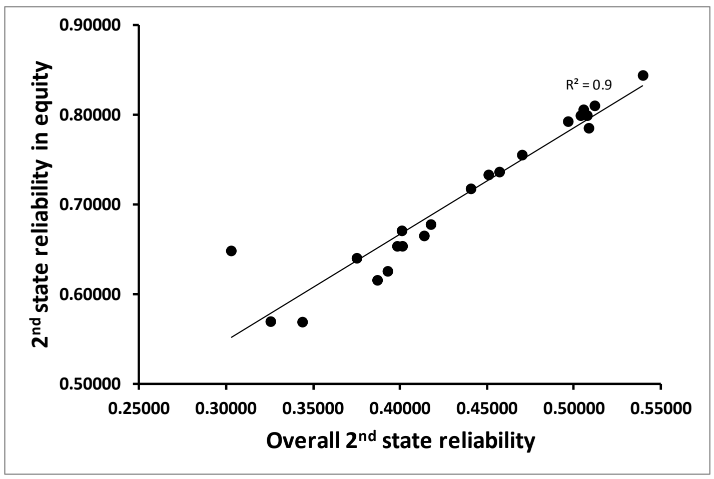

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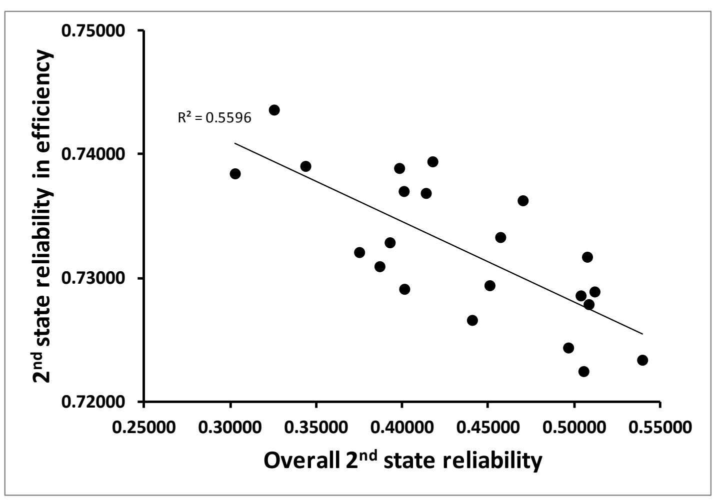

c)

Figure 5.10 Overall multiple aspects second state reliability outcomes against: a) adequacy-based reliability results; b) equity-based reliability results; c) efficiency-based reliability results

Figure 5.8 revealed that the overall reliability results were highly correlated and almost the same as efficiency-based reliabilities. However, adequacy- and equity-based reliabilities had a negative correlation with the overall reliability. Therefore, efficiency was the dominant aspect in computation of overall multiple aspects zeroth state reliability. It is interesting to mention that adequacy and equity were the dominant aspects in the first and second states reliability (Figures 5.9 and 5.10). In contrary to zeroth state reliability, a negative correlation was observed between overall multiple aspects first and second states reliabilities and the reliability for efficiency aspect only. Therefore, the dominant aspect of the overall multiple aspects reliability may vary from one state to another. Hence, it is imperative to compute the overall reliability considering all aspects at different states of component failures.

MCDA was applied to rank the set of 22 layouts in different aspects and states of pipe failure. Subjective weights can be easily assigned to each state of multiple aspects reliability if historical information about type and number of pipe failures for the layouts is available. This research did not incorporate the subjective weights in the decision-making, as the test case was a hypothetical WDS with no history. Objective weights demonstrated the scattering in the results of each applied criterion (each state of reliability results) in MCDA to the total scattering for all criteria (all states of reliability). Among the incorporated criteria in MCDA, the criterion, which scattered more, received a larger objective weight and contributed more in the final decision. The concept of information entropy (Shannon, 1948) was employed to assign the objective weight to each state of overall multiple aspects reliability (criterion). Table 5.14 shows the results.

Table 5.14 Assigned weight to each state of multiple aspects reliability (criterion) in MCDA

weight	0^{th} State multiple aspects reliability	1^{st} State multiple aspects reliability	2^{nd} State multiple aspects reliability	Entropy
Objective	0.01041	0.07749	0.78665	0.12545
Independency	0.20973	0.26020	0.21658	0.31349
Overall	0.05843	0.17754	0.51608	0.24795

In the Table, the zeroth state of overall reliability received the lowest objective weight. As the state of overall reliability increased, the objective weight increased. With a sudden increment, the highest objective weight went to the second state of multiple aspects reliability. The flow entropy, which represented higher state of overall reliability, received the second largest objective weight. Therefore, the objective weights (Table 5.14) showed that the second state multiple aspects reliability of layouts scattered and fluctuated in higher range compared to the other states of reliabilities. This indicates that any small changes in the layouts at the second state of multiple aspects reliability led to larger variations in results. Objectively, the second states of multiple aspects reliability should contribute more in the final decision for ranking the layouts. Considering the amount of correlation that may exist among incorporated criteria in MCDA, the independency weights were also computed (Table 5.14). The highest independency weight went to the flow entropy, which represented higher state of overall reliability. The first, second and zeroth state of multiple aspects reliability received lower independency weights compared to the flow entropy, respectively. This implied that zeroth and second states of multiple aspects reliability results had higher correlation with the other states of reliabilities and should contribute less in the ranking of the layouts. Finally, the overall weights were estimated as the normalized geometric mean of objective and independency weights. Table 5.14 also shows the results of the overall weights. Second state of multiple aspects reliabilities and flow entropy as a representative of higher states of overall reliability received the largest overall weights among all the criteria in MCDA. This highlighted the importance of higher states of reliability in ranking the layouts. Hence, engineers/designers should pay more attention to the higher states of overall reliabilities while choosing the most reliable layouts. Unfortunately, this has been historically neglected.

Assigning the overall weights to each criterion and using three MCDA techniques of WSM, WPM and TOPSIS, the WDS layouts were scored and ranked. Table 5.15 shows the results based on zeroth, first and second states of multiple aspects reliability and MCDA.

Table 5.15 Ranking WDS layouts based on different states of multiple aspects reliability, and MCDA

Layout Number	Rank No. 0^{th} state multiple aspects reliability	Rank No. 1^{st} state multiple aspects reliability	Rank No. 2^{nd} state multiple aspects reliability	Rank No. (WSM)	Rank No. (WPM)	Rank No. (TOPSIS)
1	4	17	16	16	16	16
2	3	19	18	19	19	18
3	13	15	14	15	15	15
4	15	11	11	11	11	11
5	14	10	10	10	10	10
6	21	6	5	3	3	3
7	20	7	7	7	7	7
8	22	1	1	1	1	1
9	12	8	8	8	8	8
10	11	9	9	9	9	9
11	9	16	15	14	14	14
12	2	21	20	20	20	20
13	19	5	6	4	4	6
14	18	2	2	2	2	2
15	17	4	4	6	6	5
16	16	3	3	5	5	4
17	10	20	19	18	18	19
18	1	22	21	21	21	21
19	8	12	12	12	12	12
20	5	14	22	22	22	22
21	6	18	17	17	17	17
22	7	13	13	13	13	13

While the results of the three techniques of MCDA were fairly identical, they were different from the results for zeroth, first and second states of multiple aspects reliability. Dissimilarities in the multiple aspects ranking outcomes were more noticeable in layouts with less number of linking pipes and less overall multiple aspects reliability. Thus, it is essential to incorporate different states of multiple aspects reliability outcomes into decision-making process to get the most realistic results. Each state of multiple aspects reliability had its own contribution in final ranking. Table 4.5 shows the ranking results of the same layouts reported in this chapter.

In chapter 4, Gheisi and Naser (2015a) ranked the same WDS layouts using different states of reliability but in single aspect of water adequacy. Clearly, the results of ranking based on single aspect are different from those for multiple aspects reliability ranking particularly for the lower states of reliabilities. Therefore, relying on just one aspect cannot guarantee an ideal overall performance of the WDS in future. To perform a comprehensive reliability assessment, it is imperative and highly recommended to apply multiple aspects and states reliability analysis.

5.6 Summary

A comprehensive WDS reliability analysis should study various states and combination of component failures along with the system responses to those failures in various aspects. This research applied the novel technique of quadrant and octant analysis to study the response of a WDS to pipe failures in two or three aspects simultaneously at different states of failure (pipe failure combinations). This novel technique enables researchers to evaluate the performance of a WDS in any two or three quantifiable aspects simultaneously at various levels of failure.

A set of 22 different layouts of a hypothetical WDS was tested. The responses of 22 different WDS layouts to one and two pipes failure at a time were studied in three aspects of adequacy, equity and efficiency. Mean of the performance responses and the performance deviations from the mean in two or three aspects were evaluated using the quadrant and octant analyses. Contribution probability of pipe failures events to each quadrant and octant zone in every two or three aspects was computed. It was interesting to see that the WDS layouts with the highest adequacy and equity in water delivery had the lowest efficiency due to the water leakage losses. Results showed a strong positive correlation between adequacy and equity in water delivery. Hence, the layouts which can provide more water for consumers during pipe failures were also able to distribute the water among users in a more fairly manner. However an evident negative correlation was observed between efficiency of WDS layouts and water adequacy and equity performance indices in case of one pipe failure at a time events. Distribution systems with high ability to deliver water to consumers during one-pipe failures usually suffer from low efficiency and higher amount of leakage losses. Hence, engineers/designers should be careful about this fact and evaluating the performance of a WDS in just one aspect cannot guaranty the perfect overall performance of the WDS in future. Results of quadrant and octant multiple aspects performance analysis of layouts revealed which WDS layout have more/less chance of receiving less/more water in a fairly manner comparing to the mean condition.

Using the results of performance response analyses, in the next step an attempt was made to compute the overall multiple aspects reliability of layouts under different state of pipe failures. The results of zeroth state multiple aspects reliability revealed that WDS layouts were highly reliable in adequacy and equity aspects. However, the overall zeroth state reliability of the systems dramatically decreased when considering various aspects together. This highlights the significance of multiple aspects analysis. Hence, evaluating the reliability of a WDS in just one specific aspect without incorporating the other important aspects can lead to unrealistic and misleading results. Results revealed that efficiency was the dominant aspect in computation of overall multiple aspects zeroth state reliability. It is interesting to mention that in first and second states reliability the dominant aspect was found to be the adequacy and equity. Therefore, the dominant aspect in computation of the overall multiple aspects reliability may vary from one state to another state of reliability. Hence, to get the best results it is imperative to compute the overall reliability considering all aspects at different states of component failures.

In the next step, the novel and comprehensive technique of multiple aspects and states reliability ranking was performed. MCDA was applied to rank the set of 22 Layouts in different aspect and states of pipe failure. Results of weight assignment to each criterion showed that as the state of overall reliability increase the objective weights gradually increase. The highest objective weight was assigned to the second state of overall multiple aspects reliability and flow entropy, which represents higher state of overall reliability. Therefore, objectively higher states of multiple aspects reliability results should contribute more in the final decision of ranking the layouts. The highest independency weight goes to flow entropy, which represents higher state of overall reliability and lower weights were assigned to first, second and zeroth state of reliability, respectively. It indicates that zeroth and second states of multiple aspects reliability results have higher correlation with the other states of reliability outcomes and should contribute less in final reliability ranking of WDS layouts. Finally results of overall weigh assignment to each criterion showed that higher states of multiple aspects reliability results received higher overall weights. It reflects the importance of higher states of reliability results in reliability ranking of the WDS layouts. Hence, engineers/designers should pay more attention to the higher states of overall reliability outcomes rather than the lower states while choosing the most reliable layouts, which unfortunately has been largely ignored so far. Using the computed overall weights the MCDA was performed. MCDA ranking results were fairly identical to each other, but different from ranking results of zeroth, first and second states of multiple aspects reliability. Hence, it is essential to incorporate different states of multiple aspects reliability outcomes into decision-making process to get the most comprehensive results. In the next step, multiple aspects reliability ranking results of this study were compared with the ranking results of the same WDS layouts reported in literature. It was observed that the results of ranking based on single aspect is different from multiple aspects reliability ranking outcomes, particularly for the lower states of reliability outcomes. Therefore, relying on just one aspect cannot guaranty the perfect overall performance of the WDS in future. To perform a comprehensive reliability assessment it is imperative and highly recommended to apply the novel technique of multiple aspects and state reliability ranking using MCDA, which simultaneously looks at WDS reliability from different aspects.

Chapter 6: Reliability under a Wide Range of Future Uncertainties[5]

> "*We need to recognize the limits to human foresight. We need to recognize that forecasts are always wrong and that our future is inevitably uncertain. We thus need to look at a wide range of possible futures and design our projects to deal effectively with these scenarios.*" (De Neufville and Scholtes, 2011, p. 15)

An engineered system such as a WDS is mainly built to provide services for a range of clients. The nature of clients' needs is dynamic and varies over time (e.g. water demand variation over time). Moreover, designed systems gradually deteriorate and run into several random component failures. Engineers traditionally design a WDS by using deterministic assumptions based on a certain future with projected water demands and certain pipe friction losses (Savic, 2005; Babayan et al., 2005; Giustolisi et al., 2009). However, future is uncertain and unexpected events known as trend-breakers can always make predictions wrong (De Neufville and Scholtes, 2011). Consequently, water authorities spend a large amount of money to adapt and update the WDSs to the latest client's needs and variations (adaptation costs). To prevent or lessen the adaptation costs, it is essential to incorporate a level of reliability under a wide range of future uncertainties into all decisions at planning, design, operation, and maintenance phases. Such a level of reliability can be incorporated in the form of passive or active reliability. A passively reliable WDS is a robust and insensitive system, which can function properly under a wide range of future uncertainties (Giustolisi et al., 2009; Babayan et al., 2005, Xu and Goulter, 1999). However, an actively reliable WDS is a flexible or a changeable system, which can respond to future changes in a timely, performance-efficient and cost-effective manner to keep the system functional under a wide range of future uncertainties (Fricke and Schulz, 2005; Olewnik and Lewis, 2006; Saleh et al., 2001; Scholtes, 2007; De Neufville, 2004).

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Uncertainty has positive and negative sides including upside opportunities, which should be exploited, and downside losses or risks to be mitigated. A robust WDS is unchangeable and commonly overdesigned systems (bulletproof system), which are designed to mitigate the possible risk and losses, associated with future uncertainties. Unlike a robust WDS, the flexible system is changeable one, which can take the advantage of upside opportunities over and above the capability to mitigate the possible future risks and losses (Schulz et al., 2000; De Neufville, 2004). A flexible WDS can be adopted at several successive stages in lifetime in a timely, performance-efficient and cost-effective manner (staged development) to closely follow the trajectory of future changes in demand or supply (Eckart et al., 2011; Tsegaye, 2013). Flexibility is highly recommended to deal with lifetime future changes such as long-term and strategic planning of WDSs which require estimation of water demand and supply for a far future (Basupi and Kapelan, 2013). Very recently, Spiller et al. (2015) reviewed all the flexible design alternatives applied in urban water and wastewater systems such as stepwise staged design, modular design, design based on component platform and remanufacturing design. They concluded that flexibility is the key to ensure long-term water sector systems sustainability due to slow variables governing the lifetime uncertainty in water division. To handle other short-term and temporary sources of uncertainty such as sudden failure of pipes or fire flows in a WDS, resulting in highly dynamic variability in operating condition, researchers generally look for a robust and passively reliable WDS (Gomes and Karney, 2005; Gheisi and Naser 2014a; Spiller, et al., 2015). Such failure events happen suddenly and may temporarily and locally undermine the functionality of a WDS for a short period of time. It is difficult, if not impossible, to monitor sudden failure events to respond to them in a timely and cost-effective way. Moreover, there is not enough time for a changeable WDS to respond to those short-term and temporary eventualities using flexibility. A flexible WDS can be adopted timely to closely follow the trajectory of future long-term variations in demand or supply (stepwise development). However, a flexible WDS also needs a level of robustness at each stage of development to handle other temporary sources of uncertainty such as sudden failure of pipes or fire flows. The question is how to determine which WDS layout is the most robust or passively reliable to more easily handle a wide range of short-term and temporary uncertainties. To answer this question, this dissertation introduced a novel technique to rank a set of WDS layouts base on their level of robustness under a wide range of uncertainty. Given the various short-term and temporary sources of uncertainty, the ultimate objective of this study is to introduce a technique to find the most broadly robust and passively reliable layout for a WDS among a set of designs. A broadly robust layout is a long-lasting and passively reliable layout, which can meet functionality under wide range of short-term and temporary sources of uncertainty and unplanned events. The goal is to expand the novel concept of multiple states reliable layout, which was initially developed by Gheisi and Naser (2015a) to the concept of broadly robust layout. WDS layouts selected using the technique introduced by Gheisi and Naser (2015a) were merely able to handle different states of possible component failure combinations (mechanical uncertainty). However, the major sources of uncertainty for a WDS are broader including the hydraulic and mechanical uncertainties (Giustolisi et al., 2009; Babayan et al., 2005; Lansey et al., 1989; Xu and Goulter, 1999; Kapelan et al., 2005; Fu and Kapelan, 2011; Kang and Lansey, 2012).

This chapter provides water authorities with a useful tool to rank a set of WDS layouts based on their levels of robustness under wide range of short-term and temporary sources of mechanical and hydraulic uncertainties. There is an inverse relationship between level of reliability in both forms of robustness or flexibility and the costs of adaptation to future needs and variations. As the level of reliability of a WDS increase, the future expenditure to adapt that passively or actively reliable WDS to unforeseen variations decrease. In fact inserting an optimum level of reliability in the form of robustness or flexibility into a WDS at the planning, design, operation or maintenance phase can be an investment for the uncertain future and a key to success (Schulz et al., 2000; de Neufville, 2002). A WDS with the optimum level of reliability is the layout with the least amount of total cost. Total cost is the summation of reliability cost and adaptation cost. Reliability cost is the amount of money, which the water authorities should invest to insert a specific level of reliability in the form of robustness or flexibility into a WDS at present. The adaptation cost is the amount of money, which should be spent in future to adapt the WDS to the unforeseen variations (Schulz et al., 2000).

6.1 Methodology

In this study, technique of multiple criteria decision analysis (MCDA) was employed to rank a set of WDS layouts (alternatives) based on their level of reliability under short-term and temporary sources of mechanical and hydraulic uncertainty. Weighted sum model (WSM; Fishburn, 1967), weighted product model (WPM; Bridgman, 1922; Miller and Starr, 1969) and technique for order of preference by similarity to ideal solution (TOPSIS; Hwang and Yoon 1981) were applied. Resilience index and network resilience index were chosen as the criteria to measure WDS reliability under the short-term and temporary sources of hydraulic uncertainty. Zeroth and first state of reliability measures lower state of mechanical reliability and flow entropy was applied as a representative of higher state of mechanical reliability (Gheisi and Naser, 2015a). A reliability ranking technique considering both mechanical and hydraulic aspects was implemented and weights were also assigned to each criterion.

MCDA takes the advantage of assigning weight to each criterion to compute an overall score for each alternative (i.e., WDS layout). Weights represent the importance and percentage contribution of each criterion in final score. Sorting the alternatives based on their final score can result in reliability ranking. Combinative weighting approach proposed by Jahan et al. (2012) was employed in this study. It combines the subjective, objective and independency weights to estimate an overall weight using normalized geometric mean of weights. Subjective weights can be determined based on the engineering judgment or expertise of the decision makers using the available history of failures in a WDS. However, objective weights depend on the variation of reliability results for WDS layouts. Objective weights show what criterion should have more contribution in final decision based on the variation of reliability results. The criterion under which reliability outcomes vary more significantly over changing the layouts should receive larger objective weight and contribute significantly in final decision. This research applied the concept of information entropy of Shannon (1948) to find the amount of scattering and variation in reliability results under a specific criterion. Accordingly, the objective weights were estimated as the ratio of scattering in reliability results for each criterion to the total scattering under all applied criteria in MCDA (Hwang and Yoon, 1981]. Independency weight is the third applied weight in the combinative weighting approach (Jahan et al., 2012). The independency weight can be applied to lessen the correlation among applied criteria in MCDA (Jahan et al., 2012). The criterion with a large correlation is highly correlated with the other criteria in MCDA and receives less independency weight.

6.1.1 Resilience Index

The total input power into a WDS should be enough to overcome system's major and minor energy losses and provide consumers with adequate amount of water with sufficient pressure. Any sudden hydraulic changes in a WDS such as fire flow may result in a dramatic increase of energy losses in vicinity of the affected region. A WDS, which has some surplus power at demand nodes in addition to the minimum, required power is hydraulically more reliable and may handle unexpected hydraulic uncertainties more easily (Todini, 2000). With the aim of quantifying the available surplus power in a WDS, Todini (2000) presented the concept of resilience index (RI). Resilience index is the ratio of the surplus hydraulic power at demand nodes to the hydraulic power required to meet the consumers' demands (Todini, 2000; Farmani et al., 2005; Reca, 2008, Prasad and Park, 2004; Saldarriaga and Serna, 2007). Resilience index is mainly cited in literature to be correlated with the hydraulic flexibility and functionality of a WDS under hydraulic uncertainties (Todini, 2000; Farmani et al., 2005; Reca, 2008; Raad et al., 2010; Di Nardo, 2010; Baños et al., 2011, Atkinson et al., 2014). Resilience index can be estimated by equation (4.2) (Todini, 2000).

6.1.2 Network Resilience Index

Considering mechanical uncertainty, Todini's resilience index does not incorporate the degree of redundancy into an analysis. A branched WDS with high surplus power at demand nodes (high resilience index) cannot properly handle mechanical uncertainty. Although the excess powers in demand nodes are high but in case of pipe failure many consumers particularly those located at the end of branches may not receive water due to lack of redundancy in the system (Prasad and Park, 2004). To address this problem and find the reliable loops, Prasad and Park (2004) added a term of "pipe diameter uniformity" to Todini's resilience index. The aforementioned uniformity coefficient measures the degree of diameter consistency among a set of pipes ending at one node. Ratio of the average pipes diameter connected to one node to the maximum diameter reaching that node defines pipe diameter uniformity. Higher pipe uniformity and less variation in diameter of pipes can increase the chance of higher redundancy and existence of more reliable loops in a WDS (Prasad and Park, 2004). The network resilience can be estimated by equation (4.3) (Prasad and Park, 2004).

6.1.3 Zeroth and Higher States Reliabilities

This dissertation applied the technique developed in Chapters 3 and 4 to determine the reliability of a WDS under different states of pipe failures. It measures reliability as a probability-weighted average of performance indices of the WDS. Assigned weight to each performance index was defined as the probability of occurrence of a specific combination of pipe failure. Probability of occurrence was obtained using the concept of components availability. This technique has several advantages and was employed several times in the literature to estimate lower states of reliabilities (Gargano and Pianese, 1998; Gargano and Pianese, 2000; Tanyimboh et al., 2001; Kalungi and Tanyimboh 2003; Surendran et al., 2005). Zeroth state reliability (R^0) of a WDS was obtained by equation (4.4).

In this study, performance of the WDS was evaluated using water utility index of supply ratio or the supplied fraction of required water. It was obtained by dividing the amount of water delivered to consumers during an operational or failure condition to the minimum quantity that consumers require. The equations (4.7a) to (4.7c) based on the concept of availability (A) and unavailability (U) of the pipe i (A_i and $U_i = 1 - A_i$) was employed to determine the probability of failure for different pipe combinations (Fujiwara and De Silva, 1990; Fujiwara and Tung, 1991). Following Cullinane et al. (1992), equation (4.8) was employed in this study to estimate the availability of pipe i with the diameter D_i (in meter). Cullinane et al. (1992) indicated that a pipe could be in operation or failure condition. In another word a pipe can be in a time between two sequential failures or in the time required to repair or pipe replacement. Pipe availability was defined as the ratio of the time when the pipe is in operation or it is between two sequential failures to the pipe lifetime. Pipe lifetime comprises the time between two sequential failures and the time required to repair or replacement.

In Chapter 3, the equations for higher states of reliabilities were derived. Following Tanyimboh et al. (2001), Kalungi and Tanyimboh (2003) and Gheisi and Naser (2014a and 2015a) equations (4.5) and (4.6) was used to determine the first (R^1) and k^{th} state of reliability (R^k), respectively. First and k^{th} state of reliability represents the reliability of a WDS when there is at least one and k (≥ 2) number of simultaneous pipe failures in the system.

6.1.4 Flow Entropy

Chapter 4 indicated the statistical flow entropy (defined by equation 4.1) as proper surrogate measure for higher states of reliability analysis. Thus, this dissertation employed flow entropy as the representative of higher states of reliability in MCDA.

6.2 Test Case

Following the literature (Tanymboh and Templeman, 2000; Tanyimboh and Sheahan, 2002; Tanymboh et al., 2011; Gheisi and Naser, 2015a and b), this research tested a hypothetical WDS (Figure 4.1) with a set of 22 layouts (alternatives) as of Figure 4.2. All the demand nodes are at elevation 0 m. The pipes are 1 km long with a Hazen-Williams coefficient of 130. Table B.1 in Appendix B shows the diameter of the pipes for each layout. The pressure head at source node 1 is 100 m. Minimum required residual head at each node is 30 m. Failure of a pipe may cause a sudden pressure drop in the system. The original version of EPANET2 (Rossman, 2000) is unable to study the pressure deficient conditions when the residual pressure head at a node is not enough to fully satisfy the demand. Therefore, this research applied the modified version of EPANET2 known as EPANET-Emitter (Pathirana, 2010) to perform the hydraulic simulations in pressure-deficient conditions.

6.3 Results and Discussion

Table 6.1 demonstrates the independency, objective and overall weights computed and assigned to each criterion. Results of independency analysis in Table 6.1 revealed that the applied criteria were not highly correlated with each other. However, the applied criteria of zeroth state of reliability and resilience index were the most independent criteria. Furthermore, the first and second state of reliability showed relatively more dependency and correlation with the other criteria. Objective weight analysis in table 6.1 based on the concept of entropy revealed that the criteria of flow entropy, second state of reliability and network resilience index had the highest amount of variation and scattering in reliability results. Moreover, as the table indicates, the criteria of resilience index, first and zeroth state of reliability received lower objective weights due to their less dispersion in reliability results. Subjective weights were not assigned due to lack of information about type and number of possible hydraulic and mechanical failures, which my happen in practice. Combining all the assigned weights, Table 6.1 also demonstrates the overall estimated weights. Clearly, higher overall weights were assigned to the criteria of flow entropy, second state of reliability and network resilience index. This implies that the higher combination of pipe failures and also existence of more surplus power in a WDS along with the uniformity of pipes should receive more attention in decision-making process. This is an important finding since researchers often consider lower combination of pipe failures and they believe that the chance of failure of more than one pipe at a time in a WDS is very little (Cullinane et al. (1992), Su et al., 1987). Using the overall weights and three MCDA methods of WSM, WPM, and TOPSIS, the WDS layouts of the test case were all ranked based on their reliability. Table 6.2 shows three reliability ranking results under future hydraulic and mechanical uncertainty. The three reliability-ranking results were relatively similar and more comprehensive comparing to other techniques. The reliability ranking technique introduced in this chapter considered six mechanical and hydraulic reliability criteria of zeroth state of reliability, first state of reliability, second state of reliability, flow entropy, resilience index and network resilience index at the same time.

6.4 Summary

Researchers have mainly considered one pipe failure at a time when assessing WDS reliability as they believe that the chance of failure of more than one pipe at a time in the system is very little. In this chapter, the technique of multiple criteria decision analysis approach was employed to conduct a comprehensive reliability ranking for a set of WDS layouts (alternatives) considering six reliability criteria. Mechanical and hydraulic reliability criteria of zeroth, first, and second state reliability, as well as flow entropy, resilience index and network resilience index were applied in decision making at the same time. Both independency and objective weights of attributes were applied reflecting the relative importance of each reliability criterion. Results showed that the higher overall weights were assigned to the criteria of flow entropy, second state of reliability, and network resilience index. This implies that the higher combination of pipe failures and also existence of more surplus power in a WDS along with the uniformity of pipes should receive more attention in decision-making process. The methodology introduced in this Chapter can be applied as a more comprehensive approach for reliability analysis of WDS.

Table 6.1 Assigned weight to each criterion

	0^{th} Reliability	1^{st} Reliability	2^{nd} Reliability	Flow entropy	Resilience index	Network resilience index
Independency Weights	0.24708624	0.121735968	0.123205222	0.132358138	0.232636914	0.142977518
Objective Weights	1.09023E-06	0.058810438	0.261562601	0.376625222	0.075267987	0.227732661
Scape Overall Weights	0.000648215	0.105675144	0.224201527	0.27884715	0.165264909	0.225363055

Table 6.2 Reliability ranking of distribution systems' layouts based on three MCDA techniques

Design Number	Rank # (WSM)	Rank # (WPM)	Rank # (TOPSIS)
1	17	17	18
2	22	21	22
3	9	9	11
4	14	14	14
5	13	13	13
6	4	4	2
7	7	7	8
8	1	1	1
9	8	8	9
10	11	11	12
11	15	15	16
12	12	12	10
13	6	6	5
14	3	3	3
15	2	2	4
16	5	5	6
17	10	10	7
18	21	22	15
19	16	16	19
20	20	20	21
21	18	18	17
22	19	19	20

Chapter 7: Conclusion, Contributions, Limitations, and Recommendations for Future Research

7.1 Summary

The advanced reliability models developed in this dissertation enable water authorities and engineers to:

1) measure the reliability of a WDS under simultaneous multiple pipes failure scenario,
2) estimate the higher states reliabilities of a WDS using surrogate reliability measure of flow entropy,
3) conduct reliability rating for a set of WDS layouts under various states and combinations of pipe failure (multiple states reliability),
4) measure the performance response of a WDS to various states and combinations of pipe failure from different aspects simultaneously (multiple aspects/multiple states reliability), and
5) find the most reliable WDS layout among a set of design layouts which can meet functionality under a wide range of future mechanical and hydraulic uncertainties.

Application of the developed advanced techniques in this dissertation will eventually lead to a highly reliable water distribution system. Furthermore, the most significant outcomes of the current dissertation were as follows:

1. **Higher-State Reliability Analysis:** Simultaneous failure is more likely to occur in older networks or WDSs located in harsh climatic conditions. Previous studies have focused on WDS reliability when pipes fail individually. The current research developed a technique to determine the reliability of a WDS experiencing different degrees of simultaneous pipe failure and to assess errors in reliability that occur when an inappropriate level of simultaneous failure is assumed. The model was applied to two test cases including a hypothetical and an in-practice WDSs. Comparing the various states of reliability provided valuable information about systems' sensitivity to simultaneous multiple pipes failures. Results demonstrated that a system may be able to achieve a higher level of reliability if more realistic expectations of simultaneous failure are assumed.

2. **Multiple States Reliability Analysis:** Large computational workload is associated with higher-states reliability assessments. Studying various reliability measures, this research revealed statistical flow entropy had stronger correlation with higher states of reliability and was a better surrogate measure. A MCDA was applied to rank a set of WDS layouts (alternatives) using various states of reliabilities (criteria). The MCDA considered the relative importance of each state of reliability in the process of finding the most reliable system (decision making). The MCDA revealed the higher-states reliabilities should have more contribution in the decision-making process.

3. **Multiple Aspects and States Reliability Analyses:** This dissertation employed the techniques of quadrant and octant analyses to study the response of a hypothetical WDS to various simultaneous failures in two or three aspects. Under different states of failure, the overall multiple aspects reliability of the system was estimated. It was found that evaluating the reliability in one aspect without incorporating other aspects would be misleading. A MCDA was employed to rank the WDS's layouts. Results of single-aspect-based-ranking were found considerably different from those when multiple aspects reliabilities were considered. The differences were significant at lower states of reliabilities. The research concluded that multiple states/aspects reliability analyses would assure more reliable operation of a WDS.

4. **Wide-Range Reliable WDS:** The technique of MCDA was employed to conduct a comprehensive reliability ranking for a set of WDS layouts (alternatives) considering both mechanical and hydraulic reliability criteria. Results implied that the higher combination of pipe failures and also existence of more surplus power in a WDS along with the uniformity of pipes should receive more attention in wide-range reliability analysis. Considering several reliability criteria (instead of only a single criterion) would be more realistic approach for reliability assessment of WDS.

7.2 Contributions

This dissertation developed four advanced techniques to study the reliability of a WDS. The advanced techniques developed in this dissertation can be employed by engineers to highly secure the continuous delivery of water with adequate pressure to consumers. The following list summarizes the most outstanding contributions of this dissertation:

- Developing higher-state reliability analysis as a complementary approach to check the performance of a WDS in the event of simultaneous multiple pipes failures. The developed model can be coupled with optimization as a complementary criterion to enhance system design, including such considerations as pipe placement, size, and service area.
- Developing the advanced technique of multiple states reliability analysis, which can provide more convincing results as it considers various states of reliability and flow entropy at the same time. Moreover, it is capable of incorporating the judgment and expertise of the designers/engineers in choosing more reliable layouts using the subjective weights when there is sufficient information about the type and number of pipe failures.
- Developing the technique of multiple aspects and states reliability analysis, which can measure the reliability of a WDS from different aspects at different states and combinations of pipe failure, simultaneously.
- Develop a model to conduct a wide-range reliability analysis for a set of WDS layouts. This advanced technique can be employed by designers/engineers to determine which design layout can handle wide range of short-term and temporary sources of future mechanical and hydraulic uncertainties more easily.

7.3 Limitations

The advanced techniques developed herein to conduct higher state, multiple states, and multiple aspects WDS reliability analyses have few limitations. The computational workload involved in such analyses can be significant, even for a very small WDS, and may limit the application of the developed methodologies to simple systems. Moreover, the advanced WDS analysis techniques developed in this study are limited to pipe outage/break scenario when pipes fail completely and have to be replaced. Technique of multiple aspects WDS reliability analysis is limited to the two/three quantitative aspect of a WDS performance, which can be measured using performance indices. Qualitative aspects of a WDS performance cannot be studied using the technique introduce in this study.

7.4 Recommendations for Future Research

- This research introduced several advanced WDS reliability techniques under pipe failure, while pipe failure events were assumed independent. However, an in-practice WDS may have pipes with different spatial characteristics and two or more pipes in close proximity may be more likely to fail simultaneously. Moreover, pipes may have different consequences when they fail. For example, a pipe serving a large demand area or critical users may be considered more vital to operate than a pipe serving a small demand area or non-critical users. This needs to be studied in further details in future.
- The current study focused only on pipe failures; further research is needed to analyze WDS reliability when other system components (such as pumps, valves, and storage reservoirs) fail.
- In order to obtain an optimal layout, the tradeoff between WDS reliability and cost should be taken into consideration. Moreover, the test case in the research reported in this study was highly simplistic and it could be very informative to demonstrate the robustness of the developed approach by its application to an in-practice WDS.
- This dissertation does not address the mechanisms that lead to multiple pipes failures. Distinguishing between coinciding (random) multiple failures and clusters of failures with the same underlying cause can be addressed in future research.

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Appendices

Appendix A: Water distribution system in the city of Hanoi

Table A.1 Nodal demand for the WDS in the city of Hanoi (case 2)

Node No.	Demand (L/s)	Node No.	Demand (L/s)
1	–	17	240
2	247	18	374
3	236	19	17
4	36	20	354
5	201	21	258
6	279	22	135
7	375	23	290
8	153	24	228
9	146	25	47
10	146	26	250
11	139	27	103
12	139	28	80
13	261	29	100
14	171	30	100
15	78	31	29
16	86	32	224

Table A.2 Length and diameter of pipes for the WDS of the city of Hanoi (source of data for case 2: Shibu and Reddy, 2011)

Links	Length (m)	Diameter (mm)	Links	Length (m)	Diameter (mm)
1-2	100	1016	18-19	800	609.6
2-3	1350	1016	19-3	400	508
3-4	900	1016	3-20	2200	1016
4-5	1150	1016	20-21	1500	508
5-6	1450	1016	21-22	500	406.4
6-7	450	1016	20-23	2650	1016
7-8	850	1016	23-24	1230	762
8-9	850	1016	24-25	1300	762
9-10	800	1016	25-26	850	609.6
10-11	950	762	26-27	300	406.4
11-12	1200	609.6	27-16	750	304.8
12-13	3500	609.6	23-28	1500	406.4
10-14	800	406.4	28-29	2000	406.4
14-15	500	304.8	29-30	1600	304.8
15-16	550	406.4	30-31	150	304.8
16-17	2730	304.8	31-32	860	406.4
17-18	1750	406.4	32-25	950	609.6

Appendix B: Case study specifications

Table B.1 Diameter in millimeters for the pipes connecting the subsequent nodes for the case study (data derived from Tanyimboh and Templeman, 2000)

Design number	1-2	1-4	2-3	2-5	4-5	4-7	3-6	5-6	5-8	7-8	7-10	6-9	8-9	8-11	10-11	9-12	11-12
1	348	310	266	226	–	289	238	–	189	186	185	213	–	202	143	105	177
2	284	368	268	–	225	286	240	–	188	184	184	215	–	200	143	105	176
3	328	335	275	169	174	272	248	–	189	174	259	225	–	–	229	143	151
4	326	336	265	185	186	270	237	–	221	161	177	212	–	213	130	100	180
5	298	360	223	191	190	298	184	–	229	166	219	139	227	–	191	182	100
6	310	354	206	227	226	265	160	209	209	157	172	231	–	200	123	139	157
7	294	365	194	214	212	291	141	181	206	154	216	190	194	–	188	185	100
8	302	361	192	228	226	275	138	175	239	179	169	182	178	184	119	162	135
9	325	337	227	231	232	234	190	–	293	–	185	149	194	178	139	149	147
10	353	307	225	273	–	286	187	181	178	182	184	227	–	190	142	135	159
11	315	345	231	210	210	265	195	–	260	–	226	156	211	–	198	175	109
12	350	309	275	214	–	289	249	–	165	200	257	226	–	–	227	145	147
13	307	355	221	208	206	282	182	–	255	188	172	137	204	189	124	150	147
14	318	346	197	246	247	233	146	182	270	–	184	197	160	170	139	162	133
15	345	319	205	276	–	299	159	153	207	210	177	179	178	177	133	158	137
16	231	404	210	–	275	295	162	152	206	206	176	181	176	175	133	158	137
17	361	314	266	245	251	162	238	–	315	276	276	214	–	–	248	113	180
18	405	236	267	308	–	208	240	–	283	238	269	217	–	–	241	124	170
19	251	390	232	–	302	244	193	182	223	–	199	233	–	163	163	146	148
20	375	274	227	302	–	249	189	183	223	–	204	230	–	162	166	145	149
21	323	336	227	227	–	318	190	190	–	226	195	235	–	164	159	148	147
22	250	390	231	–	225	315	192	189	–	224	194	236	–	163	159	148	147

Appendix C: Anderson–Darling normality test

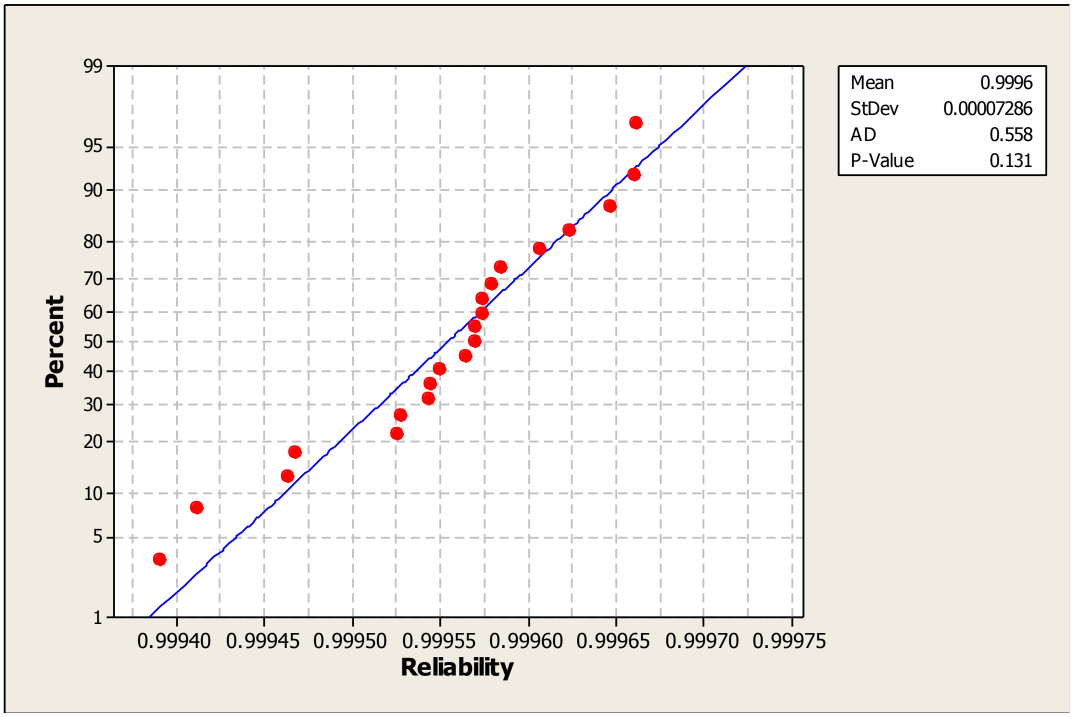

Figure C.1 Normal probability plot of measured reliability

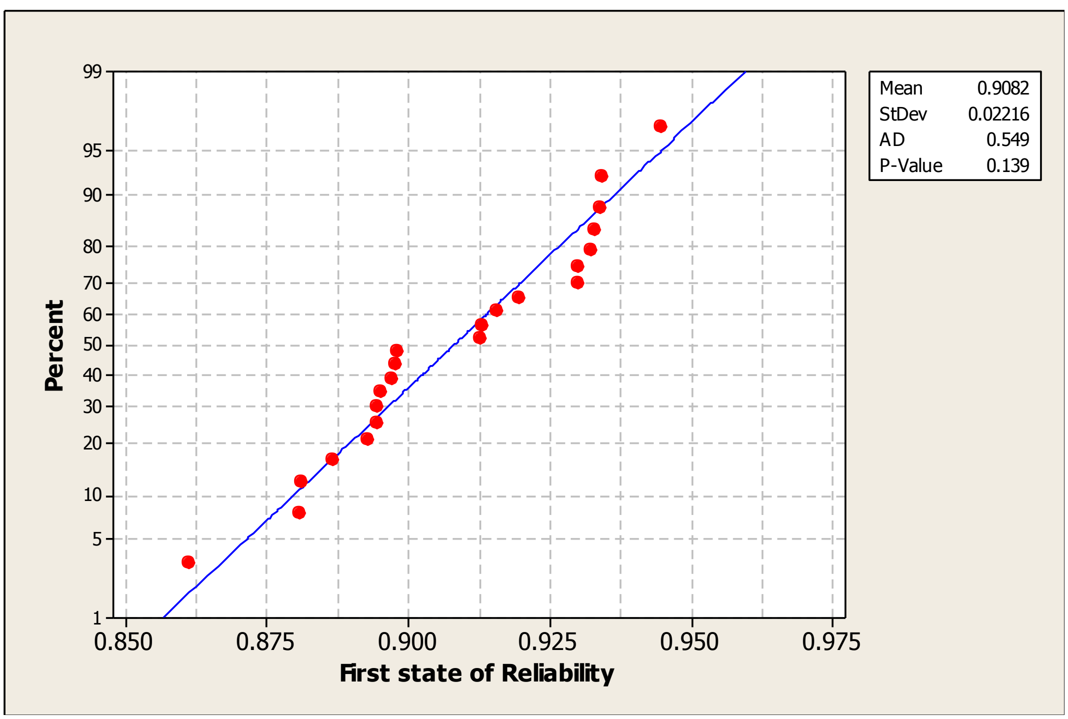

Figure C.2 Normal probability plot of measured first state of reliability

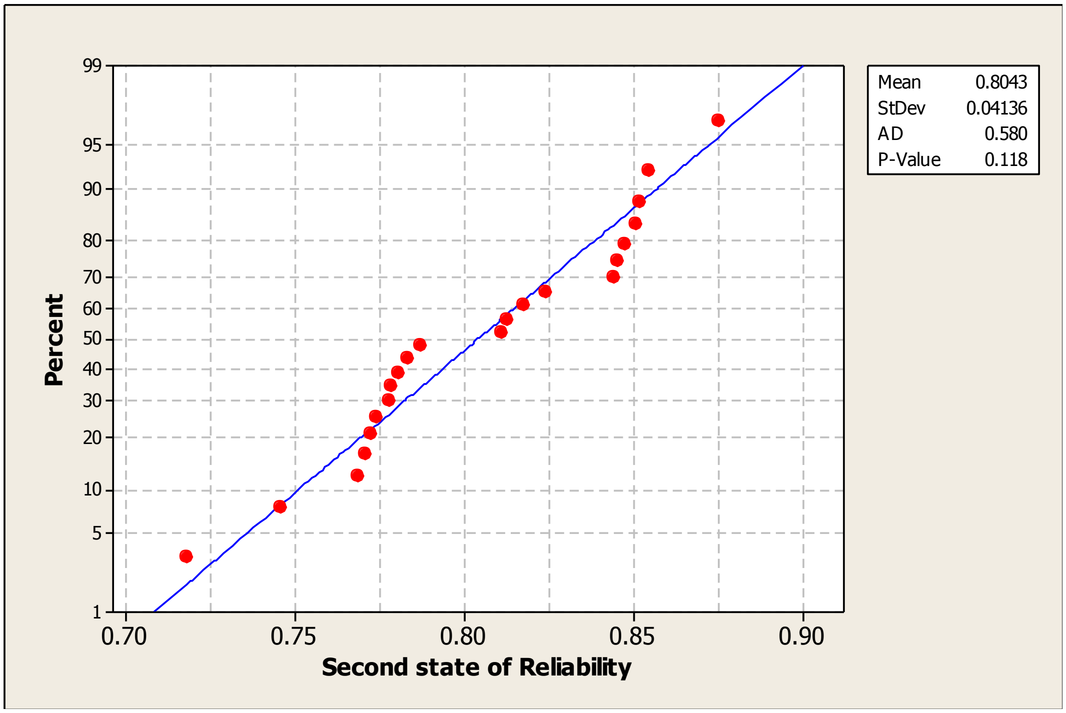

Figure C.3 Normal probability plot of measured second state of reliability

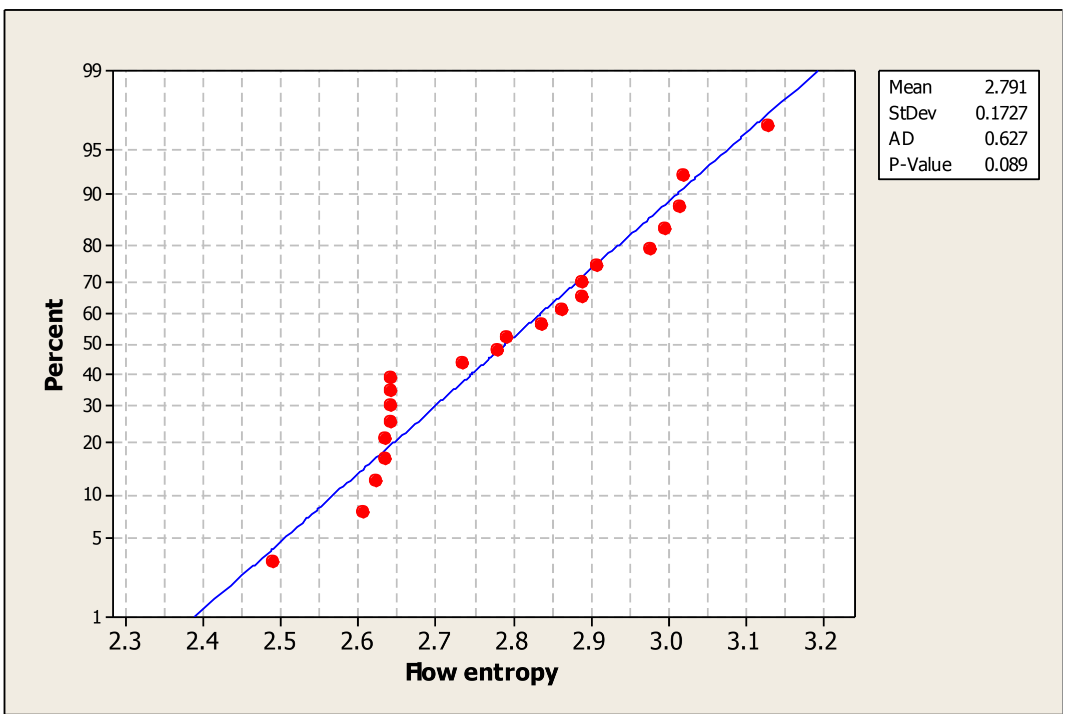

Figure C.4 Normal probability plot of measured flow entropy

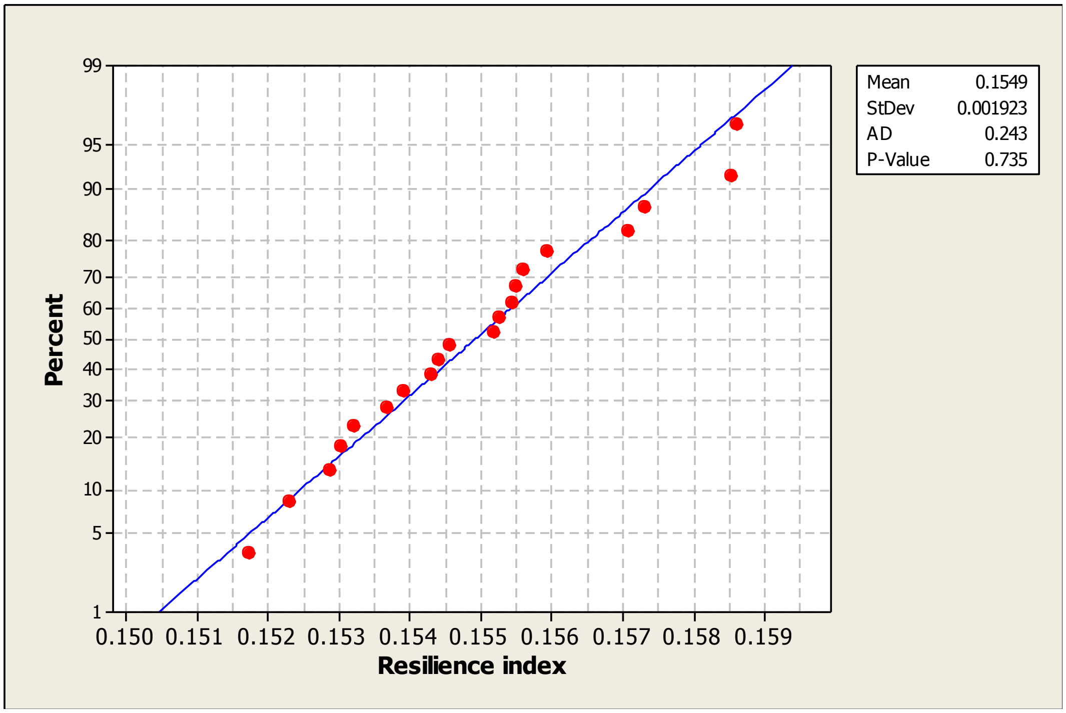

Figure C.5 Normal probability plot of measured resilience index

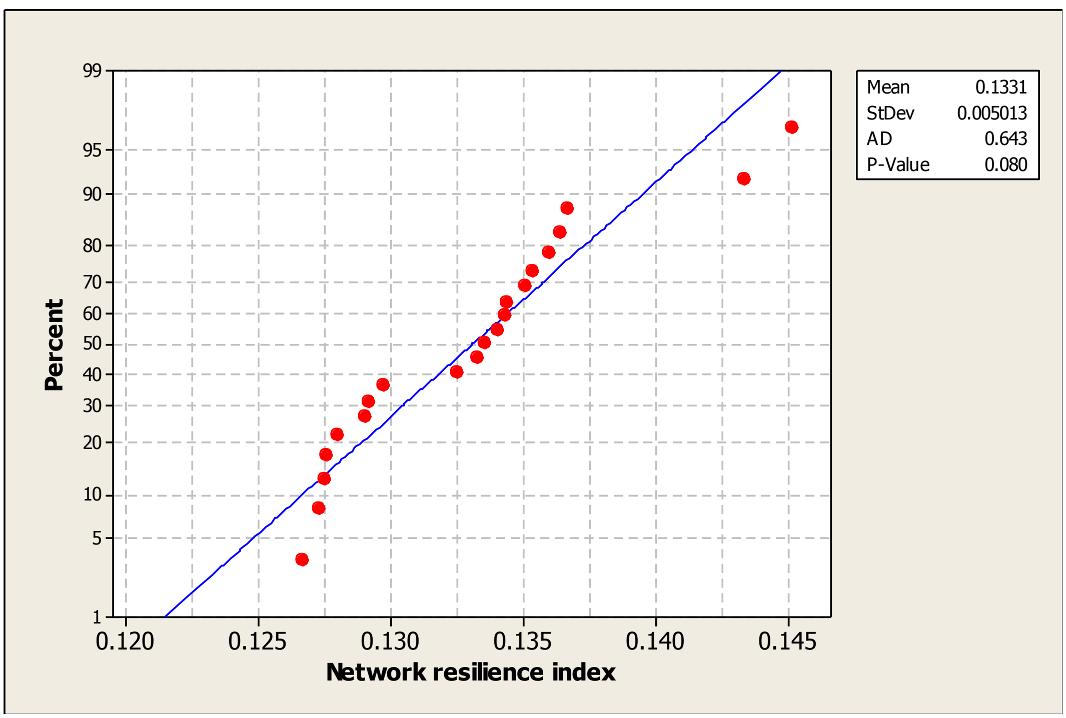

Figure C.6 Normal probability plot of measured network resilience index