FLEXIBLE DESIGN OF URBAN WATER DISTRIBUTION SYSTEMS

by

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ABSTRACT

Urban water distribution systems (UWDS) are highly inter-connected and under many uncertainties from water demand, pipe roughness, and component failure. Accurate projections of these uncertainties are almost impossible, and thus it may not be a proper method to design the system to meet its performance criteria for the forecasted scenario. The system is designed for the deterministic not for the uncertainties, as a result it may not be efficient or effective to be operated under different future scenarios. Flexible design is shown as a useful strategy to cost-effectively respond to uncertainties because of its consideration of uncertainties in advance, and has been successfully applied in many engineering systems.

The objective of flexible design is to identify flexibility sources in UWDS and embed them into the system design to respond to uncertainties. The thesis discussed different terms to define the property of the system to respond to uncertainties and proposed a definition of flexibility for UWDS. It then proposed different measures to indicate flexibility value and introduced an efficient method to handle numerous uncertain parameters in the model. It also develops an efficient method to identify high value flexibility sources based on the Flexibility Index. Finally the thesis presents a flexibility-based optimisation model that enable water engineers to compare different flexible design alternatives and generate optimal solutions.

A definition of flexibility in UWDS is proposed to illustrate broadly its property to respond to uncertainties, since it is not so useful, or at least in this thesis to distinguish similar terms to define the property of the system to respond to uncertainties. Identified flexibility sources by the proposed method is not useful for the flexibility-based optimization model to design a system, but it might be a powerful tool to locate the weak points in the system or provide better update options during rehabilitation of the system. The computational efficiency of the proposed flexibility-based optimisation model was demonstrated by dramatic decreasing on the number of the required hydraulic simulation in the case study. Flexible designs in the case study are more expensive than inflexible design, but have better hydraulic performance under uncertainties.

To my family

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LIST OF ABBREVIATIONS

UWDS	urban water distribution system
GA	Genetic Algorithms
WDS	water distribution system
SC	Surplus Capacity
RL	Reliable Loop
PDN	Pressure on Demand Node
PMPN	Pressure on Minimum Pressure Node
MCS	Monte Carlo Simulation
LHS	Latin Hypercube Sampling
STM	Scenario Tree Method
FORM	First Order Reliability Method
DFS	depth-first search
FI	Flexibility Index
EA	evolutionary algorithms
MOEA	multi-objective evolutionary algorithms
NSGA	Non-Dominated Sorting-based multi-objective evolutionary algorithm
NPD	nodal pressure deficiency

Chapter 1 Introduction

1.1 Problem statement

Forecasts are "often wrong". This is also true for an urban water distribution system (UWDS), where the designed capacity rarely realistically meets the exact required capacity. The reason is that the future is often unconstrained and could be affected by many uncertainties. Flexible designs consider these uncertainties in advance and make the systems planned for them, and as a result the systems can perform well despite the existence of these uncertainties. Therefore, the objective for flexible design in UWDS becomes designing the system to avoid risks from uncertainties cost-effectively. Water engineers must plan such a system that it can function economically under different possible futures.

There are fruitful applications in other engineering systems, which showed that flexibility had value for the system under uncertainties (Gessner and Jardim 1998; Zhao and Tseng 2003; De Weck et al. 2004; Kalligeros 2006; Richard de Neufville et al. 2006; Cardin et al. 2008). The work in this thesis is motivated by a gap in literature, where there are inadequate publications addressing the problem of defining flexibility in UWDS, finding appropriate measures to indicate its value for the system under uncertainties, and developing an applicable methodology to generate flexible design. Flexibility in UWDS has been mentioned in some papers, but to date no methodology has been developed to guide water engineers on how to design flexibility in UWDS to respond to uncertainties.

1.2 Uncertainty

UWDS are designed and operated to provide sufficient water to consumers over a long period of time, meeting performance requirements such as required quantity, quality, and pressure under both normal and abnormal operating conditions (Goulter 1995). The classical design based on expected future circumstances can not keep the system performing effectively and efficiently, since many factors, in economic, societal, and technological, could be in effect and direct evolution of real circumstances away from the original prediction. It has been stated in the literature (Lansey et al. 1989; Xu and Goulter 1999) that the major uncertainties in UWDS are water demand, pipe roughness, component failure, and pressure requirement. These uncertainties would affect the performance of UWDS and put them at risk of being unable to deliver a satisfactory service:

1. Nodal demands in UWDS are highly uncertain. Since it is impossible to define accurately the location and quantity of consumers, and the future demand and required pressure head have seldom been predicted accurately. The excess of actual demand over the designed value makes system unable to deliver sufficient water at appropriate pressure. As a result, some pressure deficiencies would exist in the system. On the other hand, the surplus of designed capacity over the required capacity also causes some problems. The main problems are waste of investment and deterioration in water quality. Both of two mismatches between the designed capacity and the required capacity result in difficulties in making good decisions when designing UWDS.

2. The remaining system capacity with time is another uncertainty in UWDS. The ability of a system to carry the designed flow will decrease with time due to corrosion and deposition in the system. The roughness coefficient of the pipes can be used to reflect these changes in the system capacity (Hudson 1966) and these coefficients are affected by many inter-dependent factors. The impacts of these factors on pipe roughness are not well known, and as a result there are high uncertainties in the projections of roughness coefficients in pipes.

3. The remaining state of system configuration is the third uncertainty parameter. The remaining state would change with failure of different components, such as pipe burst, valve blockage, and pump breakdown, which results in decrease in the system delivery capacity, making it unable to deliver required demand at appropriate pressures. The consequences could be partial pressure decreases at nodes or totally shut down for some

consumers. The original capacity can be persisted by some operations (e.g., emergency pumping) and would be recovered after maintenance is made. Although component failures result in supply deficiency for a short period, their effects on performance are significant. Therefore, for a good design some strategies have to be considered to respond to component failures.

These major uncertainties are unavoidable during the lifecycle of UWDS and have to be considered by water engineers when designing the system. Good decisions should be made today to guarantee that they could still function well in the future. Considering complexity of UWDS and the existence of many uncertainties, it becomes challenging to find the best solution regarding the combination of the right system components and their individual designs (mainly capacity design).

In summary, system performance in UWDS fluctuate due to the existence of uncertainties, therefore more innovative design and response techniques are required to handle these uncertainties. There is a need to embed some responses in the system design, by considering these uncertainties in advance.

1.3 Aim and objectives of the work

The overall aim of this work was to generate flexible design for the urban water distribution system (UWDS), which could have improved pressure performance under uncertainties.

The objectives of this research can be specified as:

1. To study different definitions of flexibility in the system to define flexibility in UWDS, not only covering the key properties of the ability of the system to respond to uncertainties but also interpreting well the characteristics of UWDS.

2. To study different possible flexibility measures and compare them on computational

demand and applicability in flexibility identification and flexibility optimisation to propose proper flexibility measure for this research.

3. To study different methods to model uncertain nodal demand, pipe roughness, and component failure to propose an efficient method to model uncertain nodal demand, pipe roughness, and component failure for UWDS to generate flexible design.

4. To study different components in UWDS and to explore their potential of providing flexibility.

5. To propose an efficient optimisation model to generate flexible design for UWDS and to test its applicability by a case study.

1.4 Bridging the gap: thesis

1.4.1 Approach

In recent literature (Gessner and Jardim 1998; Zhao and Tseng 2003; De Weck et al. 2004; Kalligeros 2006; Richard de Neufville et al. 2006; Cardin et al. 2008), flexible design has been well researched and applied to respond to uncertainties in the engineering systems. Unfortunately, the methodologies for flexible design in UWDS are immature and in their infancy. The methodology proposed in the thesis attempts to bridge this gap. It would change water engineers' thinking during the design process, and help them produce an optimal design solution with flexibility embedded.

This thesis introduces an efficient method to help water engineers identify high value flexibility sources in UWDS, and proposes a flexibility-based optimisation model to enable water engineers develop a system solution with flexibility embedded to respond to uncertainties. The flexible design of UWDS could be mimicked as a multi-stage decision process. The most flexible option would include the decisions on the system configuration at each stage, with their inter-relationship analysed in the proposed model. Decisions on the initial system capacity are made to meet the requirements of the first stage and may also capture some requirements for the subsequent stages. Decisions on subsequent stages would be made keeping in mind that the decisions in previous stages have already become known. Both of them have been considered in the model, and thus the optimal solution can be found with the sub-solution in each stage. The proposed method considers the uncertain circumstances and captures them with embedded flexibility while the classic approach is based only on the expected scenario. As a result, the design solution for the proposed method can give the flexibility value in the system lifecycle, which provides a cost-effective way to respond to uncertainties.

UWDS consist of many functional components and would exist for a very long time, which are integrated as a whole to provide a satisfactory service to one or several communities. The proposed flexible design generates the optimal solution on the existing components within each stage by exploring the possible design space. As a result, the method designs the system with the best ability to respond to underlying uncertainties, which integrally will make the system deliver more value in an uncertain world.

The thesis first introduces the concept of flexible design, including the definition of flexibility in UWDS, some measures to indicate the flexibility value, and a framework for achieving flexible design. It then discusses some flexibility sources in UWDS and develops an efficient method to identify high value flexibility sources in the system. Finally, to achieve flexible design in UWDS, an efficient uncertainties modelling and a flexibility-based optimisation model are developed.

1.4.2 Contributions

The thesis tried to develop a new methodology, which could generate flexible design for UWDS. The resulted flexible design has improved pressure performance under uncertainty. The methodology proposed a design process, which could help water engineers not only consider uncertainties but also identify proper responses to them.

Flexibility was defined in numerous engineering systems. However, there is not a proper definition of flexibility for UWDS. The thesis tried to develop a definition of flexibility for UWDS, not only covering the key properties of flexibility but also interpreting well the characteristics of UWDS.

There were numerous system performance measures for UWDS in the literature. However, their applicability for flexibility identification and flexibility optimisation has not been studied. The thesis proposed different possible flexibility measures and compared them on computational demand and applicability for flexibility identification and flexibility optimisation.

Some methods were developed to model either uncertain nodal demand and pipe roughness or component failure. However, they have not been well handled within one model. The thesis developed an integral uncertainty model to consider all these uncertainties. The model applied "robustness" concept to transfer the stochastic problem into a deterministic one, by incorporating "safety margins" into the uncertain nodal demands. The model also approximated the system performance under component failure, by only checking the performance of two s-t spanning trees with partial or full load demand. As a result, these two techniques generated great computational saving.

Components in UWDS are assigned with their basic functionality, e.g. using pipe to transfer water. However, they have not been studied on their potential to provide flexibility (improve pressure performance under uncertainties). In the thesis, major components in UWDS were explored on their potential to provide flexibility under uncertainties.

Components in the UWDS are integrated with each other and with high complexity. It is difficult to analyze flexibility value on the element-level that which component in the system can provide more flexibility. Also this process is computational demanding. The thesis developed an efficient flexibility identification method, which consider inter-connection among the different components.

There are numerous decisions for flexible design in UWDS. It is difficult, if not impossible to compare them one by one. The thesis developed a flexibility-based optimisation model to efficiently compare different designs and generate optimal flexible design. The resulting optimisation model incorporates the uncertainty modelling and identified flexibility sources into a GA process. Water engineers can then use this model to generate flexible design for UWDS. Furthermore, different flexible designs can be produced by simply setting different control parameters in the model. The model could be easily initialised and re-run until the satisfactory solution is obtained.

The thesis finally demonstrated the application of the developed methodologies in one case study for designing flexibility for UWDS. The optimal solution is presented and the performance is analyzed. The purpose is to show the applicability of the methodology and illustrate the advantages and disadvantages. After these discussions, future recommendations are suggested to improve and explore the current methodology.

1.5 Thesis outline

Chapter 2 discusses the concept of flexible design. It reviews the definition of flexibility in the different areas and proposes criteria for defining flexibility. It then proposes a definition of flexibility for UWDS. It also reviews some measures to indicate the value of flexibility, and discusses their advantages and disadvantages. Chapter 3 reviews some methods to model uncertainties, and discusses their suitability for modelling uncertain nodal demands and component failures in UWDS. It then develops an efficient method to integrally model uncertainties in UWDS. Chapter 4 discusses some flexibility sources in UWDS and develops a method to identify high value flexibility source in the system. Chapter 5 reviews the basic components of the GA process, and proposes a flexibility-based optimisation model. The optimisation incorporates uncertainty modelling and identifies flexibility sources into a GA process. Chapter 6 illustrates an application of the proposed flexibility-based optimisation model in one case study. The final chapter summarises the thesis and proposes some recommendations for future research. The outline of the thesis is illustrated in Figure 1-1.

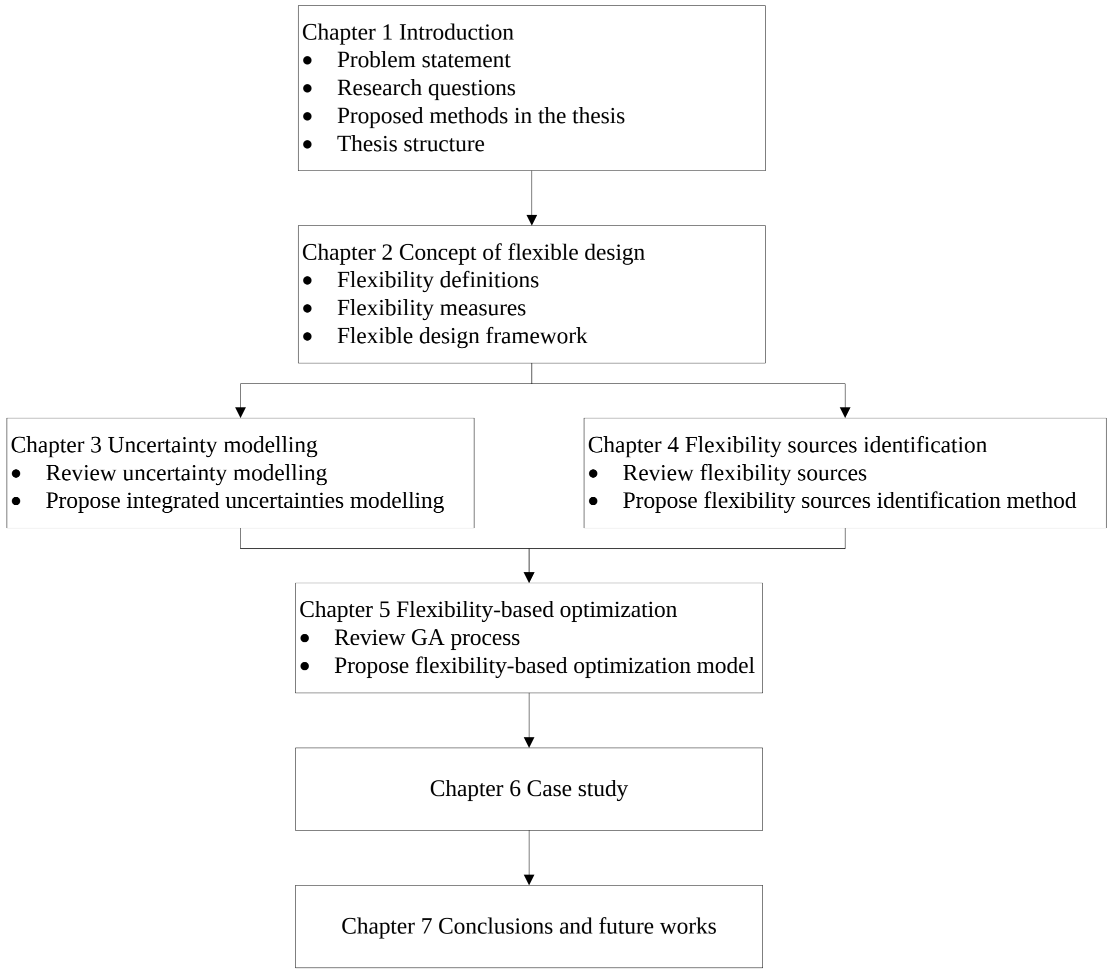

Figure 1-1 Structure of the thesis

The concept of flexible design (Chapter 2) provides basic guidance for uncertainty modelling (Chapter 3), flexibility sources identification (Chapter 4), and flexibility-based optimisation (Chapter 5). Uncertainty modelling and flexibility sources identification are sub-components for flexibility-based optimisation. Flexibility sources identified in Chapter 4 are decision spaces for flexibility-based optimisation. The integral uncertainty model in Chapter 3 is used to check performance of different designs for flexibility-based optimisation. Case study in Chapter 6 is used to apply the flexibility-based optimisation in Chapter 5.

Chapter 2 Concept of flexible design in UWDS

2.1 Introduction

One of main objectives of UWDS is to ensure sufficient water supply to consumers. However, numerous uncertainties in UWDS challenge water engineers to design cost-effective systems that meet the minimum service level (e.g., minimum pressure on demand node). Uncertainties in nodal demand, pipe roughness, and component failure can cause variations in nodal pressures, which may result in pressure dropping in some nodes below the required minimum pressure. Therefore, there is a need for water engineers to develop strategies in advance (flexibility) to minimise pressure deficiency from these uncertainties. Flexibility is a proactive strategy, which has been applied by researchers to mitigate risks or exploit opportunities in engineering systems (Zhao and Tseng 2003; De Weck et al. 2004; de Neufville et al. 2006; Kalligeros 2006; Cardin et al. 2008). Flexibility enables the system with the capability to respond to uncertainties in a cost-effective manner. This chapter explores some basic concepts in flexibility: flexibility definitions, flexibility measures, and flexible design framework.

This chapter compares similar terms to describe the property of the system to respond to uncertainties in Section 2.2. It then detailed reviews different definitions for flexibility in engineering systems, discusses criteria to develop the definition, and proposes a definition for UWDS in Section 2.3. It also introduces some measures to indicate flexibility in UWDS, and discusses their advantages and disadvantages in Section 2.4. Finally it introduces a flexible design framework in Section 2.5 and gives a brief chapter summary in Section 2.6.

2.2 Property of the system to respond to uncertainties

2.2.1 Robustness

Robustness is defined as: '*Robustness characterize a systems ability to be insensitive towards changing environments, robust systems deliver their intended functionality under varying* *operating conditions without being changed*' (Fricke and Schulz 2005). They also argued that robust system could meet functionality for varying conditions without changing the system while flexible system requires changes from external to meet its functionality. Although this argument could be used to distinguish between robustness and flexibility, the essential of them are similar, which showed the property of the system to respond to uncertainties. Robustness could be viewed as one kind of flexibility.

2.2.2 Adaptability

Adaptability is defined as: '*a system's ability to adapt itself towards changing environments*' (Fricke and Schulz 2005). Adaptable systems can change themselves to meet functionality for varying conditions. They argued that changes in adaptable systems come from internal while changes in flexible systems are from external. Although this argument could be used to distinguish between adaptability and flexibility, adaptability and flexibility are essentially similar, the property of the system to respond to uncertainties.

2.2.3 Reliability

Reliability describes the ability of a system to perform an intended system function under specific stated conditions for a defined period of time (Tung 1985; Awumah et al. 1990). Like robust systems, reliable systems could meet functionality without internal or external changes. Researchers in water distribution systems did not particularly distinguish between robustness and reliability.

2.2.4 Resilience

Resilience is defined as '*the ability of the system to adsorb disturbances and still retain essentially the same structure and function*' (Van der Brugge 2009). Resilience is characterised by retaining the system structure and function, while flexibility only has to guarantee the systems function but has not to preserve the original system structure.

Robustness/reliability and resilience refer to the property of the system to meet functionality without changes, while adaptability and flexibility refer to the property of the system to meet functionality with changes. The difference between adaptability and flexibility is that changes for adaptability are from internal while changes for flexibility are from external. Although these could be used to distinguish the specific property of the system to respond to uncertainties, they are essentially similar. They all illustrate the property of the system to respond to uncertainties. In this thesis, flexibility is broadly defined. Any property of the system to respond to uncertainties could be viewed as one kind of flexibility, that is robustness/reliability, resilience, and adaptability are kinds of flexibility.

2.3 Definition of Flexibility

2.3.1 Definitions of flexibility in different systems

There are numerous definitions for flexibility in different systems, and until now there is no definition that is commonly accepted. Whitney (2002) argued that '*flexibility comes in many forms, and that there is no single definition that fits all circumstances*'. That is to say that the definition of flexibility varies from system to system, and may also change from one application problem to another for one system. Several typical definitions for flexibility from different systems are presented first.

In the manufacturing systems:

- Slack (1987) defined flexibility as '*the range of possible states; the time needed to move from one state; and the cost required to change the state*'.

- Upton (1995) defined flexibility in manufacturing as '*the ability to change or react with little penalty in time, effort, cost, or performance*'.

The similarity of these two definitions is that both definitions interpreted flexibility as the ease of a system to adapt to future changes. The ease is measured by the required time and cost for the changes. The difference between these two definitions is that Slack (1987) considered the range of possible states while Upton (1995) considered the performance after changes. According to Slack (1987), it may be right that there is more flexibility if the system can respond to more possible states even with more cost. However, it was not considered whether the response could meet the performance requirement or not. For Upton (1995), this was included into the definition. Flexibility should not only have the ease to respond to uncertainties, but should also guarantee the performance after the response.

In the network-based systems:

- Moses (2003) defined flexibility as '*the number of paths in them*'.

Many engineering systems are network-based, such as transportation systems, water supply systems and electricity systems. The components represented as nodes and links, are connected with each other with information, water, or energy transferring among the nodes by the links. As connectivity within these systems is high, they normally have some flexibility to respond to uncertainties. When the number of connectivity increases, it is thought that more flexibility could be created because more choices are available to exchange information, water, or energy among nodes. As a result, the more paths there are, the more flexibility is generated. However, this definition is very conceptual, and without real analysis, it is likely that engineers could use this definition incorrectly.

In the space systems:

- Nilchiani and Hastings (2007) defined flexibility as '*the ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner*'.

The drivers for the need of flexibility are potential changes, which can be internal or external. These changes would decrease the delivered value, and the purpose of flexibility is to sustain the delivery value. The resultant flexibility enables response in a timely and cost-effective manner. This definition states the reason for flexibility, the measure for flexibility, and the result for flexibility. However, the problem representation is low, which may cause some confusion because flexibility may vary from one problem to another within a single system.

In the water resources systems:

- Jeffrey et al. (1997) defined flexibility in water supply systems as follows: '*flexibility indicates a potential for change or the existence of alternative positions/strategies/configurations*'.

- Ramirez (2002) defined flexibility in water supply systems as '*inherent capability to successfully adapt to unforeseen changes*'.

- Chung et al. (2009) defined flexibility in WDS as '*the ability of a system to make rectification in real-time operations to respond to uncertain consequences*'.

The drives for requiring flexibility are unforeseen changes or uncertain consequences. The flexibility is viewed as alternative strategies to achieve original function, adaptability, or capability to provide different operations. Although they captured some features of flexibility, all these three definitions did not clearly state the criteria to measure flexibility. Flexibility should not only have the capacity to respond or adapt to uncertainties, but should also respond to uncertainties in a cost-effective manner.

There are also some definitions, which tried to define flexibility with more generality:

- Saleh et al. (2001) defined flexibility as '*the property of a system that allows it to respond to changes in its initial objectives and requirements—both in terms of capabilities and* *attributes—occurring after the system has been field, i.e., is in operation, in a timely and cost-effective way*'.

- McConnell (2007) defined flexibility in complex systems (with both physical and social systems presents) as '*the ability for a system to actively transform, or facilitate a future transformation, to better anticipate or respond to changing internal or external conditions*'.

Both definitions could be easily used in different areas because they are defined for this purpose. The reason for flexibility, the measure for flexibility, and the result for flexibility are all discussed in a general version, which enables the definition to be easily applied to different areas. However, the problem representation is low, and thus may not result in an accurate and representative definition.

From the different definitions presented, it can be concluded that flexibility in general is the ability of the system to respond to uncertainties in a cost-effective manner. Uncertainties are the drivers for requiring flexibility, cost-effectiveness is the measure for flexibility, and responses in a cost-effective manner are the results of flexibility.

2.3.2 Criteria to develop definition of flexibility

Flexibility is a word rich with ambiguity (Saleh et al. 2001). Many authors intuitively interpreted flexibility as the ability to respond to future changes. However, this general meaning causes confusion between flexibility and other terms related to the ability to respond to changes. These terms have been discussed in detail by Saleh et al. (2001) and Ross et al. (2008), and therefore provide some key characteristics for achieving a clear and useful definition of flexibility.

According to Saleh et al. (2001), a definition of flexibility should provide the following information:

- *A time reference associated with the occurrence of change*
- *A characterisation of what is changing*
- *An indication for providing metrics of flexibility*

Ross et al. (2008) proposed that a definition of flexibility should be based on following characteristics:

- *The agent of change: The reason and trigger to set a change in motion*
- *The mechanism of change: The path the system must take to transition from its prior to its post state*
- *The effect of change: The differences in systems states and performance before and after a change have taken place*

A characterisation of what is changing is similar to the mechanism of change, which explains the details of the change, including the change itself and also conditions, resources, and constraints for the change. An indication for providing metrics of flexibility is similar to the effect of change, which could be understood as the criteria to measure flexibility. Although Saleh et al. (2001) and Ross et al. (2008) have made improvement on the definition of flexibility by capturing some important characteristics, these are inadequate. First, they did not consider portability of the definition. The portability here is defined as the ease of definition for flexibility, when applied from one field to another. A good definition for flexibility should have the capacity to enable wider application. Secondly, problem representation was not considered in their definitions. The problem representation is defined as the effectiveness of the definition of flexibility to capture the key features of the problem. A definition without key features of the problem can be too general, to be distinguished from other similar terms. Therefore, to provide a clear and useful definition for flexibility, the following characteristics have to be captured:

- Drivers for the change: the reasons flexibility is required
- The mechanisms of change: explain the characteristics of the change
- Metrics to measure flexibility: how the flexibility is quantified and compared
- High portability: easiness to be applied in other areas
- Good problem representation

The drivers of the change explain why flexibility is required. It can also be used to identify sources of flexibility. The mechanism of change describes the characteristics for the change. It could also be used to indicate the easiness of the change. The metrics to measure flexibility could quantify the value created by flexibility under uncertainties. The high portability can guarantee the applicability of the definition of flexibility from one field to another. The good problem representation makes sure that the key features of the problem are represented in the definition.

2.3.3 Definition of flexibility in UWDS

To provide a clear and useful definition for flexibility in UWDS, the definition must consider the drivers for the change, the mechanism of the change, the metrics to measure flexibility, and also have high portability and good problem representation. The main uncertainties for hydraulic design of UWDS are nodal demand, pipe roughness, and component failures. These uncertainties would affect the pressures provided on the demand nodes, which is the reason why flexibility is required for UWDS. These changes can be in the system configuration or operations. The metrics to measure flexibility can be considered from the system structure or the system performance. Flexibility in UWDS is defined as:

'The ability of the system to enable cost-effective changes (configuration or operation) to both internal uncertainties (pipe roughness and component failure) and external uncertainties (nodal demands)'.

The definition clearly states the drivers of the change, both internal (in the system) and external (out of the system). The mechanism of the change is indicated by the required change on configuration or operation. The metrics to measure flexibility are indicated by the cost-effective changes. High portability is achieved by applying some general words, i.e., internal, external, and cost-effective. A good problem representation is achieved by stating the specific uncertainties in UWDS, i.e., nodal demand, pipe roughness, and component failure.

2.3.4 Compare study of different definitions of flexibility

Different definitions for flexibility have been discussed, and after discussion the key characteristics for providing a clear and useful definition of flexibility are proposed. Based on the key characteristics, the definition of flexibility in UWDS is proposed. Here these different definitions for flexibility are summarised based on portability and accuracy. Portability illustrates the easiness of the definition applied in other areas. 'High Portability' means the definition could be widely applied while 'Low Portability' means the definition could not be widely applied unless some modifications are made. The accuracy includes three key characteristics and problem representation. Three key characteristics are basic components to propose a proper definition of flexibility. They are flexibility drives, change mechanisms, flexibility metrics. A 'General problem representation' means the definition is based on broad concept while 'Detail problem representation' means the definition is proposed on a special case. As a result, a definition with detail problem representation may be difficult to be applied in other areas. The study on these different definitions of flexibility was summarised in Table 2-1.

Table 2-1 Definitions of flexibility in different fields

	Portability		Accuracy				
			Key characteristics			Problem representation	
	Low	High	Flexibility drivers	Change mechanisms	Flexibility metrics	General	Detail
Slack (1987)		×			×	×	
Upton (1995)		×			×	×	
Jeffrey et al. (1997)	×			×	×		×
Saleh et al. (2001)		×		×	×	×	
Ramirez (2002)		×		×		×	
Moses (2003)	×				×		×
McConnell (2007)		×		×		×	
Nilchiani and Hastings (2007)		×	×	×	×	×	
Chung et al. (2009)	×			×	×		×
Huang (2011)		×	×	×	×		×

2.4 Measures of Flexibility

Hydraulic performance of a water distribution system under uncertainty could be studied by checking simulation results for the system under different states. The minimum pressure on the demand node is a design criterion to ensure that the required flow can be provided on that node. There are many studies in the literature, which tried to develop some criteria to efficiently measure performance of WDS (Mays 2000; Todini 2000; Tolson et al. 2004; Jayaram and Srinivasan 2008). In this thesis, measures of flexibility are divided into two classes: indicator-based and performance-based. The indicator-based measures generally do not have strong theoretical foundations. On the contrary they are developed considering practical requirements. The basic idea is that performance is measured by some indicators, which offers a plausible coherence between the indicators and the performance. The indicator-based measures can be quantified without running the hydraulic simulation, while performance-based measures are based on the simulation result for the system. Pressures on demand nodes are checked under different circumstances, to see whether the minimum pressure is met or not. Some flexibility measures are introduced in this section.

The first one is entropic measure of water distribution system. The network should have multiple links connected to the node to improve performance under component failure. One general expression of entropy functions was developed by Shannon (1948), and is shown as follows:

$$F_j = -\sum_{i=1}^{M} P_i \ln P_i \tag{2.1}$$

where P_i = any parameter of the system; M = number of subsystems; and F_j = entropic measure of the system.

Some modifications had been made by Awumah et al. (1991) to match it to the water distribution network problem. The first step is to define the parameter P_i in Eq. 2.1, such that the essential physical conditions in water distribution networks are included. Consider a network with N nodes in which the nodes constitute the subsystems. For a particular flow pattern under consideration, let the i^{th} link of the $n(j)$ links incident on node j carry a flow of q_{ij} and

$$X_{ij} = \frac{q_{ij}}{Q_j} \tag{2.2}$$

where

$$Q_j = \sum_{i=1}^{n(j)} q_{ij} \tag{2.3}$$

X_{ij} represents the contribution of the total flow to node j by the link between nodes i and j, thus X_{ij} is a measure of the relative capacities of links incident on node j. This parameter is an indicator of the potential contribution of the link to the required demand to that node when another incident link fails, thus X_{ij} is chosen as P_i. Eq. 2.1 is restated as follows to give an entropic measure of local redundancy at node j, in which the parameter q_{ij}/Q_j is the relative flow capacity of links incident on the node. S_j is entropic measure of local redundancy at node j:

$$S_j = -\sum_{i=1}^{n(j)} \left(\frac{q_{ij}}{Q_j} \right) \ln \left(\frac{q_{ij}}{Q_j} \right) \tag{2.4}$$

Redundancy for the network as a whole is a function of redundancies S_j of the individual nodes in the network. Let Q_0 be the sum of flows in all links of the network, i.e., $Q_0 = \sum_{j=1}^{N} Q_j$, in which N = number nodes in the network. For redundancy of the network, it is the relative importance of a link to the total flow, not the relative importance of a link to the local flow that is the important parameter in assessing overall network performance. This requirement suggests that q_{ij}/Q_j in Eq. 2.4 be replaced by q_{ij}/Q_0. This replacement gives rise to the following equation:

$$\hat{S} = \sum_{j=1}^{N} \sum_{i=1}^{n(j)} \left(\frac{q_{ij}}{Q_0} \right) \ln \left(\frac{q_{ij}}{Q_0} \right) \tag{2.5}$$

where $\hat{S}$ = network redundancy.

The term $\bar{S}_j$, the individual contribution to network redundancy from node j, in parentheses in Eq. 2.5, can be decomposed into

$$\bar{S}_j = \frac{Q_j}{Q_0} S_j - \frac{Q_j}{Q_0} \ln \frac{Q_j}{Q_0} \tag{2.6}$$

Hence, Eq. 2.5 becomes

$$\hat{S} = \sum_{j=1}^{N} \frac{Q_j}{Q_0} S_j - \sum_{j=1}^{N} \frac{Q_j}{Q_0} \ln \frac{Q_j}{Q_0} \tag{2.7}$$

where $n_{(j)}$ = number of links incident on node j, q_{ij} = the flow of the ith link of the $n_{(j)}$ links incident on node j, Q_j = total flow of the $n_{(j)}$ links incident on node j, Q_0 = the sum of flows in all links of the network, N = number of nodes in the network.

The second measure is resilience index, which was introduced by Todini (2000). In a looped network, surplus power at each node could be dissipated internally in case of failures. This surplus can be used to characterise the resilience of the looped network.

If we denote with

$$P_{tot} = \gamma \sum_{k=1}^{n_r} Q_k H_k \tag{2.8}$$

the total available power at the entrance in the water distribution network, where γ is the specific weight of water, Q_k and H_k are the discharge and the head, respectively, relevant to each reservoir k, while n_k is the number of reservoirs, the following simple relationship exists:

$$P_{tot} = P_{\text{int}} + P_{ext} \tag{2.9}$$

where P_{int} is the power dissipated in the pipes while $P_{ext} = \gamma \sum_{i=1}^{n_n} q_i h_i$ is the power that is delivered to the users in terms of flow q_i and head h_i at each node i, with n_n the number of nodes.

A resilience index I_r may be defined as:

$$I_r = 1 - \left(P_{\text{int}}^* / P_{\max}^* \right) \tag{2.10}$$

where $P_{\mathrm{int}}^{*} = P_{tot} - \gamma \sum_{i=1}^{n_n} q_i^* h_i$ is the amount of power dissipated in the network to satisfy the total demand and $P_{\max}^{*} = P_{tot} - \gamma \sum_{i=1}^{n_n} q_i^* h_i^*$ the maximum power that would be dissipated internally in order to satisfy the constraints in terms of demand and head at the nodes.

After appropriate substitutions, the resilience index I_r can be written as:

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^* (h_i - h_i^*)}{\sum_{k=1}^{n_r} Q_k H_k - \sum_{i=1}^{n_n} q_i^* h_i^*} \tag{2.11}$$

The resilience index can be easily modified in order to account for the presence of pumps by modifying P_{tot}, to give:

$$P_{tot} = \gamma \sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} P_j \tag{2.12}$$

where P_j is the power introduced into the network by the j^{th} pump and n_{p} the number of pumps. Consequently the resilience index becomes:

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^* (h_i - h_i^*)}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} (P_j / \gamma) - \sum_{i=1}^{n_n} q_i^* h_i^*} \tag{2.13}$$

The third measure is connectivity measure of water distribution system. ‘Connectivity’ denotes the situation in which every demand node in the network is connected to at least one source (Wagner et al. 1988). Each link is said to have a probability p_i of functioning at any point in time and a probability q_i = 1-p_i of being inoperative. Links are assumed to fail independently, which may be questioned in light of field experience (Wagner et al. 1988). At any point in time, some of the links may have failed. The probability of any one configuration of operative and inoperative links occurring can be calculated as the product of the p_i's for the operative links times the product of the q_i's of the failed links. For connectivity calculations, each configuration corresponds either to a connected system, where every demand node is connected via functioning links to some source, or to a disconnected system. Conceptually, calculating the overall probability of a given system being connected is a straightforward combinatorial problem. For any system, these probabilities can be calculated by testing each configuration individually and adding up the probabilities of each configuration that is connected.

$$P_c = \sum_{i=1}^{N_c} p_i \tag{2.14}$$

Where P_c = connectivity measure of the system, N_c = number of configurations that is connected, p_i = probability of the connected configuration i.

The fourth measure is Surplus Capacity (SC) in the system. Urban water distribution system is generally sized with a capacity, which can respond to the most forecasted conditions. This capacity is defined as the minimum capacity the system has to provide. Then the additional capacity in each component of the system could be viewed as potential of the system to respond to abnormal high water demand and component failure. The surplus capacity in component i is defined as follow:

$$SC_i = \frac{DP_i - DP_i^{\min}}{DP_i^{\min}} \tag{2.15}$$

Where SC_i = surplus capacity in component i, DP_i = real design parameter indicating the capacity, $DP_i^{\min}$ = minimum design parameter indicating the capacity.

The term in denominator is applied to normalise the value for the surplus capacity in different component. Thus different SC_i could be compared with each other. For safe consideration, Surplus

Capacity in the system is defined as the minimum surplus capacity in its components, which is shown as:

$$SC = \min_{i=1}^{M}\{SC_i\} = \min_{i=1}^{M}\left\{\frac{DP_i - DP_i^{\min}}{DP_i^{\min}}\right\} \tag{2.16}$$

The fifth measure is Reliable Loop (LP). Demand node is still connected to the system if there is alternative link connected to this node, even when one of them is taken out of service. More alternative routes mean more capability for the system to respond to component failure. The number of links incident to node *i* is denoted as n_i. The RL is similar with connectivity measure of water distribution system, but is simplified, which is just indicated by minimum value of the number of links incident to the demand node. The mathematical formulation of RL for WDS is shown as:

$$RL = \min\{n_i\},\ \mathrm{i} = 1, 2, \ldots, NN \tag{2.17}$$

where n_i is number of links to node *i*, and *NN* is the total number of node.

The sixth measure is Pressure on Demand Node (PDN). When high demand or component failure happens in WDS, it induces pressure drop on the demand node, and as a result the required flow cannot be provided. Flexibility tries to enable the system provide sufficient water even under high demand or component failure, which is achieved by leaving additional capacity on the node. The additional capacity on the node is indicated by the pressure on that node. Therefore, the flexibility can be measured by the pressure improvement on the demand node. The pressure improvement on demand node *i* under average demand scenario is shown as:

$$PDN = P_i - P_i^{fix} \tag{2.18}$$

where P_i is nodal pressure on the chosen demand node *i* after embedding flexibility, and P_i^{fix} is nodal pressure on the chosen demand node *i* before embedding flexibility.

The seventh measure is Pressure on Minimum Pressure Node (PMPN). The objective of WDS is to provide sufficient water for each demand node. Therefore, the key constraint for designing WDS is to guarantee the required minimum pressure on the minimum pressure node for the system. Therefore, flexibility can be indicated by the pressure improvement on the minimum pressure node in the system. The mathematical formula for PMPN is shown as:

$$PMPN = P_{\min} - P_{\min}^{fix} \tag{2.19}$$

where $P_{\min}$ is nodal pressure on the minimum pressure node after embedding flexibility, and $P_{\min}^{fix}$ is nodal pressure on the minimum pressure node before embedding flexibility.

The eighth measure is developed based on the variation of nodal pressure. Because of uncertainties, there are many possible future states. For a specific system configuration, one pressure scenario could be simulated under each water demand scenario [Q_{j1}, Q_{j2}, …, Q_{jN}]:

$$P = \lfloor P_{j1}, P_{j2}, \ldots, P_{jN} \rfloor \tag{2.20}$$

Nodal pressure under these future states would be quite different, which could then be described by variations in distribution. For a system before embedding flexibility, pressure distribution on node *i* is calculated as:

$$\sigma(P_i^{fix}) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{i,j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{i,j}^{fix})^2} \tag{2.21}$$

where $P_{i,j}^{fix}$ is nodal pressure on node *i* under state *j* before embedding flexibility, and *n* is the number of future states.

After embedding flexibility, the pressure distribution on node *i* is recalculated:

$$\sigma(P_i) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{i,j} - \frac{1}{n}\sum_{j=1}^{n}P_{i,j})^2} \tag{2.22}$$

where $P_{i,j}$ is nodal pressure on node *i* under state *j* after embedding flexibility, and *n* is the number of future states.

Flexibility tries to improve the system performance under different future states, and therefore could be measured as the improvement on the variation of nodal pressure.

$$F_{P_{\mathrm{var}}} = \sigma(P_i^{fix}) - \sigma(P_i) \tag{2.23}$$

$$= \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{i,j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{i,j}^{fix})^2} - \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{i,j} - \frac{1}{n}\sum_{j=1}^{n}P_{i,j})^2} \tag{2.24}$$

where $P_{i,j}^{fix}$ is nodal pressure on node *i* under state *j* before embedding flexibility, $P_{i,j}$ is nodal pressure on node *i* under state *j* after embedding flexibility, and *n* is the number of future states.

The ninth measure is based on the variation of nodal pressure on the minimum pressure node in the system. Minimum pressure node in general is the most critical node in the system, which could easily drop below the required minimum level. The minimum pressure node is identified by simulating nodal pressure under one specific demand scenario (e.g., most likely scenario). For a specific system configuration, one pressure scenario could be simulated under each water demand scenario [Q_{j1}, Q_{j2}, …, Q_{jN}]:

$$P = \lfloor P_{j1}, P_{j2}, \ldots, P_{jN} \rfloor \tag{2.25}$$

Nodal pressure on the minimum pressure node under these future states would be quite different, which could then be described by variations in distribution. For a system before embedding flexibility, pressure distribution on minimum pressure node is calculated as:

$$\sigma(P_{\min}^{fix}) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\min,j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{\min,j}^{fix})^2} \tag{2.26}$$

where $P_{\min i,j}^{fix}$ is nodal pressure on minimum pressure node under state j before embedding flexibility, and n is the number of future states.

After embedding flexibility, the pressure distribution on minimum pressure node is recalculated:

$$\sigma(P_{\min}) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\min,j} - \frac{1}{n}\sum_{j=1}^{n}P_{\min,j})^2} \tag{2.27}$$

where $P_{\min,j}$ is nodal pressure on minimum pressure node under state j after embedding flexibility, and n is the number of future states.

Flexibility tries to decrease the pressure variation on the minimum pressure node under uncertainties, and therefore could be measured as the improvement on the variation of nodal pressure:

$$F_{P_{\mathrm{var}}}^{\min} = \sigma(P_{\min}^{fix}) - \sigma(P_{\min}) \tag{2.28}$$

$$= \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\min,j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{\min,j}^{fix})^2} - \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\min,j} - \frac{1}{n}\sum_{j=1}^{n}P_{\min,j})^2} \tag{2.29}$$

where $P_{\min,j}^{fix}$ is nodal pressure on minimum pressure node under state *j* before embedding flexibility, $P_{\min,j}$ is nodal pressure on node *i* under state *j* after embedding flexibility, and *n* is the number of future states.

The tenth measure is based on the variation of nodal pressure on the most variable node in the system. The most variable node is defined as the node with the largest deviation of nodal pressure. The most variable node is very sensitive to uncertainties, as the pressure can also easily drop below the required minimum levels. Most variable node is identified as the node with largest value for Eq. 2.21. Therefore, flexibility could be indicated by the improvement on the deviation of nodal pressure on the most variable node. The mathematical formulation of this measure is defined as:

$$F_{P_{\mathrm{var}}}^{\mathrm{var}} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\mathrm{var},j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{\mathrm{var},j}^{fix})^2} - \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\mathrm{var},j} - \frac{1}{n}\sum_{j=1}^{n}P_{\mathrm{var},j})^2} \tag{2.30}$$

where $P_{\mathrm{var},j}^{fix}$ is nodal pressure on the most variable node under state *j* before embedding flexibility, $P_{\mathrm{var},j}$ is nodal pressure on the most variable node under state *j* after embedding flexibility, and *n* is the number of future states.

All the measures presented in this section are measures to indicate flexibility. Connectivity measure, SC and RL are developed based on the practical requirements, which do not require running hydraulic simulation for WDS. However, they do not interpret characteristic of flexibility properly. They may not be suitable flexibility measures for both flexibility identification and flexibility optimisation in UWDS. All others are developed based on pressure on the node or flow in the pipe, which require hydraulic simulation of WDS. Entropy measure, Resilience measure, PDN and PMPN require less hydraulic simulation, while $\sigma(P_i)$, $\sigma(P_{\min})$, and $\sigma(P_{\mathrm{var}})$ require more hydraulic simulation. Entropy measure considers only component failure and Resilience measure may not be suitable for multi sources, therefore they may not be suitable for both flexibility identification and flexibility optimisation in UWDS. Considering their high computational demand, $\sigma(P_i)$, $\sigma(P_{\min})$, and $\sigma(P_{\mathrm{var}})$ are not chosen as flexibility measures for this thesis. Although both PDN and PMPN are computationally efficient, PMPN interprets characteristic of flexibility better. Thus PMPN is used for both flexibility identification and flexibility optimization in the thesis. Flexibility Index (FI) in Chapter 4 and flexibility constraints in Chapter 5 and Chapter 6 are developed on PMPN. All these measures were studied for computational demand and applicability (See Appendix I). The comparison of findings for these seven measures are summarised in Table 2-2.

Table 2-2 Summary of different flexibility measures

Flexibility Measures		Computational Demand		Applicability	
		Low	High	Flexibility Identification	Flexibility Optimization
Performance-based	Entropy Measure	×			
	Resilience Measure	×			
	PDN	×		×	
	PMPN	×		×	×
	$F_{P_{\mathrm{var}}}$		×	×	
	$F_{P_{\mathrm{var}}}^{\min}$		×	×	
	$F_{P_{\mathrm{var}}}^{\mathrm{var}}$		×	×	
Indication-based	Connectivity Measure	×			
	SC	×			
	RL	×			
The computational demand assessment evaluates the number of required hydraulic simulation. The applicability assessment evaluates the suitability of the measure for applicability to flexibility identification and flexibility optimization in UWDS.					

2.5 Flexible design framework

The framework for flexible design generally refers to the process to achieve flexibility for the system. Numerous frameworks have been developed in terms of engineering systems (Wang 2005; McManus and Hastings 2006; Nilchiani and Hastings 2007; Lin et al. 2009). They included some key steps. First, different uncertainties are identified, and their effects on the system performance are studied. Second, different flexibility sources are explored, and third different flexible designs are compared based on flexibility measures. The general flexible design framework for UWDS is shown in Figure 2-1.

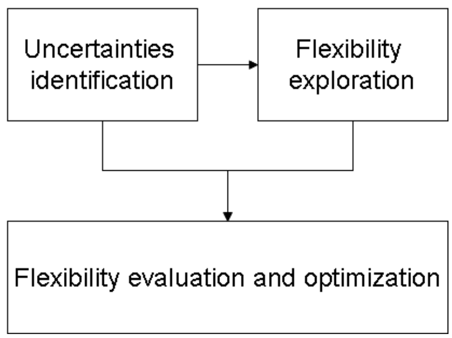

Figure 2-1 General flexible design framework for UWDS

This framework includes three processes. ‘Uncertainties identification’ identifies major sources of uncertainties, which affect the system performance significantly. ‘Flexibility exploration’ identifies different flexibility sources, and these sources can improve the system performance under uncertainties. ‘Flexibility evaluation and optimisation’ will compare different designs by checking their performance under uncertainties. The thesis focuses mainly on the ‘flexibility evaluation and optimisation’. This process is computationally demanding because of the requirements for checking the system performance under uncertainties. Therefore, to achieve flexible design with affordable computational costs, ‘flexibility evaluation and optimisation’ should be properly designed. Chapter 3 discusses uncertainties modelling for flexible design, Chapter 4 explores flexibility sources in UWDS, while Chapter 5 introduces a flexibility-based optimisation model to generate flexible designs for UWDS.

2.6 Chapter summary

This chapter discussed the general concepts for flexible design in UWDS, showing flexibility definitions, flexibility measures, and flexible design framework. Different definitions for flexibility in systems were shown, and the key characteristics for flexibility definitions were discussed. Based on these characteristics, a definition of flexibility for UWDS was proposed. Finally, the proposed definition and other different definitions are summarised based on the key characteristics of flexibility definitions.

Flexibility measures are discussed under indicator-based and performance-based measures. Indicator-based measures are developed based on the practical requirements, and do not have strong theoretical foundation. Performance-based measures are developed based on the improvement of system performance, and require hydraulic simulation. Ten measures were developed in this chapter, and were evaluated on computational demand and applicability for flexibility identification and flexibility optimisation.

Finally a general flexible design framework for UWDS was introduced. The framework includes three major processes for the flexible design: ‘uncertainties identification’, ‘flexibility exploration’, and ‘flexibility evaluation and optimisation’. ‘Uncertainties identification’ will identify major sources of uncertainties. ‘Flexibility exploration’ will identify different flexibility sources. ‘Flexibility evaluation and optimisation’ will compare different designs, by checking their performance under uncertainties.

Chapter 3 Uncertainty modelling for flexible design of UWDS

3.1 Introduction

Recognising uncertainties is important for design of UWDS. Performance of the system has to be checked under different conditions. Nodal demand, pipe roughness, and component failure were identified as three of major uncertainties in UWDS, and have been heavily studied by different researchers (Lansey et al. 1989; Xu and Goulter 1999; Babayan et al. 2005; Kapelan et al. 2005; Giustolisi et al. 2009). For flexible design of UWDS, incorporating the effects of these uncertainties are important, to enable the system with the capability to respond to uncertainties in a cost-effective manner. This chapter reviews some methods to model these three uncertainties and more importantly proposes an efficient method to model these uncertainties together.

This chapter reviews different methods to model uncertainties in Section 3.2, and then proposes a method to integrally model uncertain nodal demands, pipe roughness, and component failures in Section 3.3. Finally, a brief summary for the Chapter is presented in Section 3.4.

3.2 Literature review about uncertainties modelling of nodal demand, pipe roughness, and component failure

The reviewed methods for modelling uncertain demand and pipe roughness are illustrated in Section 3.2.1. The reviewed methods for model component failures are presented in Section 3.2.2. A summary of these methods are given in Section 3.3.3.

3.2.1 Modelling of uncertain demand and pipe roughness

The simplest method for modelling uncertainties of nodal demands and pipe roughness coefficients is by sampling methods. And one of most popular sampling methods is Monte Carlo Simulation (MCS), which generates thousands of samples. Each sample represents one possible future, which includes one realisation for a group of uncertain parameters. It is assumed that these uncertain parameters can be described by some probability distributions, and then under each sample, one value for each parameter is randomly taken from the distribution. For a network with *NN* demand nodes and *NP* pipes, a group of *NS* samples could be expressed as:

$$S = \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_{NS} \end{bmatrix} = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1(NN+NP)} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2(NN+NP)} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{NS1} & \xi_{NS2} & \cdots & \xi_{NS(NN+NP)} \end{bmatrix} \tag{3.1}$$

where S is full samples, S_i is sample i, ξ_{ij} is the simulated value for uncertain parameter j in sample i, which can be a number under one stage or a vector under multi-stage. For example, for the two-stage, $\xi_{ij} = [\omega_{ij}^1, \omega_{ij}^2]$.

It is simple and easy to apply MCS to model uncertain parameters. However, it incurs significant computational cost (Helton and Davis 2003), which is obvious for UWDS. Although MCS provides a simple method to model uncertainties from nodal demand and pipe roughness, it is quite computational demanding, since there are numerous demand nodes and pipes in UWDS. As a result, MCS requires large number of samples to achieve the robustness of the simulation result. When incorporating MCS to achieve flexible design of UWDS, the optimisation methods, especially Genetic Algorithms, would require huge computational time to reach the optimal solution, since the problem has a large decision space. Also, a design solution has to be checked for numerous samples, to assess whether the solution is good or not.

The second reviewed method is Latin Hypercube Sampling (LHS), which is an alternative sample-based method for MCS. LHS was firstly introduced by Mckay et al. (1979), and can significantly decrease the computational cost by stratifying all uncertain parameters simultaneously. It ensures that all portions of the sample space are sampled, and also that each of the uncertain parameters has all portions of its distribution. An illustrative example of LHS for two uncertain parameters is shown in Figure 3-1. Both uncertain parameters are uniformly distributed, and divided into 6 intervals with equal probability.

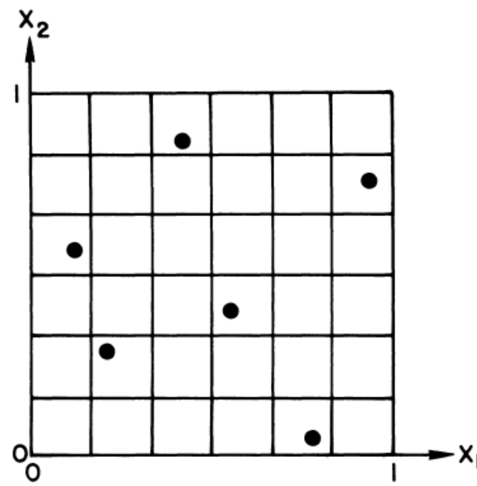

Figure 3-1 A example of LHS for X = [X_1, X_2] distributed uniformly (Stein 1987)

Latin Hypercube Sampling can be achieved by the following process, to generate a sample of size *NS* from a vector of uncertain parameters X = [X_1, X_2, …, X_{NX}] in consistency with the probability distributions PDF_1, PDF_2, …, PDF_{NX}. The range of each uncertain parameter is divided into *NS* disjoint intervals of equal probability. One value is selected randomly from each interval, and thus a vector with *NS* values for each uncertain parameter is obtained. Then *NS* values of X_1 are paired randomly with *NS* values of X_2 without changing the order of *NS* values for X_2. As a result, *NS* pairs of [X_1, X_2] are generated. These *NS* pairs are combined randomly with X_3 without changing the order of *NS* values for X_3. Then *NS* combinations of [X_1, X_2, X_3] are generated. This process is continued until X_{NX}. The final *NS* combinations of [X_1, X_2, …, X_{NX}] constitutes the Latin Hypercube Sampling. For this procedure, each uncertain parameter must be independent of each other. A method to generate LHS from correlated parameters was developed by Iman and Conover (1982). LHS was also applied by Kapelan et al. (2005) to model uncertain nodal demands and pipe roughness coefficients in WDS, and showed significant computational saving compared with MCS.

The third reviewed method to model uncertain nodal demand and pipe roughness is Scenario Tree Method (STM). STM was used by Wang (2005) for flexible design in water resources systems, and was introduced by Ahmed et al. (2003) to model uncertainties for a multi-stage capacity expansion. STM is a decision-tree method, in which the uncertain parameters are represented in a discrete way. Figure 3-2 illustrates a simple example of STM to model uncertain water demand on node *j* under one-stage. q_{ij}^{k} is the nodal demand of node *j* at state *i* of stage *k*. It is assumed that there are two possibilities for the nodal demand, and a probability is attached to each possibility. It is not necessarily only two possibilities that can be considered, it could be three or more. However, it would become more complex and more computational demanding.

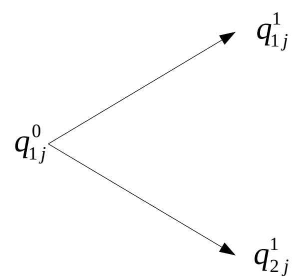

Figure 3-2 A scenario tree to model single uncertain demand

Then STM can also be extended to model two uncertain parameters for the network. The scenario tree for modelling two uncertain nodal demands is shown in Figure 3-3, where q_{ij}^{k} is nodal demand of node *j* on state *i* of stage *k*. It is also assumed that there are two possibilities for each demand node, and as a result it yields four possibilities for modelling two uncertain parameters.

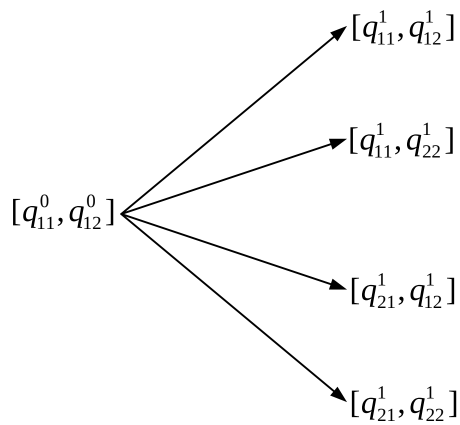

Figure 3-3 A scenario tree to model two uncertain demands

It was found that for a network with *NU* uncertain parameters, the total number of scenarios is 2^{NU}, which increases exponentially with the number of uncertain parameters. As a result, it would be computational demanding to apply STM to model uncertain nodal demands and uncertain pipe roughness coefficients for UWDS, due to numerous uncertain parameters (demand nodes and pipes) in the system. The problem becomes even more intractable when applying STM to model nodal demands and pipe roughness coefficients under multi stages. Another difficulty in applying STM is how to estimate the probability for each scenario.

The fourth reviewed method is First Order Reliability Method (FORM), which was firstly applied by Xu and Goulter (1998) for WDS, to estimate system performance under uncertainties in nodal demands, pipe capacity, and reservoir/tanks. The method assumed that nodal heads under these uncertainties were normal distributed. The mean values of nodal heads were obtained from the deterministic network model using the expected values for these uncertain parameters. The variance of the nodal heads were estimated by using the first-order second moment approach (Yen et al. 1986):

$$\sigma_{H_i}^2 = \sum_{j=1}^{NN+NP+NF} \sum_{k=1}^{NN+NP+NF} \hat{b}_{ij}\hat{b}_{ik} Cov(x_j, x_k) \quad i = 1,\ 2,\ \ldots,\ NN \tag{3.2}$$

where $Cov(x_j, x_k)$ denotes the covariance between the random parameters x_j and x_k ; $\hat{b}_{ij}$ = element of a matrix $\hat{B}$, which is from a linearized hydraulic model below; *NF* = total number of reservoirs/tanks; *NP* = total number of pipes in the network; and *NN* = total number of nodal demands.

For pairwise statistically independent random variables, the equation (3.2) becomes

$$\sigma_{H_i}^2 = \sum_{j=1}^{NN+NP+NF} \hat{b}_{ij}^2 \sigma_{x_j}^2 \quad i = 1, 2, \ldots, NN \tag{3.3}$$

where $\sigma_{x_j}^2$ = variance of the uncertain parameter x_j .

The linearized hydraulic model was developed using a first-order Taylor series expansion at the expected values of the nodal demands and pipe roughness coefficients, which can be expressed as:

$$H = \hat{H} + \hat{B}X \tag{3.4}$$

where $\hat{B} = [A \vdots B \vdots E]$, $X = \begin{bmatrix} Q \\ C \\ H_0 \end{bmatrix}$.

$$\hat{H} = \overline{H} - A\overline{Q} - B\overline{C} - E\overline{H}_0 \tag{3.5}$$

$$A = -J^{-1} \tag{3.6}$$

where $J = NN \times NN$ Jacobian matrix; and $J = \partial F / \partial H$.

$$B = AJ_c \tag{3.7}$$

where $J_c = NN \times NP$ sensitivity matrix specifying the change in the capacity of each pipe in the network with change in the roughness of each pipe in the network; and $J_c = \partial F / \partial C$.

$$E = AJ_{H_0} \tag{3.8}$$

where $J_{H_0} = NN \times NF$ sensitivity matrix with respect to change of reservoir/tank level, equal to $\partial F / \partial H_0$; *Q, C, H*$_0$, and *H* = vectors of uncertain nodal demands, uncertain pipe coefficients, uncertain reservoir/tank levels, and uncertain nodal heads, respectively; $\overline{H}$ = vector of the estimated mean values of nodal heads obtained from the deterministic network model using the expected values of nodal demands $\overline{Q}$, reservoir/tank levels $\overline{H}_0$, and pipe roughness coefficients $\overline{C}$; *NF* = total number of reservoirs/tanks; *NP* = total number of pipes in the network; and *NN* = total number of nodal demands.

The method showed good performance on approximating nodal pressure under uncertainties, but there are also criticisms about it. First, it is computational demanding even for the small network. Xu and Goulter (1999) tried to improve the computational efficiency by using critical nodal performance to approximate the system performance. Even after this approximation, it still has high computational consumption, because FORM requires repetitive calculation of first-order derivatives and matrix inversions (Tanyimboh and Kalungi 2001; Babayan et al. 2007). Secondly, it may be very difficult or sometimes impossible to calculate first-order derivatives, in terms of the networks containing control devices (Babayan et al. 2005).

3.2.2 Component failure and its modelling

Compared with uncertain modelling of nodal demands and pipe roughness coefficients, modelling for component failure in UWDS is straightforward, and can easily be achieved in EPANET (Rossman 2000). For example, if a pipe fails, it is taken out of service by setting the status of the pipe as closed. Any component is assumed to be either functional or unfunctional. Therefore, for a system with M components, there are a total of 2^M possible system configurations. As a result, it is computational demanding to enumerate all these system configurations. This number could be decreased by only enumerating the system configurations with one pipe failure, because the joint probability of simultaneous failures of two or more pipes are very low (Xu and Goulter 1998). As a result, the total possible system configurations could be reduced to M+1. The performance of the system under single failures could be analysed by setting the status of the failure component as closed and then running the EPANET model. However, it still consumes huge computational time due to numerous components in UWDS.

3.2.3 Summary of the reviewed uncertainties modelling

Different methods are reviewed for modelling uncertainties of nodal demands, pipe roughness coefficients, and component failures. Four methods were reviewed for uncertain nodal demands and uncertain pipe roughness coefficients. Among them MCS is the most popular method. It is easily applied to model uncertain nodal demands and uncertain pipe roughness coefficients, but consumes too much computational time. An alternative method is LHS, which has significant computational saving compared with MCS. However, it is still computational demanding to be applied in the optimisation, especially Genetic Algorithms. The scenario tree method is a decision tree method, which can analyse the cost-benefits of decision-making under different scenarios. However, it seems too computational demanding for modelling uncertain nodal demands and uncertain pipe roughness coefficients, because there are numerous nodes and pipes in the system. The FORM provides a method with the least computational demand. However, it may be very difficult or sometimes impossible to calculate first-order derivatives, in terms of the networks containing control devices. For the component failure of UWDS, performance of the system can be analysed under single failures where only one component fails at one time. However the method still consumes significant computational time. Therefore, for flexible design of UWDS a more efficient method should be proposed to model uncertain nodal demands, pipe roughness coefficients, and component failure in an integrated model.

3.3 Integrated uncertainties modelling of uncertain water demand, pipe roughness, and component failure

A general description of the integrated uncertainty modelling is given in Section 3.3.1. The proposed method for modelling uncertain nodal demands and pipe roughness is illustrated in Section 3.3.2. The proposed method for modelling component failures is presented in Section 3.3.3. An integral model of uncertain nodal demands, pipe roughness, and component failures is introduced in Section 3.3.4. Finally, the proposed method is applied in a simple network in Section 3.3.5, and a summary of the proposed method is given in Section 3.3.6.

3.3.1 General description of the integrated uncertainty modelling

For flexible design of UWDS, uncertainties of nodal demands, pipe roughness coefficients, and component failures should be integrally considered in the planning stage. As a result, the design can have the capacity to respond to these uncertainties in a cost-effective manner. Uncertain nodal demands and uncertain pipe roughness coefficients are handled by incorporating "safety margins" on the expected values for these uncertain parameters. The magnitude of safety margins indicates the ability of the system to respond to uncertain nodal demands and uncertain pipe roughness coefficients. The performance of the system under component failure is approximated by analysing the performance of two independent spanning trees. The magnitude of inputs in nodal demands and pipe roughness coefficients under these two spanning trees indicates the ability of the system to respond to component failures.

3.3.2 Dealing with uncertain nodal demands and pipe capacities

This method was introduced by Babayan et al. (2007) for optimal design of WDS under uncertainties. The method was computational efficient because it transferred the original optimisation under uncertainties, from a stochastic problem to a deterministic problem. The method is based on redundancy in design, where "safety margins" are added on the expected values of uncertain parameters, and then a deterministic problem is formulated and solved under new inputs on these uncertain parameters. The method assumed that uncertain parameters are replaced by adding some safety margins to the expected values:

$$X_{i,t} = (1+\alpha_{i,t})\overline{X}_{i,t},\ i=1,\dots,NU_t,\ t=1,\dots,T \tag{3.9}$$

where NU_t = number of uncertain parameters (nodal demands + pipes) on stage t, T = number of stages, $\overline{X}_{i,t}$ = expected value of uncertain parameter $X_{i,t}$; and $\alpha_{i,t}$ = coefficients which determine the degree of redundancy in the resulting design.

When inputs are replaced by these new values after adding safety margins, the optimal solution could be identified by exploring the design space under these new inputs. The main question faced by the water engineers is how to properly choose the magnitude of the above "redundancy coefficients" (if too small the system will not be robust enough, and if too large the system will become over-redundant with unnecessarily high costs). Babayan et al. (2007) introduced a simple algorithm to help find a good combination of $\alpha_{i,t}$, however the cost difference between the design by applying uniform parameters and significant parameters is small and the computational demand for the method of applying significant parameters are much higher than that for the method of only applying uniform parameters. Therefore, the method of applying uniform parameters is used in this research.

3.3.3 Dealing with Component failure

Component failure is another unavoidable event within UWDS, and systems should be designed so that the capacity of the remaining system configuration is still enough to deliver water to the consumers. Ormsbee and Kessler (1990) proposed a level-one redundant water distribution system, which requires at least two independent paths with enough capacity between the source and each demand node. Then water could still be supplied to users even when there is one failure somewhere in the system. The method generated two independent spanning trees from the water distribution system by applying st-numbering in graph theory. Then each tree was designed with the capacity to supply sufficient water with appropriate pressure. Some graph theory terminologies are introduced below.

An *undirected graph* G (N, E) consists of a set of nodes, N, and a set of edges, E, where each edge corresponds to an unordered pair (u, v) of nodes. A *directed graph* G (N, A) consists of a set of nodes, N, and a set of directed edges, A, where each directed edge corresponds to an ordered pair of nodes. A *directed edge* (u, v) has *head*, u, and *tail*, v, such that edge leaves u and enters v. For UWDS, water could flow either from node 1 to node 2 or from node 2 to node 1 in a pipe unless a valve is installed to secure one direction. Thus UWDS is treated as an undirected graph.

$\hat{G}$ is a *subgraph* of G if the node and edge sets of $\hat{G}$ are subsets of the node and edge sets of G. $\hat{G}$ is a spanning subgraph of G if both their node sets are equal. A graph is *acyclic* if it contains no circuits. A *tree* is an undirected, connected, acyclic graph whose edge called *branches*. A *spanning tree* of a graph is a spanning subgraph which is a tree.

Two independent trees can be generated by the following process. Nodes in the network are first numbered by a searching algorithm (st-numbering), which was presented by Even and Tarjan (1976) and Tarjan (1986). Then, two directed-spanning trees rooted at the source can be readily identified. All nodes in one tree are connected by the links following the direction from lower to higher number. All nodes in the other tree are connected by the links following the direction from higher number to lower number. The source S is considered the lowest number in the first case and the highest number in the second case. This concept is illustrated in Figure 3-4.

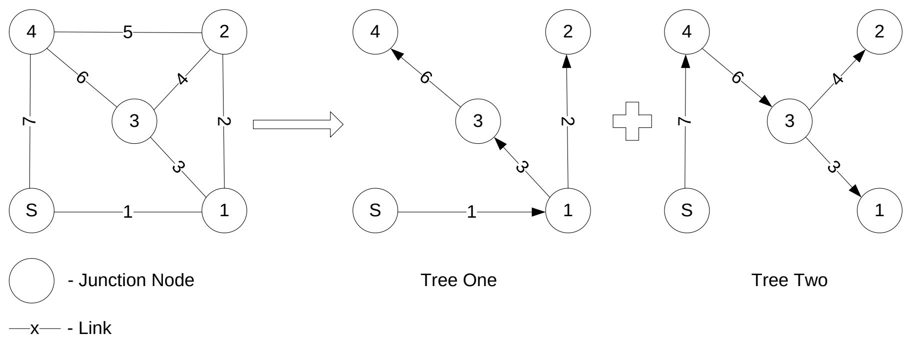

Figure 3-4 Two-tree decomposition after s-t numbering (Ormsbee and Kessler 1990)

The st-numbering algorithm consists of two processes. The first process is a depth-first search (DFS), during which vertex numbers and low values of them are computed. As a result, each edge could be defined as either tree edge or back edge. Tree edges define a DFS spanning tree rooted at S and containing paths from S to each vertex. Back edges are defined as the edge which leads from a vertex to one of its ancestors in the spanning tree. Suppose we number the vertices from 1, and *n* in the order they are first visited during the search, and this number is a preorder numbering for the spanning tree. We shall denote the number of a vertex *v* by *pre*(*v*). For each vertex *v*, let *low*(*v*) be low values, which shows smallest number reachable from *v* by a path consisting of zero or more tree edges followed by at most one back edge.

Depth-first search is a tree-search in which we first scan the adjacency list of the most recently added vertex x for a neighbour not in T, and if there is such a neighbour, we add it to T. If not, we backtrack to the vertex which was added to T just before x, and examine its neighbours and so on. The resulting spanning tree is called a DFS-tree, and a depth-first search for a connected network is shown in Figure 3-5. In the figure, s = 1 and t = 2. Tree edges are indicated by solid lines and each vertex *v* of the tree is labelled by the pair (*pre*(*v*), *low*(*v*)).

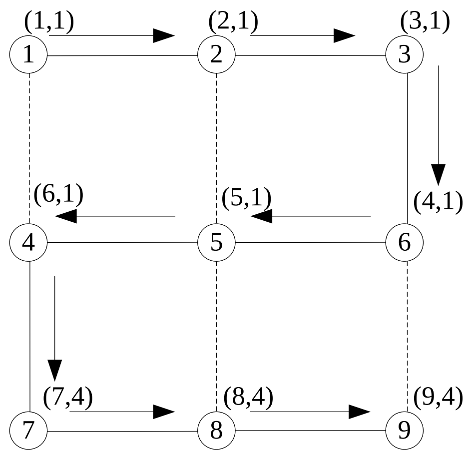

Figure 3-5 A depth-first search tree of a connected network

The second process constructs a list L of the vertices, such that if the vertices are numbered in the order they occur in L, a st-numbering result. The second process is a preorder traversal of the spanning tree. Initially L = [s,t] and s has a sign of minus. The process consists of repeating the following step for each vertex $v \notin \{s,t\}$ in preorder:

Add a vertex. If sign (low(v)) = plus, insert v after p(v) in L and set sign (p(v)) = minus, if sign (low(v)) = minus, insert v before p(v) and set sign (p(v)) = plus

The second process for the above network is illustrated in Figure 3-6. The final s-t numbering for the network is shown in Figure 3-7.

VERTEX ADDED	LIST
	1-,2
3	1-,3,2+
4	1-,4,3+,2+
5	1-,5,4+,3+,2+
6	1-,6,5+,4+,3+,2+
7	1-,6-,7,5+,4+,3+,2+
8	1-,6-,7-,8,5+,4+,3+,2+
9	1-,6-,7-,8-,9,5+,4+,3+,2+

Figure 3-6 The list L generated by the second process of the s-t numbering algorithm

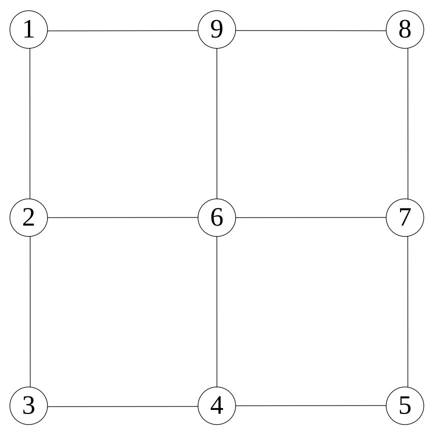

Figure 3-7 The resulting s-t numbering for the network

Once the network is numbered by the above algorithm, two directed-spanning trees, rooted at the source, can be readily identified: one from lower number to higher number and the other from higher number to lower number. The source S is considered the lowest number in the first case and the highest number in the second case. Two s-t spanning trees generated from the above network are illustrated in Figure 3-8.

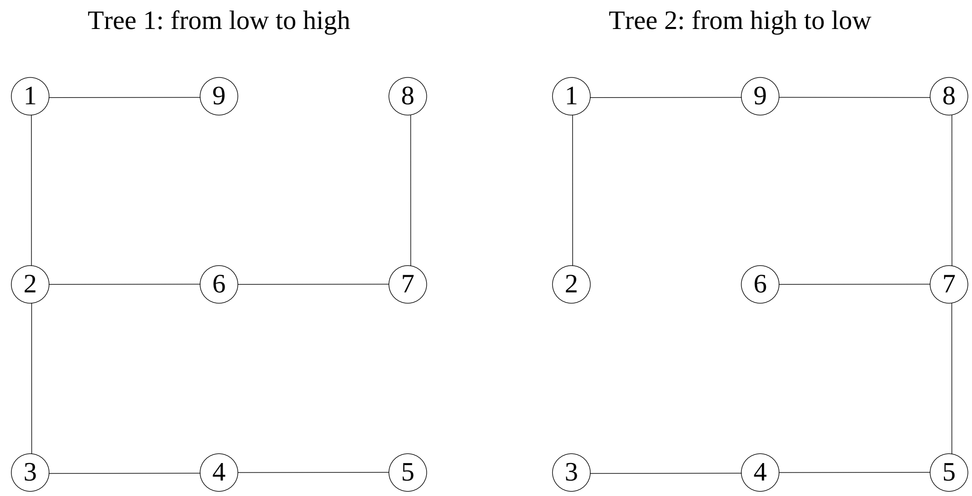

Figure 3-8 Two s-t spanning trees for the network

Admittedly, there can be several different pairs of spanning trees for a given network. Here a study was made to show the effect of different numbering by the depth-first search (DFS) on the final pair of spanning tree. See Appendix II for details. Numerous depth-first search trees could be generated from one connected network. A pair of two spanning trees from different depth-first search might be same with each other.

The choice of each link (pipe) in a particular spanning tree may be made based on external considerations of the design engineer, or by using general design heuristics (Kessler et al. 1990; Ormsbee and Kessler 1990). Three general rules were introduced for water distribution systems:

1. *Select the links (pipes) that yield a shortest-path spanning tree (i.e., the collection of shortest paths between the source and every demand node)*

2. *Maximize the number of overlapping edges between the two trees*

3. *Minimize the number of overlapping edges in a sequence, i.e. along a common path between the two trees.*

However, there is no strict or approved rule developed for the best choice of a pair of two spanning trees. That is to say there is no way to determine the best pair of trees prior to a full hydraulic evaluation of each pair. Thus the thesis just tried to maximise the number of overlapping edges between the two trees.

3.3.4 Integrating three uncertainties in one model

The methods to separately model uncertain nodal demands, pipe roughness coefficients, and component failures were introduced in the previous sections. However, these three uncertainties should be integrally considered for flexible design of UWDS. Thus, an integral uncertainty model is required, which models these three uncertainties in a single model. For this model, uncertainties could be represented as one scenario tree. A scenario tree is a collection of scenarios with a specific estimated probability within a time period. One scenario is one realisation of uncertainties, which represents one possible future. An example of a scenario tree, modelling the three types of uncertainties above for UWDS is illustrated in Figure 3-9. The example considers only two stages, and it was found that more hydraulic simulations are required as more stages or more states in each stage are considered. Therefore, to improve computational efficiency, it is important to control the number of stages and the number of states on each stage for flexible design in UWDS by using the proposed method.

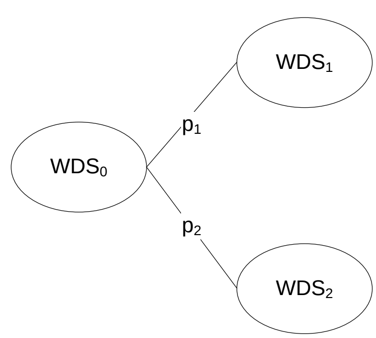

Figure 3-9 An illustrative scenario tree

where WDS_i represents future system state. p_j represents the occurrence probability of the transition between two states.

For each system state, it checks the performance of the system without component failure with full nodal demands, which are equal to expected values plus safety margins, and the performance of the system under two spanning trees with partial nodal demands. These three simulations for WDS_i are illustrated in Figure 3-10.

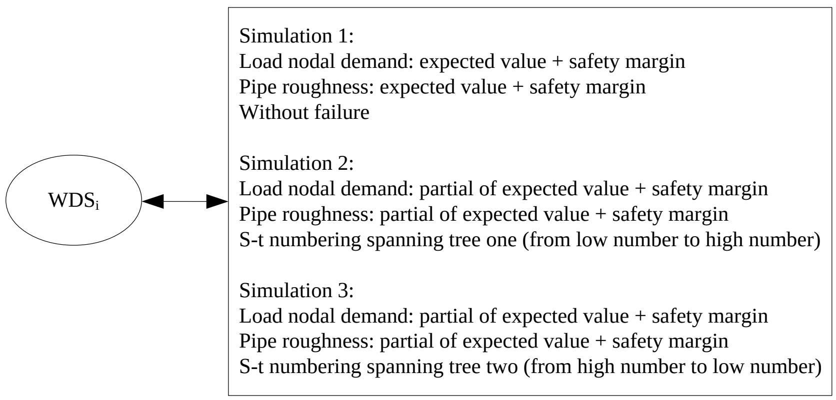

Figure 3-10 Detailed simulations for WDS_i

3.3.5 Illustration of the proposed integrated uncertainties modelling in a network

This proposed integrated uncertainty modelling is applied to model uncertain nodal demands, uncertain pipe roughness coefficients, and component failure for a simple network development. The network development is divided into two stages, and the network transition process is illustrated in Figure 3-11. WDS_0 is the system constructed in stage 1, and then either WDS_1 or WDS_2 will be constructed in stage 2. The probabilities of these two transitions are assumed as 50%, and S denotes the only water source for the network. The expected value for each nodal demand is assumed as 30 l/s, the expected value for each pipe roughness coefficient is assumed as 120 in stage 1, and 110 in stage 2. The safety margin for nodal demand is 10%, the safety margin for pipe roughness coefficient is -10%, and the demand load under each s-t spanning tree is full nodal demand.

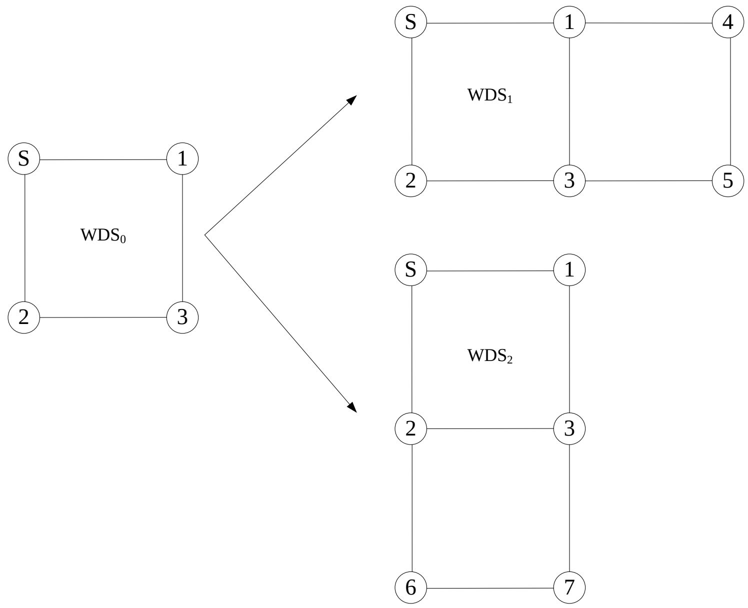

Figure 3-11 Possible transitions for the network example

The load demand for each node is:

Q_i = (1+10%)*30 = 33 l/s, $i = 1, 2, \ldots, NN$

Roughness coefficient for the new pipe is:

C_j = (1-10%)*120 = 108, $j = 1, 2, \ldots, NP_{new}$

Roughness coefficient for the old pipe is:

C_j = (1-10%)*110 = 99, $j = 1, 2, \ldots, NP_{old}$

DFS is applied to WDS_1 and WDS_2. Nodes are re-numbered according to the order the node is first visited during DFS. Also, a low value for each node is computed. The results are shown in Figure 3-12.

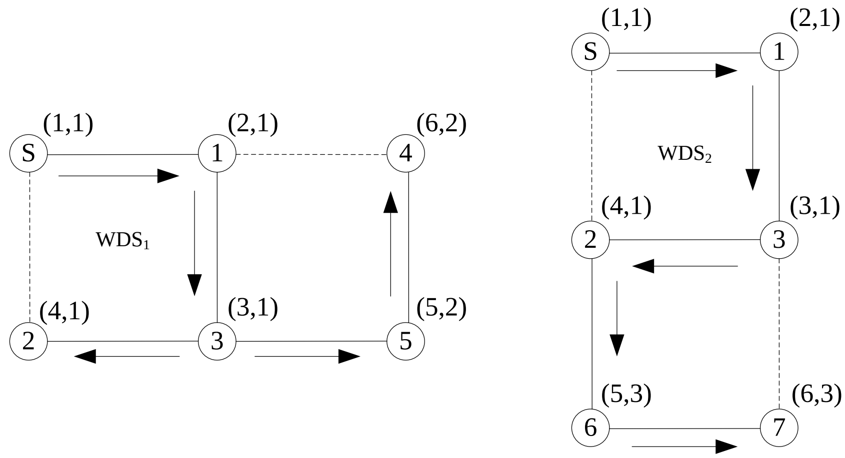

Figure 3-12 DFS for WDS_1 and WDS_2

After nodes are re-numbered and low value for each node computed, the second process for s-t numbering is applied. The process for WDS_1 and WDS_2 is illustrated in Figure 3-13, and the final s-t numbering for these two networks are shown in Figure 3-14.

WDS_1 VERTEX ADDED	WDS_1 LIST	WDS_2 VERTEX ADDED	WDS_2 LIST
	1-,2		1-,2
3	1-,3,2+	3	1-,3,2+
4	1-,4,3+,2+	4	1-,4,3+,2+
5	1-,4+,3-,5,2+	5	1-,4-,5,3+,2+
6	1-,4+,3-,5-,6,2+	6	1-,4-,5-,6,3+,2+

Figure 3-13 The second process of s-t numbering for WDS_1 and WDS_2

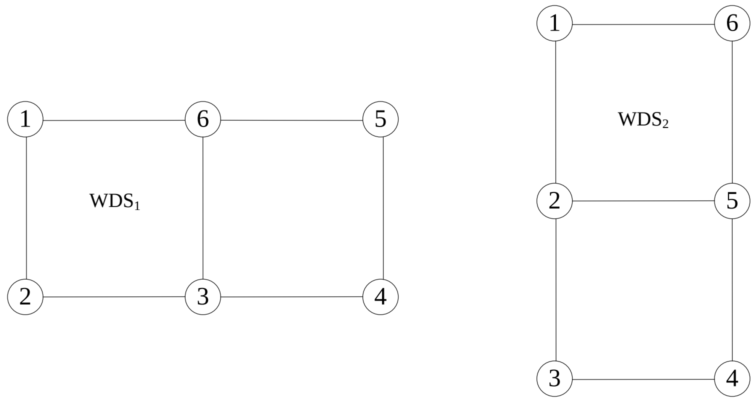

Figure 3-14 The resulted s-t numbering for WDS_1 and WDS_2

With s-t numbering for WDS_1 and WDS_2, two s-t spanning trees for each network can be generated, which are illustrated in Figure 3-15. s-t spanning trees for WDS_0 are taken from the sub-trees of WDS_1 or WDS_2.

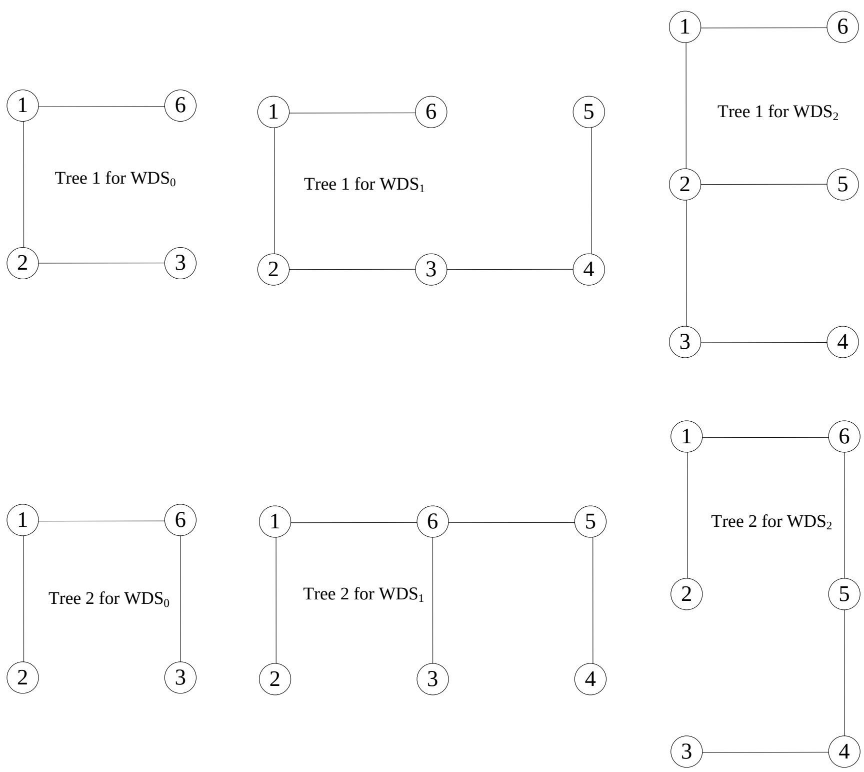

Figure 3-15 Two s-t spanning trees for WDS_0, WDS_1 and WDS_2

Finally an integral uncertainty model is illustrated in Figure 3-16.

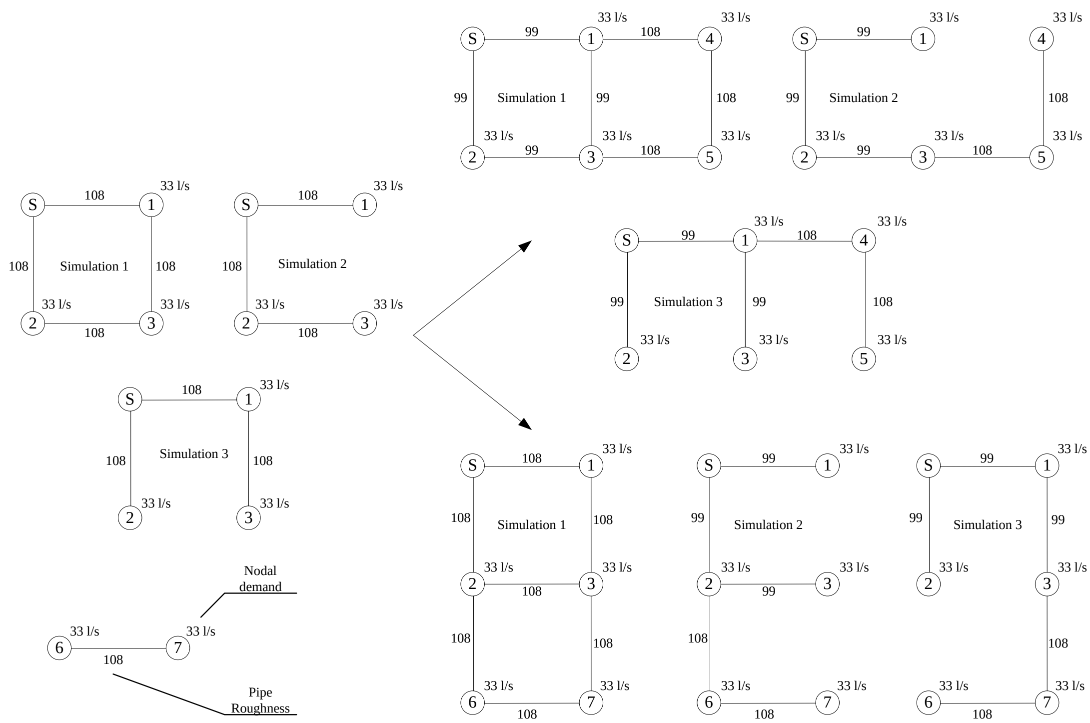

Figure 3-16 The integral uncertainty model for the example network

3.3.6 Discussion about the proposed integrated uncertainties modelling

The proposed integral uncertainty modelling considered uncertain nodal demands, pipe roughness coefficients, and component failures within a single model. It therefore enables water engineers evaluate different designs under uncertainties, and achieve flexible design. Furthermore, the method is computationally efficient, and requires only three simulations for each state. As a result, the method could be incorporated into Genetic Algorithms to efficiently search for the optimal solution. Although the method improves the computational efficiency significantly, the load demands and pipe roughness coefficients are decided only subjectively in this thesis. In reality, these values should illustrate the trade-off between the risk and the cost. This area could be viewed as one for future research.

3.4 Chapter Summary

This chapter reviewed methods for modelling uncertain nodal demands, uncertain pipe roughness coefficients, and component failures. Four methods were discussed for uncertain nodal demands and uncertain pipe roughness coefficients, and these were MCS, LHS, STM, and FORM. It was concluded that they consume significant computational time. For component failure in UWDS, the system configuration was analysed for its performance under single failures, and this method was also computational demanding. For achieving flexible design of UWDS, an efficient and integral uncertainty modelling was required.

Thus an integral uncertainty modelling was proposed, which models uncertainties in UWDS efficiently. The model transferred the stochastic problem into a deterministic one, by incorporating "safety margins" into the uncertain nodal demands and uncertain pipe roughness coefficients. The model also approximated the system performance under component failure, by only checking the performance of two s-t spanning trees with partial or full load demand. As a result, these two techniques generated great computational savings.

Chapter 4 Identification of flexibility sources in UWDS

4.1 Introduction

The primary hydraulic objective of an urban water distribution system is to provide enough energy to deliver sufficient water to users. The available energy in reality may not be sufficient to meet this requirement, since there are many uncertainties. The major uncertainties considered in this thesis are nodal demands, pipe roughness coefficients, and component failures. To improve system performance under these uncertainties, flexibility is considered, which can allow cost-effective responses to these uncertainties.

Nodal pressure could be checked to see whether the system has a satisfactory performance or not. Uncertainties may cause pressure deficiency on the nodes, which results in the system failing to deliver required demands on these nodes. Many sources in UWDS could be used to maintain nodal pressures above the required minimum pressures despite these uncertainties, and these sources could be viewed as potential flexibility sources. According to de Neufville (2006), flexibility in UWDS could also be divided as two types: flexibility "on" system and flexibility "in" system. Flexibility "on" system are "*strategies or technologies, which can be applied to reduce uncertainties, when treating system itself as a 'black box'*". Flexibility "in" system, on the contrast, "*consider technical parts of the system, trying to redesign and improve the system, for example, to search for the better combination of system components and also the design for each component*".

This thesis focused only on flexibility "in" UWDS, and components in UWDS are divided into two types: one is energy-generating component, and the other is energy-consuming component. The energy-generating component is defined as one that can provide energy to deliver water. The energy-consuming component, on the contrary, is defined as the one that consumes energy when water goes through it. In other words, energy would be increased when water goes through the energy-generating component and energy would be decreased when water goes through the energy-consuming component. For example, pumps are energy-generating components and pipes are energy-consuming components. From the energy-generating side, flexibility can be from the components, which can have the capacity to generate variable energy. From the energy-consuming side, flexibility could be from the components, which can have the capacity to consume variable energy.

The chapter reviews different flexibility sources in UWDS in Section 4.2, and then proposes an efficient method to identify high value flexibility sources in UWDS in Section 4.3. Finally, it gives a brief chapter summary in Section 4.4.

4.2 Literature review of flexibility sources

4.2.1 Flexibility from each major component

4.2.1.1 Pipe

Pipelines constitute the majority for components in UWDS, and thus the largest investment for the system. A pipe is an energy-consumed component, and total energy will be decreased when water goes through it. The relationship of the energy on the two sides of a pipe could be expressed as (water flows from node 1 to node 2):

$$H_2 = H_1 - h_f \tag{4.1}$$

where H_1 and H_2 are the total energy on node 1 and on node 2, respectively. h_f = headloss in the pipe. The headloss has different forms, and two of the most commonly used are Darcy-Weisbach and Hazen-Williams equations (Mays 2000):

The Darcy-Weisbach equation could be expressed as:

$$h_{f,DW} = f \frac{L}{D} \frac{V^2}{2g} = 0.0826 \frac{Q^2}{D^5} Lf \tag{4.2}$$

where f = dimensionless friction factor, L = pipe length (m), D = pipe diameter (m), $V = Q/A$ = mean flow velocity (m/s), Q = discharge (m^3/s), A = cross-sectional area of the pipe (m^2), and g = acceleration caused by gravity (m/s^2).

The Hazen-Williams equation is expressed as:

$$h_{f,DW} = 10.654\left(\frac{Q}{C}\right)^{\frac{1}{0.54}} \frac{1}{D^{4.87}} L \tag{4.3}$$

where C = Hazen-Williams coefficient, which is assumed to be constant and independent of the discharge.

From the above equations, as more water goes through the pipe, more headloss is created. If the pipe diameter is not big enough, nodal pressure on the downstream of the pipe may fall below the required minimum pressure. Therefore, pipe diameter should be sized for high water flow to meet the minimum pressure requirement. Such pipe diameter will enable sufficient pressure not only for small water flow, but also for large water flow. Additional capacity in a single pipe could be reviewed as one of flexibility sources, to respond to uncertain nodal demand.

However, nodal pressure on the downstream of the pipe may also fall below the required minimum pressure because of pipe failure. When the pipe is taken out of service, the node is separated from the system. As a result, water can not arrive there. To enable water arrive there, an alternative route should be prepared. The alternative route can be achieved by paralleling another pipe aside with the original pipe or designing the node into a loop, which is illustrated in Figure 4-1. When one pipe is in failure, the node could still be connected to the system by the alternative pipe.

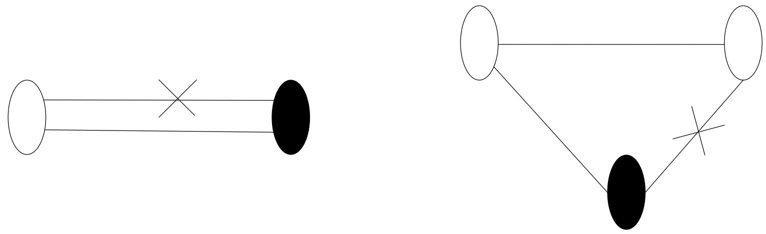

Figure 4-1 Paralleling another pipe and designing the node into a loop

In a word, the minimum pressure under uncertain nodal demands and pipe failures can be achieved by additional capacity in pipes and well looped pipe networks. The system with big capacity in pipes, but poorly looped pipe networks can respond to uncertain nodal demands, but not to the component failure. On the contrary, the system with well looped pipes but small capacity in pipes can respond to component failure in some degree but not to uncertain nodal demands. Therefore, only the system with additional capacity in pipes and well looped pipe networks can respond to uncertain nodal demand and component failure together. That is to say that the flexibility in pipes come from the additional capacity in pipes and well looped pipe designs.

4.2.1.2 Pump

Pumps are another important component for UWDS, which are mainly used to lift water to supply high elevation consumers, and thus, a pump is an energy-generated component, and energy will be increased when water goes through it. Two principal parameters for a pump are flow (*Q*) and head (*H*). A pump curve is used to describe the relationship between *Q* and *H*, when different *Q* is supplied from the pump. The curve could be summarised as the equation (Rossman 2000):

$$H_G = A - BQ^C \tag{4.4}$$

where H_G = head gain, Q = flow rate, and A, B, C are constants, which are based on the characteristic of the pump. The curve for a single-speed pump is illustrated in Figure 4-2.

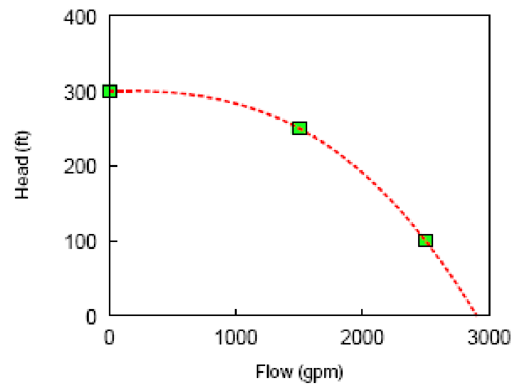

Figure 4-2 An example curve for a single-speed pump (Rossman 2000)

From the curve above, it is observed that the more the flow rate, the less the head that can be generated from the pump. Therefore, nodal pressure under large flow rates may fall below the required minimum pressure. This becomes more pronounced if the head loss in pipe is considered, because more head loss would be generated in such cases. To avoid pressure deficiency on the node or achieve flexibility, large pump or variable-speed should be chosen, which enables sufficient head to be generated even in the case of large flow rates. For the variable-speed pump, different curves can be generated by applying different speed N. Three curves for a variable-speed pump at N = 2.0, 1.0, and 0.5 are illustrated in Figure 4-3.

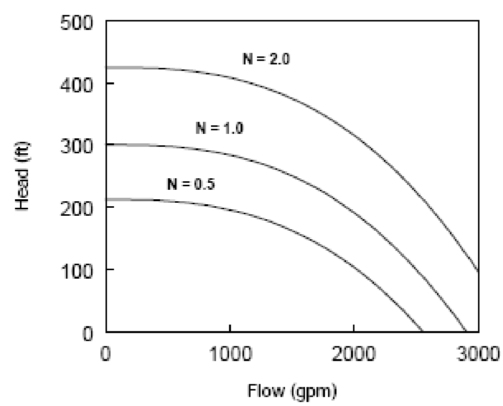

Figure 4-3 An example curve for a variable-speed pump (Rossman 2000)

4.2.1.3 Storage (reservoir or tank)

Storage (reservoir or tank) is another important component in UWDS, which is used to ensure the reliability of supply, maintain pressure, equalize pumping and treatment rates, reduce the size of transmission mains, and improve operational flexibility and efficiency (Mays 2000). Here only energy related characteristics are discussed, and water level in a reservoir is assumed as constant. However, water level in a tank is assumed as variable during the filling and the draining of the tank. Thus, flexibility in the reservoir and the tank are discussed separately.

Water level in the reservoir indicates the available energy to supply water, which is assumed to be the same as the elevation of the reservoir, and this energy does not change with different flow rates from the reservoir. The relationship between available head and flow is illustrated in Figure 4-4.

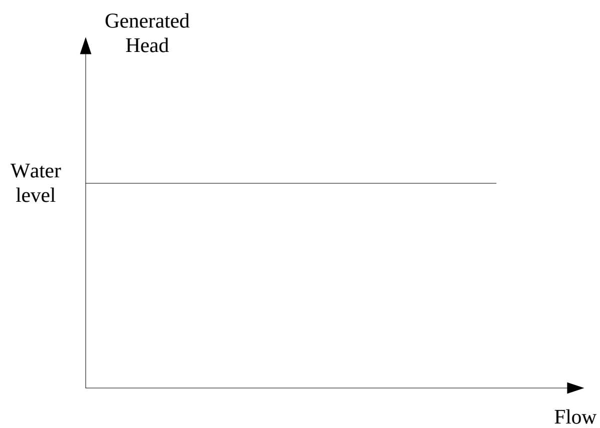

Figure 4-4 Relationship between generated head and flow from a reservoir

The generated head is constant no matter how much flow there is. In the cases of large flow, nodal pressure may fall below the required minimum pressure, because larger headloss will be generated in pipes. To avoid this risk, water level in the reservoir has to be increased, which is impossible to be achieved without the use of the pump. The only other choice is to design the reservoir in another place with more favourable water level.

The water level in the tank indicates the available energy to supply water, similar to reservoir. However, this energy will change as the water level changes with the filling and draining of the tank. During the process of draining the tank, water is supplied to users from the tank, and as a result the water level in the tank decreases. The rate of decrease is related to both the flow rate into the tank, and the diameter of the tank. This process will stop when the critical point (e.g., minimum level in the tank) is reached. The draining process in general is during high demand. In the process of filling the tank, water is supplied from the source to the tank, and therefore the water level in the tank increases. The increase rate is related to the flow rate out of the tank and the diameter of the tank. A typical relationship between generated energy and flow is illustrated in Figure 4-5. The real relationship may vary, depending on the variation in demand, controls for the tank, and operations of the pump.

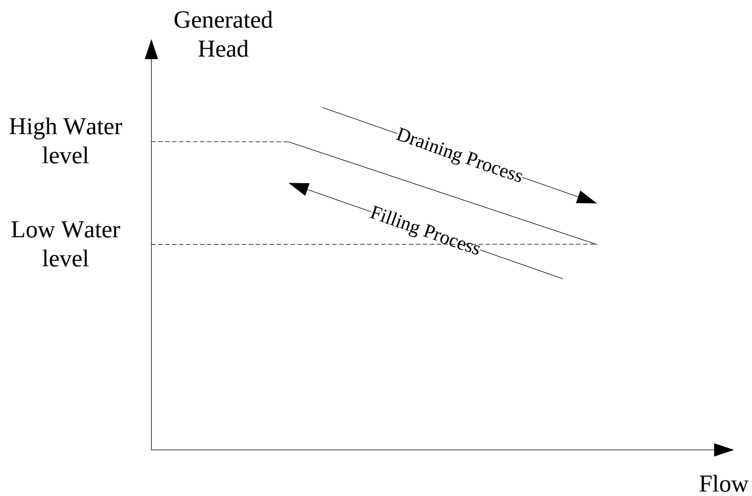

Figure 4-5 A typical relationship between generated energy and flow in a tank

From the figure above, it is a higher possibility that nodal pressure may fall below the required minimum pressure during the period of high flow. This is due to the low generated energy in the tank, and increased head loss in pipes. To avoid this risk, flexibility can be introduced by increasing the diameter of the tank, and designing the tank at favourable locations. When the diameter of the tank is increased, the water level in the tank would not drop dramatically. When designing the tank at a favorable site, higher nodal pressures may be generated.

4.2.1.4 Valve

Valves are important components for achieving well operated UWDS. They can be divided into four types (Mays 2000), which include: (1) isolation valves to separate a portion of the system (2) control valves for regulating pressure and flow (3) blow-offs valves to drain water from dead ends (4) air release and vacuum prevention valves. When water goes through the valve, energy will be decreased, and therefore valves are energy-consumed components. This thesis only discusses control valves, which are used to modulate flow or pressure, via operations in partly open positions, to create headloss or pressure differences between upstream and downstream locations.

The energy relationship between upstream and downstream for a valve is expressed as:

$$H_2 = H_1 - K\left(\frac{V^2}{2g}\right) = H_1 - \frac{K}{2g}\left(\frac{Q}{A}\right)^2 \tag{4.5}$$

where H_1 and H_2 are the total energy on the upstream and on the downstream of the valve, respectively. K = minor loss coefficient, $V = Q/A$ = mean flow velocity (m/s), Q = discharge (m^3/s), A = cross-sectional area of the valve (m^2), and g = acceleration caused by gravity (m/s^2).

When more flow is required on the downstream, more head loss will be generated. As a result, nodal pressure on the downstream may drop below the required minimum pressure. To avoid this risk, the valve should open more, and therefore, flexibility comes from the ability to operate the valve in the different open positions to generate more favourable pressure.

4.2.2 Flexibility from multi-components

4.2.2.1 Pump with pump

The curve for a single pump has been discussed in previous section. When more discharge goes through a pump, less head would be generated to supply water to the system. Therefore, pressure deficiency happens more likely during periods of high demand. In reality, pumps could be arranged in series or in parallel, which can generate more favourable combinations for discharge and head.

When pumps are arranged in series, discharge for each pump is the same, but more energy is added to the water after each pump. Figure 4-6 illustrates two similar pumps arranged in a series.

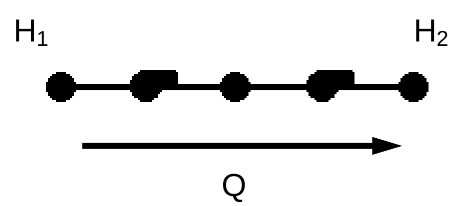

Figure 4-6 Two similar pumps in series

The relationship between the total energy on the upstream and the downstream of the pumps can be expressed by the equation:

$$H_2 = H_1 + 2H_G = H_1 + 2(A - BQ^C) \tag{4.6}$$

where H_1 and H_2 are the total energy on the upstream and on the downstream of the pumps, respectively. H_G = head gain, Q = flow rate, and A, B, C are constants, which are based on the characteristic of the pump.

The equation shows that more head could be generated when two similar pumps are arranged in series, compared to a single pump, since water is lifted twice. Therefore, this arrange has more capability to avoid pressure deficiency due to high demand or component failure.

When pumps are arranged in parallel, discharge is distributed to each pump, and new energy added by each pump is similar. Figure 4-7 illustrates two similar pumps arranged in parallel.

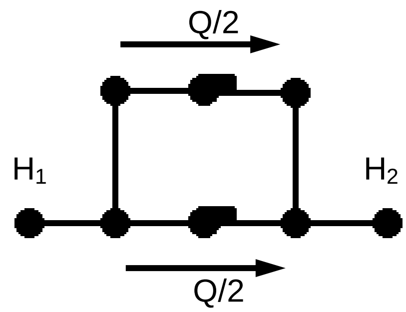

Figure 4-7 Two same pumps in parallel

The relationship between the total energy on the upstream and the downstream of the pumps are summarised in the equation:

$$H_2 = H_1 + H_G = H_1 + A - B\left(\frac{Q}{2}\right)^C \tag{4.7}$$

where H_1 and H_2 are the total energy on the upstream and on the downstream of the pumps, respectively. H_G = head gain, Q = total flow rate, and A, B, C are constants, which are based on the characteristic of the pump.

From the equation, because flow is distributed to each pump, more head could be generated when two same pumps are arranged in parallel compared with a single pump. Therefore, this arrange has more capacity to avoid pressure deficiency due to high demand or component failure.

For the pumps in series, all pumps have to be operated together. This arrangement is similar to choosing a single pump with a large capacity. Water can not go through if one of pumps is in failure. However, for pumps in parallel, water engineers can operate different number of pumps together to generate different curves. These different curves can be used to respond to different conditions. Compared to a single pump, more flexibility is enabled when multiple pumps are arranged together.

4.2.2.2 Pump with valve

When a pump operates alone, it has a limited capability to control the downstream pressure under the maximum pressure. This condition would be changed when the pump operates with the valve, and Figure 4-8 illustrates a combination of a pump and valve in series.

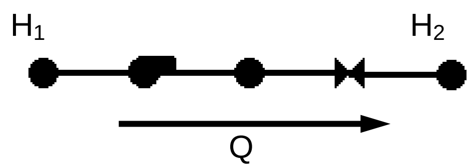

Figure 4-8 A pump and a valve in series

The relationship between the total energy on the upstream and the downstream for this arrangement is expressed as the equation:

$$H_2 = H_1 + A - BQ^C - K\left(\frac{V^2}{2g}\right) \tag{4.8}$$

where H_1 and H_2 are the total energy on the upstream and the downstream of this arrangement, respectively. It is assumed that all other headloss are ignored. K = minor loss coefficient, V = mean flow velocity (m/s), Q = discharge (m^3/s), g = acceleration caused by gravity (m/s^2), and A, B, C are constants, which are based on the characteristic of the pump.

During the period of low demand, head gain from the pump is high. Therefore, downstream pressure may be above the maximum pressure. This pressure could be reduced below the maximum pressure when there is a valve operating with the pump, because more head loss could be generated from the valve when it is in the position with small release.

4.2.2.3 Storage with valve

The available energy from the storage (reservoir or tank) is almost constant no matter how much flow there is. However, this condition would be changed when storage works with a valve, because the valve has the ability to regulate flow or pressure by operating in different open position. This combination is illustrated in Figure 4-9, where H_1 is water level in the storage, H_2 is the total energy on the node, Q is flow rate through the valve.

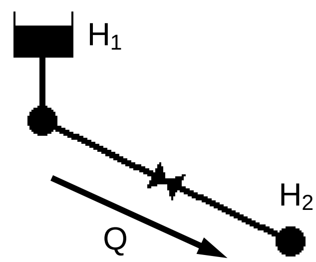

Figure 4-9 The combination of storage and valve

The relationship between H_1 and H_2 is expressed by the equation:

$$H_2 = H_1 - K\left(\frac{V^2}{2g}\right) = H_1 - \frac{K}{2g}\left(\frac{Q}{A}\right)^2 \tag{4.9}$$

where H_1 and H_2 are the total energy in the storage and on the downstream of the valve, respectively. K = minor loss coefficient, $V = Q/A$ = mean flow velocity (m/s), Q = discharge (m^3/s), A = cross-sectional area of the valve (m^2), and g = acceleration caused by gravity (m/s^2).

Using this equation, the downstream pressure of the valve can be adjusted by operating the valve at different open positions. This pressure relates to both the water level in the storage, and the operations of the valve. When more water is required in the downstream, the valve could be operated in a position with large opening. As a result, nodal pressure can still meet the required minimum pressure. On the contrary, when less water is required in the downstream, the valve could be operated in a position with small opening. Nodal pressure can be limited below the maximum pressure. More flexibility can be achieved by combining storage with valve. However, this depends heavily on sufficient energy in the storage, because the valve is an energy-consuming component, which cannot generate energy to supply water.

4.2.2.4 Storage with pump

Both storage and pumps are energy-generated components, and therefore, more flexibility can be achieved to the generated energy to supply water from the combination. When water level in the storage is not sufficient to supply the system, water could be pumped to the system. Storage and pump can be arranged in series, which is illustrated in Figure 4-10, where H_1 is water level in the storage, H_2 is the total energy on the node, and Q is flow rate through the pump.

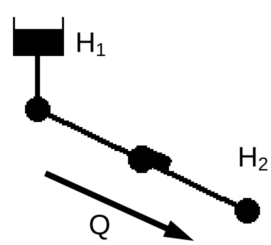

Figure 4-10 Combination of storage and pump in series

The relationship between H_1 and H_2 is expressed as the equation:

$$H_2 = H_1 + H_G = H_1 + A - BQ^C \tag{4.10}$$

where H_G = head gain, Q = flow rate, and A, B, C are constants, which are based on the characteristic of the pump.

When more flow goes through the pump, smaller H_2 is generated. Therefore, it becomes more likely that nodal pressure on the downstream will fall below the required minimum pressure during the periods of high demand. To avoid this risk, more capacity in the pump should be created. This increased pump capacity is one flexibility method to respond to variable demands.

There is another arrangement for storage and pump. In normal conditions, water level in the storage is large enough to supply water to the system. However, this energy may not be sufficient during the periods of high demand or component failure, due to increased headloss in the system. In such case, the storage and pump can be arranged in parallel, and this combination is shown in Figure 4-11.

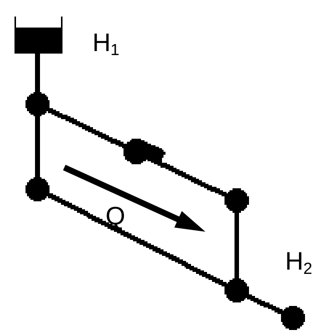

Figure 4-11 Combination of storage and pump in parallel

For this arrange, the pump is used as a back-up for extreme conditions, where only the storage is operational under most conditions. The pump is only operated when there is a pressure deficiency in the system. The relationship between H_1 and H_2 is expressed as the equations.

When only storage is operated:

$$H_2 = H_1 \tag{4.11}$$

When storage is operated with the pump:

$$H_2 = H_1 + H_G = H_1 + A - BQ^C \tag{4.12}$$

where H_G = head gain, Q = flow rate, and A, B, C are constants, which are based on the characteristic of the pump.

For this arrangement, water engineers can operate the storage to respond to most normal conditions. When there is pressure deficiency in the system, they can then operate the pump to respond to high demand or component failure. Flexibility is the choices water engineers can make to operate either only the storage, or use the storage and pump together, which is achieved by arranging the storage and pump in parallel.

4.2.2.5 Storage with pump and valve

Both the storage and pump are energy-generated components, and thus their capability to control nodal pressures below the maximum pressure level is limited. However, this capability can be improved if they are operate with the valve, and Figure 4-12 illustrates the storage, pump, and valve arranged in series.

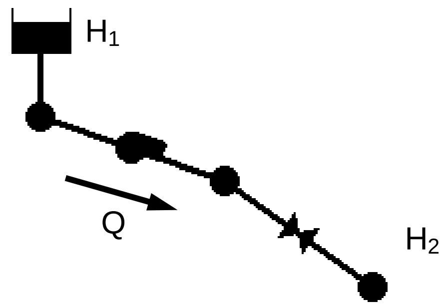

Figure 4-12 Storage, pump, and valve arranged in series

The relationship between H_1 and H_2 is summarised as the equation:

$$H_2 = H_1 + A - BQ^C - K\left(\frac{V^2}{2g}\right) \tag{4.13}$$

where H_1 and H_2 are the total energy on the upstream and the downstream of this arrangement, respectively. K = minor loss coefficient, V = mean flow velocity (m/s), Q = discharge (m^3/s), g = acceleration caused by gravity (m/s^2), and A, B, C are constants, which are based on the characteristic of the pump.

During periods of low demand, head gain from the pump is high. As a result, downstream pressure may be above the maximum pressure. However this pressure can be reduced when there is a valve operating with the pump, because more headloss can be generated from the valve when it is in the position with small opening. Then downstream pressure can be adjusted within an appropriate range by operating the valve.

4.2.3 Summary of Flexibility in the components of WDS

The major components in UWDS are pipes, pumps, storages, and valves, which can be divided into energy-generating and energy-consuming components. Flexibility in UWDS has been discussed for each component, along with some basic combinations of these components. Because of uncertainties in UWDS, there are different requirements for energy to supply water to the system. Flexibility is indicated by the capability of the system to adjust the generated or the consumed energy. That is to say that flexibility can be maximised if the energy-generating and energy-consuming components are optimally combined. However, these optimal combinations differ from system to system. Also, since components in UWDS are integrated with each other, optimal system flexibility may not be achieved by only adding optimal flexibility from each component. The inter-relationships between the components have to be considered when identifying flexibility sources for the system. In the next section, an efficient method is developed to identify flexibility sources for UWDS.

4.3 An efficient method to identify flexibility sources in UWDS

4.3.1 Detail description of the proposed method

There are numerous components in UWDS, and these components are integrated with each other. Therefore, an efficient method is proposed in this section to help water engineers identify flexibility sources in the system. The methodology consists of four steps:

Step 1: Defining the criteria for network performance, and developing a value matrix for evaluating flexibility. When the nodal pressure is above the required minimum pressure, it is assumed that the required flow can be supplied from the node. Also, nodal pressures must be above the required minimum pressures not only under most likely condition, but also under some extreme conditions. These extreme conditions are caused by uncertainties in nodal demands, pipe roughnesses, and component failures. Flexibility measures will be developed for the improvement of the hydraulic performance of the system under these uncertainties. Two flexibility measures would be introduced in the next section.

Step 2: Identifying the main uncertainties and describing possible future states over time. The major uncertainties in the design of UWDS are nodal demands, pipe roughness coefficients, and component failure. Uncertain nodal demands and uncertain pipe roughness coefficients can be described by some distributions. In this method, only extreme conditions are considered. That is to say that high nodal demands and low pipe roughness coefficients are used to check whether the nodal pressures meet the required minimum pressures or not. Component failure (mainly pipe) is simulated by setting the status of the pipe as closed, and the method only considers the condition where only one pipe is taken out of the service.

Step 3: Developing the least cost solution, when expected values are used for nodal demands and pipe roughness coefficients with no component failure happening in the system. For this least-cost solution, pressure on each node is above the required minimum pressure, and then high nodal demands, low pipe roughness coefficients, and component failures are applied on the system. The nodal pressures under these conditions are then summarised. This process tries to develop a base design, which can be used to compare its flexibility value with other designs. The least cost solution can be generated by an optimisation model using expected values as inputs for nodal demands and pipe roughness coefficients and setting the status of all pipes as open.

Step 4: Applying different flexibility sources, and calculating the flexibility measures after these flexibility sources. This step provides a quantitative view of different flexibility sources within the system to enable it respond to uncertainties in Step 2. This can help water engineers reject some sources that have low flexibility values, while keeping those with high flexibility values for further evaluation and analysis. These high flexibility sources can then be put into a flexibility-based optimisation model, which will be introduced in Chapter 5. The optimisation model will identify the optimal design with the best combination of these flexibility sources.

4.3.2 Flexibility Index

When uncertainties are applied on the least-cost design, it will cause pressure deficiency on some nodes in the system. Because of pressure deficiency, the required demand cannot be fully supplied to these nodes. Flexibility tries to improve the system performance under uncertainties, which is to say that flexibility ties to decrease pressure deficiency or decrease supply deficiency on nodes. Different possible flexibility measures are proposed and studied in Chapter 2, referring to Table 2-2. In this section, a Flexibility Index (FI) is developed, which is based on decreasing pressure deficiency on the worst node (PMPN).

The FI is based on the improvement of pressure deficiency on the most critical node in the system. The node with the highest pressure deficiency is assumed as the most critical node, at which the pressure can easily drop below the required minimum pressure. Flexibility tries to decrease the pressure deficiency on this node, and therefore flexibility sources can be identified by checking the improvement of pressure deficiency on this node. Pipe failure will generate many load conditions. The most critical node can be identified under each load condition, and may be different under different load conditions.

Pressure deficiency for node *i* under condition *j* is expressed by the equation:

$$PD_{i,j} = \begin{cases} 0 & H_{i,j} \geq H_{i,j}^{\min} \\ H_{i,j}^{\min} - H_{i,j} & H_{i,j} < H_{i,j}^{\min} \end{cases} \tag{4.14}$$

where $PD_{i,j}$ is pressure deficiency on node *i* under condition *j*, $H_{i,j}$ is pressure on node *i* under condition *j*, $H_{i,j}^{\min}$ is the required minimum pressure on node *i* under condition *j*.

The worst node can be identified by finding the node with the largest pressure deficiency under each condition. It is assumed that pressure deficiency at the worst node under condition *j* is noted as PD_j^{worst}. After the flexibility source *k* is applied, the improvement of pressure deficiency on the worst node under condition *j* is expressed as the equation:

$$IPD_j = PD_j^{worst} - PD_{j,k}^{worst} \tag{4.15}$$

where IPD_j is the improvement of pressure deficiency on the worst node under condition *j*, PD_j^{worst} is the pressure deficiency on the worst node under condition *j* before flexibility source is applied, $PD_{j,k}^{worst}$ is the pressure deficiency on the worst node under condition *j* after flexibility source *k* is applied.

A positive value of IPD_j illustrates that the flexibility source can decrease pressure deficiency on the worst node under condition *j*. On the contrary, a negative value of IPD_j indicates that the flexibility source can not decrease pressure deficiency on the worst node under condition *j*.

Flexibility tries to decrease pressure deficiency under all conditions, and therefore FI^1 is defined as the weighted sum of decreasing the pressure deficiency on the worst node under each condition. The equation is expressed as:

$$FI_k^1 = \sum_{j=1}^{J} W_j IPD_j \tag{4.16}$$

where FI_k^1 is flexibility index for flexibility source *k*, W_j is the weight for condition *j*, IPD_j is the improvement of pressure deficiency on the worst node under condition *j*, *J* is total number of conditions.

4.3.3 Illustration of applying the proposed flexibility identification method in a network

4.3.3.1 Problem Statement

The flexibility identification method is applied to identify flexibility sources for a hypothetical network, which is taken from EPANET 2 users manual (Rossman 2000). The network is illustrated in Figure 4-13.

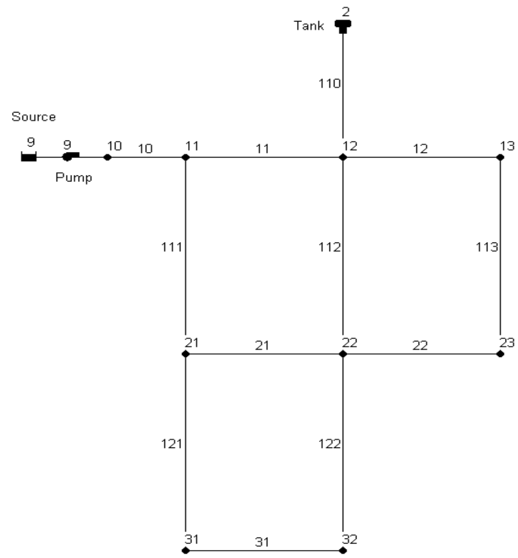

Figure 4-13 Network layout of a hypothetical WDS

The source is located on node 9, where water is treated in a central plant. A pumping station near the source lifts treated water into the system. A tank is located near node 12, which is used to balance the difference between supply and demand.

Node properties are given in Table 4-1, and the elevation of each node is given in column 2. Average daily water use at each node is given in column 3, which are treated as the expected values.

Table 4-1 Node properties of a hypothetical WDS

Node	Elevation (m)	Demand (l/s)
2	259.3	0.0
9	244.0	0.0
10	216.6	0.0
11	216.6	9.5
12	213.5	9.5
13	212.0	6.3
21	213.5	9.5
22	212.0	12.6
23	210.5	9.5
31	213.5	6.3
32	216.6	6.3

Tank properties are given in Table 4-2, and pipe characteristics are shown in Table 4-3. The C-factors are values projected for the end year of planning, and pipe 110 is riser pipe to the elevated tank.

Table 4-2 Tank properties of a hypothetical WDS

Tank Parameters	Value
Elevation (m)	259.3
Initial Level (m)	36.6
Minimum Level (m)	30.5
Maximum Level (m)	45.8
Diameter (m)	15.4

Table 4-3 Pipe properties of a hypothetical WDS

Pipe	Length (m)	Diameter (mm)	C-Factor
10	3211.65	457.2	100
11	1610.4	355.6	100
12	1610.4	254	100
21	1610.4	254	100
22	1610.4	304.8	100
31	1610.4	152.4	100
110	61	457.2	100
111	1610.4	254	100
112	1610.4	304.8	100
113	1610.4	203.2	100
121	1610.4	203.2	100
122	1610.4	152.4	100

Only one pump is installed in the pumping station, and its characteristic curve is shown in Table 4-4. The variation in water use throughout the day is given in Table 4-5, and the value of 1.6 times average use for 6-8 hours means that water use is 1.6 times the average use during those hours.

Table 4-4 Pump properties of a hypothetical WDS

Flow (l/s)	Head (m)
94.6	76.3

Table 4-5 Water use pattern of a hypothetical WDS

Time of day	Ratio
0—2	1.0
2—4	1.2
4—6	1.4
6—8	1.6
8—10	1.4
10—12	1.2
12—14	1.0
14—16	0.8
16—18	0.6
18—20	0.4
20—22	0.6
22—24	0.8

4.3.3.2 Solution

The uncertainties considered for this application are nodal demands and pipe failures. High nodal demand is assumed to be 1.3 times the expected value. The case only considers the failure condition for one pipe failing at a time. Therefore, there are total of 12 possible pipe failure conditions. This application also runs a single period simulation, and the chosen simulation time is 12 am, where the nodal demand is the average daily demand, and the water level in the tank is at the initial level. The required minimum pressure for each demand node is 110 psi (708.95 kPa). The original design values for the pump, the tank, and pipes are assumed as the least-cost solution in this application.

The flexibility sources used for testing the proposed method are by increasing pipe diameters and adding parallel pump. Each flexibility source is applied separately, while leaving others unchanged. For the flexibility sources of increasing pipe diameter, each pipe will be increased by 2 inches from its original value. For the flexibility source of adding parallel pump, only one parallel pump is added, which has the same pump curve as the original one.

After applying high demands (1.3 times of expected values) on the least-cost design, the nodal pressures under each pipe failure condition are simulated, which are summarised in Table 4-6. Under each condition, the node with the lowest pressure in the system is identified. Nodal pressure at this worst node under each condition is summarised under the column 'min', and pressure deficiency at the worst node is summarised under column 'PD'.

Table 4-6 Pressure deficiency on the worst node before flexibility

	Pressure (m)										PD (m)
	N10	N 11	N 12	N 13	N 21	N 22	N 23	N 31	N 32	min	
P 10	120.6	73.3	76.8	77.2	74.8	76.4	77.8	73.2	69.9	69.9	2.4
P 11	102.6	99.7	76.9	78.1	84.2	78.6	79.6	80.8	74.3	74.3	0.0
P 12	83.3	77.8	76.9	74.9	75.8	76.7	77.3	74.0	70.5	70.5	1.8
P 21	84.0	78.6	76.9	77.4	78.7	77.0	78.4	76.3	72.0	72.0	0.3
P 22	83.6	78.1	76.9	76.5	76.8	78.0	75.7	75.1	71.7	71.7	0.6
P 31	83.5	78.0	76.9	77.6	76.7	77.5	78.8	75.7	69.1	69.1	3.2
P 110	99.0	95.7	96.6	97.1	95.5	96.8	98.1	93.8	90.5	90.5	0.0
P 111	86.2	81.1	76.9	76.7	71.4	74.9	76.3	70.1	67.3	67.3	5.1
P 112	82.8	77.2	76.9	75.9	72.8	72.8	74.2	70.8	67.1	67.1	5.3
P 113	83.4	77.9	76.9	78.0	76.3	77.2	78.4	74.5	71.1	71.1	1.2
P 121	83.7	78.2	76.9	77.6	77.3	77.4	78.7	56.9	58.1	56.9	15.4
P 122	83.4	77.9	76.9	77.6	76.3	77.6	78.8	72.6	65.5	65.5	6.8

After paralleling a pump with a similar pump curve and applying high demands (1.3 times of the expected values), the nodal pressures under each pipe failure condition were simulated, and are summarised in Table 4-7. Under each condition, the node with the lowest pressure in the system is identified. Nodal pressure at this worst node under each condition is summarised under the column 'min', and pressure deficiency on the worst node is summarised under column 'PD'.

Table 4-7 Pressure deficiency on the worst node after paralleling a pump

	Pressure (m)										PD (m)
	N10	N 11	N 12	N 13	N 21	N 22	N 23	N 31	N 32	min	
P 10	120.6	73.3	76.8	77.2	74.8	76.4	77.8	73.2	69.9	69.9	2.4
P 11	114.5	110.8	76.9	78.2	88.6	79.1	80.1	84.0	75.1	75.1	0.0
P 12	97.6	84.7	77.0	76.0	78.7	77.8	78.4	76.5	72.4	72.4	0.0
P 21	98.8	86.7	77.0	77.6	85.8	77.4	78.8	81.6	73.3	73.3	0.0
P 22	97.6	84.9	77.0	76.5	79.1	78.4	75.8	77.0	73.0	73.0	0.0
P 31	97.7	84.9	77.0	78.0	79.5	78.2	79.3	78.5	69.7	69.7	2.6
P 110	115.2	111.9	112.7	113.3	111.6	113.0	114.3	110.0	106.6	106.6	0.0
P 111	101.2	90.3	77.0	76.7	71.5	74.9	76.3	70.2	67.3	67.3	5.1
P 112	97.4	84.5	77.0	77.2	77.6	76.4	77.8	75.3	71.2	71.2	1.1
P 113	97.6	84.8	77.0	78.0	79.0	78.2	79.3	76.8	72.8	72.8	0.0
P 121	97.9	85.3	77.0	77.9	80.7	78.1	79.3	57.6	58.8	57.6	14.7
P 122	97.5	84.7	77.0	78.0	78.5	78.2	79.4	74.8	67.8	67.8	4.5

Using equation 4.15 and 4.16, the FI^1 for paralleling a pump can be calculated. It is assumed that the weighting for each condition is the same, which is equal to 1/12. Therefore, FI^1 after paralleling a pump is equal to 1.49. The FI^1 after each flexibility source is summarised in Table 4-8.

Table 4-8 Flexibility Index 1 after each flexibility source

Flexibility Sources	FI^1 (m)	Rank
Increase Diameter for Pipe 10	0.0	10
Increase Diameter for Pipe 11	-0.3	13
Increase Diameter for Pipe 12	0.1	8
Increase Diameter for Pipe 21	0.1	9
Increase Diameter for Pipe 22	0.0	12
Increase Diameter for Pipe 31	0.5	5
Increase Diameter for Pipe 110	0.0	11
Increase Diameter for Pipe 111	0.6	3
Increase Diameter for Pipe 112	0.4	6
Increase Diameter for Pipe 113	0.2	7
Increase Diameter for Pipe 121	0.5	4
Increase Diameter for Pipe 122	1.8	1
Add Parallel Pump	1.0	2

It is concluded that adding parallel pump and increasing pipe 122 are the two most effective flexibility sources to decrease pressure deficiency in the system.

4.4 Chapter Summary

Flexibility in UWDS has been discussed for each component, and also for some basic combinations of these components. Flexibility is indicated by the capability of the system to adjust the generated energy or the consumed energy. It was concluded that it is very important to consider the inter-relationships among the components, when identifying the flexibility sources.

A method was developed to identify flexibility sources in UWDS, and this method introduced a Flexibility Index (FI) to measure flexibility. FI was developed based on Pressure on Minimum Pressure Node (PMPN). The measure was calculated considering the inter-relationships among the components. As a result, the method will help water engineers develop a quantitative view for different flexibility sources, to decrease pressure deficiency in the system. Finally, the proposed method was tested in a simple example.

Chapter 5 Flexibility-based optimisation for flexible design of UWDS

5.1 Introduction

Flexible design of UWDS involves numerous design variables, and each design variable has several choices. As a result, the design space for the problem is extremely huge, which makes it difficult to compare different design solutions one by one. In this chapter, an efficient optimisation model is developed to help water engineers achieve optimal solutions for the flexible design of UWDS. The model is based on Genetic Algorithms (GA) integrating the proposed uncertainty modelling from Chapter 3 and the identified flexibility sources in Chapter 4.

This chapter reviews Genetic Algorithms in Section 5.2, and then it proposes the flexibility-based optimisation model, based on GA process in Section 5.3. Finally, a brief chapter summary is presented in Section 5.4.

5.2 Genetic Algorithms

5.2.1 Overview of Genetic Algorithms

A genetic algorithm is developed as a search algorithm based on natural selection and the mechanisms of population genetics, and was first proposed by Holland (1975) and then further developed by Goldberg (1989) and others in the 1980s. Known as the best type of evolutionary algorithms (EA), Genetic Algorithms have roots in the biological processes of survival and adaptation and differ from the traditional approaches of existing optimisation techniques. The method relies on randomised operators that simulate recombination and mutation, to create new individuals (i.e., solutions) who then compete to survive via the selection process, which operates according to a problem-specific fitness function (Back et al. 1997).

Genetic algorithms code the decision variables as a “chromosome” and generate a number of trial chromosomes (Initialisation). These trial chromosomes are put as a group called a “population”.

Next, they evaluate these trial chromosomes and compute the "fitness" for each chromosome (Evaluation). Finally, they regenerate a collection of new trial chromosomes from old trial chromosomes by undergoing three basic operations of reproduction, crossover, and mutation. Reproduction is a survival-of-fittest selection process, which tries to guarantee that the fitter chromosomes in the current generation (parents) are more likely to reproduce and propagate to the next generation (offspring). Crossover exchanges partial segments between parent chromosomes to produce offspring chromosomes. Mutation is the occasional flipping of segment values to prevent the convergence to a local optimum (premature) and to increase the searching capability in the decision space. To reach this point, the search completes one iteration. It is expected that the more GA iterate, the higher their chance to reach the global optimal point. Therefore, after a number of generations the population is expected to evolve artificially, and the (near) optimal solution will be finally reached. The first application of GA for water distribution system was made by Simpson et al. (1994), and to date GA has been applied in a wide variety of water distribution system problems, such as optimal system design, optimal operation, calibration of water distribution models, and many others.

5.2.2 Basic Components of Genetic Algorithms

At present, many versions of GA exist, but they all share some basic features. Standard genetic algorithms are characterised by the following elements: (1) coding: choose suitable decision variable representations; (2) initialisation: generate an initial population of a number of trial chromosomes; (3) evaluation: compute fitness for each chromosome in a population; (4) selection: pick up fitter chromosomes to participate in a mating operator; (5) mating (or crossover): reproduce new chromosomes by combining characteristics from two or more old chromosomes after selection; (6) mutation: flip occasionally some segment values of new chromosomes to maintain population's diversity and to prevent its prematurity (convergence to local optima). Element (3) to (6) are repeated in sequential generations until termination criteria have been met. This general framework is illustrated in Figure 5-1.

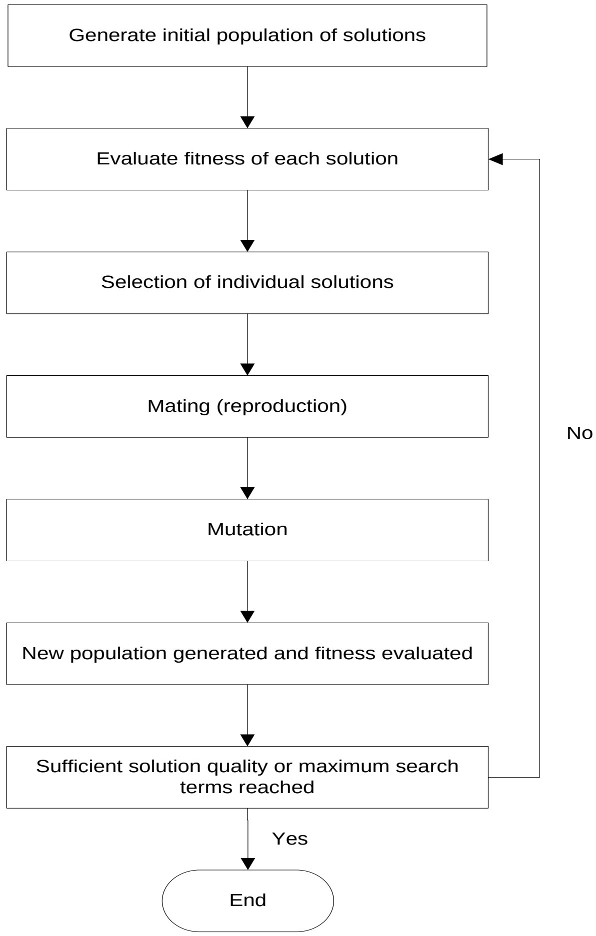

Figure 5-1 Generalized framework of a GA (Nicklow et al. 2010)

The detailed function of each component is expressed as follows:

Coding – A suitable representation should be chosen for encoding the potential decision variable set before heading to GA iteration. Without suitable representations, it is impossible for GA to function properly. Decision variables can be encoded as binary vectors, integer vectors, real-coded vectors, or mixed integer/real vectors.

Initialisation – The next step after choosing proper coding is to generate a collection of trial chromosomes as a group of "population". Each chromosome represents one solution for the problem, and can be generated randomly or from careful selection. The initialisation is one of most critical parameters, which controls the efficiency and effectiveness of GA. Population size usually takes 30-200.

Evaluation – The next step after initialisation is to evaluate the trial chromosomes and to compute the fitness of each chromosome. The computation of the fitness is equal to calculating the value of objective function for the unconstraint problem, or the value of objective function plus penalty from violating the constraints for the constraint problem.

Selection – Chromosomes in a "population" are selected for mating according to their fitness. The general rule is that the fitter the Chromosome is, the more likely it is to be chosen for mating. There are many selection operators available for GA, including tournament selection, truncation selection, roulette wheel selection, and Boltzmann selection. Within these, tournament selection can prevent early convergence, which randomly selects two pair of parent chromosomes from the current population, and the fitter one in each pair is kept for crossover. After selection, a mating pool (parents) is formed.

Crossover - Parents in the mating pool are selected to reproduce the offspring for a new population of chromosomes. Crossover implies a partial exchange between the selected parents and then generates offspring. There is a wide range of alternative crossover operators depending on the representations chosen in the algorithm. For example, in binary GA crossover can be one-point, multi-point, or uniform. Probability of crossover usually takes 0.7-1.0.

Mutation – The purpose of crossover is to identify optimal solution, but it also results in population similarity, which decreases the searching capacity of GA. Thus, the population requires the occasional flipping of some segment values on each chromosome to maintain population diversity. Mutation is an insurance technique designed against prematurity, namely converging to local optima too early. It works on the segment of chromosomes by randomly altering a bit of the value. Probability of mutation usually takes 0.01-0.05.

5.2.3 Genetic algorithms applied in optimisation in WDS

GA have become the preferred technique for the optimisation of WDS design and operation, because they demonstrate good capability to deal with complex, nonlinear, and discrete optimisation problems (Babayan et al. 2005). Simpson et al. (1994) were the first to apply GA to the design of a pipe network of Gessler (1985). Savic and Walters (1997) used GA for the least-cost design of two looped networks of Alperovits and Shamir (1977), the Hanoi network of Fujiwara and Khang (1990), and the New York Tunnels system of Schaake and Lai (1969). GA were also applied to find optimal pumping scheduling to reduce energy costs by improving the efficiency of pump operation (Mackle et al. 1995; Savic et al. 1997). Halhal et al. (1999) used a structured messy GA (Halhal et al. 1997) to find the optimal planning for the rehabilitation, upgrading and/or expansion of a water distribution system subject to limited budget. Walters et al. (1999) applied structured messy GA to improve the design of "anytown" distribution network, including the decision variables for pipe rehabilitation, pumping operation, and storage tank location and volume. Vairavamoorthy and Ali (2005) improved search efficiency of their real-code genetic algorithms (Vairavamoorthy and Ali 2000) by excluding regions of impractical or infeasible search space in optimal design of water distribution systems. Wu and Walski (2005) transformed the least-cost design and rehabilitation problems of a water distribution system, from a constrained to an unconstrained by applying a self-adaptive penalty approach.

There are also many applications of multi-objective GA to the problems of water distribution systems. Farmani et al. (2003) made a comparative study about different multi-objective evolutionary algorithms (MOEAs) and their applicability in the water distribution system. Many recently developed multi-objective optimisation of water distribution systems were based on elitist Non-Dominated Sorting-based multi-objective evolutionary algorithm (NSGA Ⅱ) (Deb et al. 2000) and their applications in water distribution systems could be found in literature (Prasad and Asce 2003; Babayan et al. 2004; Farmani et al. 2004; Farmani et al. 2005; Farmani et al. 2005; Farmani et al. 2006).

5.3 Flexibility-based optimisation model based on GA process

5.3.1 Problem Formulation

Flexibility-based optimization model tries to incorporate flexible design for UWDS into a GA process. Thus the model could guide water engineers to achieve flexible design step by step. Flexible design of UWDS requires finding the optimal solution to achieve the ability of the system to respond to uncertain nodal demands and component failures. The problem is presented here as a single objective optimisation. The objective is to minimise total cost, which includes capital investments to design each component for the system, and operation costs to operate the system. The required ability of the system to respond to uncertainties (flexibility) is set as the constraint. The decision variables include design variables of pipe diameters, pump capacities, and tank capacities and operation variables of pumps. This thesis focuses only on the pipe diameters. The problem can be analytically formulated as follows:

$$\text{Minimise } f(i) = \text{Cost}(i) \tag{5.1}$$

where Cost (i) is the cost resulting from a solution i. The cost is the total cost of pipes within the design period.

Nodal pressures in the system can indicate whether the system has sufficient capacity to supply water to users under different conditions. Nodal pressure deficiency (NPD) appears in the system when the designed capacity is lower than the required capacity. The required capacity shows flexibility of the system to respond to uncertainties. Then NPD is expressed as a penalty, and incorporated into the cost of the design. Hence:

$$f(i) = \text{Cost}(i) + W_p \text{NPD}_i \tag{5.2}$$

where Cost (i) is the cost resulting from a solution i, NPD_i is nodal pressure deficiency for the solution i, and W_p is penalty coefficient for NPD_i.

5.3.2 Initialisation

Pipe diameters are discrete, which are from a vector of available commercial diameters. Normally they could be represented as integer numbers, the order in the vector. Each integer number represents one diameter, for example, [100mm, 200mm, 300mm, 400mm] is a vector of available commercial diameters. Then [0, 1, 2, 3] is the integer representation of the vector. In GA, a solution [200, 300, 300, 200] could be coded as a binary chromosome or an integer chromosome. The representation results are shown in Figure 5-2.

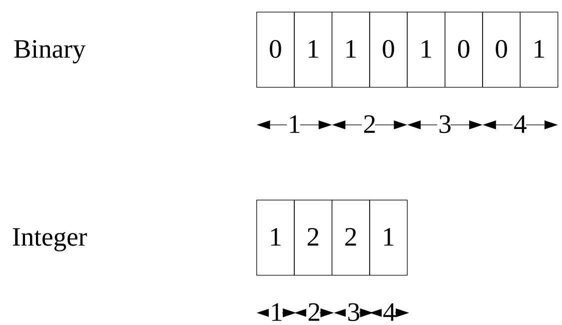

Figure 5-2 Binary and integer representation of an example solution in GA

The binary code requires longer chromosomes than the integer code to represent the solution, which will result in the requirement of more memory and processing power. Also the binary code will generate redundant states, which do not represent any of the design variables, resulting in poor performance of the GA (Vairavamoorthy and Ali 2000). Therefore, the integer code is used in the thesis, to represent the solutions for flexible design of UWDS.

Old pipes may also be replaced with new pipes, and in such case, two decision variables are required to represent the decision on an old pipe. One indicates whether the pipe is replaced or not, which takes the value of either 1 or 0. 0 means the pipe is not replaced, while 1 means the pipe is replaced. The other decision variable indicates the diameter chosen for the new pipe, which selects the value from a vector of available commercial diameters. For example, GA representation for three old pipes is shown in Figure 5-3.

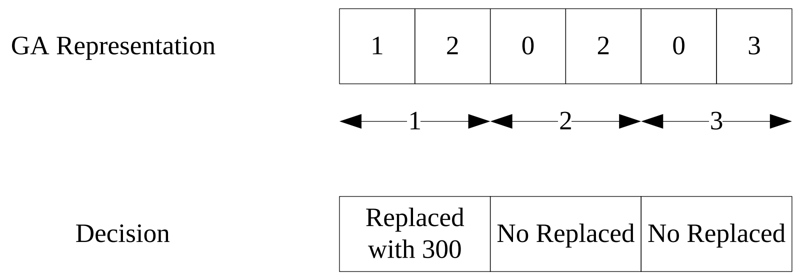

Figure 5-3 GA representation of old pipes

5.3.3 Evaluation

The fitness function includes two parts. One is from the cost of the solution, while the other is from the penalty if the solution can not meet the required flexibility (capability of responding to uncertain nodal demands and pipe failures). Hence:

$$\text{Fitness} = \text{Cost} + \text{Penalty} \tag{5.3}$$

A solution includes decisions on pipes in each stage, the cost of a solution on the first stage is computed as:

$$Cost^0 = \sum_{i=1}^{I_0} U(D_i^0) L_i^0 \tag{5.4}$$

The cost of a solution on the second stage or later is computed as:

$$Cost^t = \sum_{i=1}^{I_t} R_i^t \frac{U(D_i^t) L_i^t}{(1+r)^{t\Delta t}} \tag{5.5}$$

Then the total cost of a solution is equal to the present value of the cost on each stage, computed as:

$$Cost = \sum_{t=0}^{NT} Cost^t \tag{5.6}$$

$$= \sum_{i=1}^{I_0} U(D_i^0) L_i^0 + \sum_{t=1}^{NT} \sum_{i=1}^{I_t} R_i^t \frac{U(D_i^t) L_i^t}{(1+r)^{t\Delta t}} \tag{5.7}$$

where D_i^t = pipe diameter for pipe *i* in stage *t*; $U\left(D_i^t\right)$ = unit cost for the pipe *i* with the diameter D_i^t; R_i^t = replacement status for pipe *i* in stage *t*; L_i^t is the length for the pipe *i*; I_t = number of pipes in stage *t*; *NT* = number of stage; *r* = discount rate; and Δt = time duration within one stage.

The penalty is computed based on whether the required capacity is met or not, which is indicated by nodal pressures in the system. If nodal pressure is equal or higher than the required minimum pressure, there is no penalty for that node. If nodal pressure is lower than the required minimum pressure, there is penalty for that node. This is expressed as:

$$Penalty_i^{node} = \begin{cases} 0 & H_i \geq H_i^{\min} \\ H_i^{\min} - H_i & H_i < H_i^{\min} \end{cases} \tag{5.8}$$

where $Penalty_i^{node}$ is node penalty on node *i*, H_i is nodal pressure on node *i*, and $H_i^{\min}$ is the required minimum pressure on node *i*.

There are numerous conditions under which the system will operate. However, the performance of the system is only checked under several critical conditions. These critical conditions indicate the magnitude of the flexibility designed in the system to respond to uncertain nodal demands and pipe failures. As a result, several network simulations will be run in each state to check whether the required capability of flexibility is met or not for that state. It is assumed that a network simulation includes all information about the inputs to run a hydraulic simulation. For example, network configuration, nodal demands, and pipe roughness coefficients must be determined before running a simulation. The choices of these inputs in each simulation would determine the required capacity for flexibility, to respond to uncertain nodal demands and component failures. Under a simulation *k*, the network penalty could be computed as:

$$Penalty_k^{network} = \sum_{i=1}^{I_k} Penalty_i^{node} / I_k \tag{5.9}$$

where $Penalty_k^{network}$ is network penalty under the simulation *k*, $Penalty_i^{node}$ is node penalty on node *i*, I_k is number of nodes under the simulation *k*.

The number of simulation in each state is determined by the uncertainties modelling, which has been discussed in Chapter 3. Three minimum simulations are required to indicate the capacity of the system to respond to uncertain nodal demands and pipe failures. The first simulation is used to indicate the ability of the system to respond to uncertain nodal demands, which adds safety margins into nodal demands and does not consider any failure from the pipe. The other two simulations are used to indicate the capacity of the system to respond to pipe failures. Both of them choose partial of full nodal demands (expected value + safety margin) as demand inputs. However, one chooses the network configuration of one spanning tree from low number to high number while the other chooses the network configuration of one spanning tree from high number to low number. An example of the three simulations for state i is illustrated in Figure 5-4. Refer to Chapter 3 for more details.

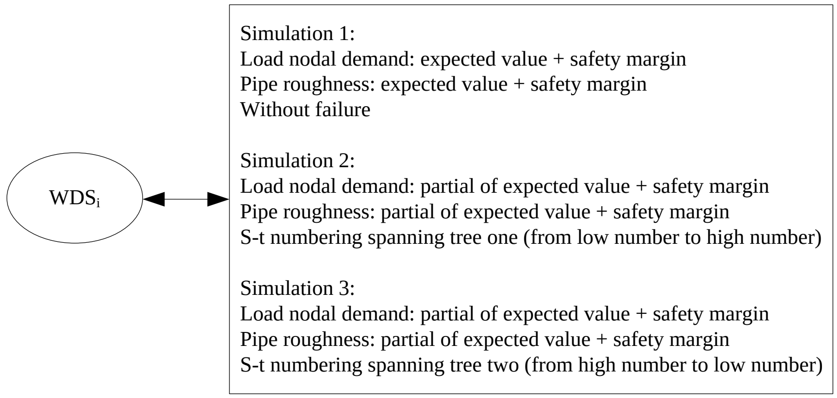

Figure 5-4 Three simulations for WDS_i

Then penalty under one state can be computed as:

$$Penalty_k^{state} = \sum_{j=1}^{3} Penalty_j^{network} / 3 \tag{5.10}$$

where $Penalty_k^{state}$ is state penalty under the state *k*, $Penalty_j^{network}$ is network penalty under the simulation *j*.

The penalty for the problem is the sum of state penalty in all states. First, an integral uncertainty model for flexible design of UWDS needs to be generated, by using the method proposed in Chapter 3. An example taken from that chapter is illustrated in Figure 5-5, for two stages and three states. On the second stage, there are two possible developments from the first state. Within each state, three simulations are used to indicate the required capacity for flexibility to respond to uncertain nodal demands and pipe failures.

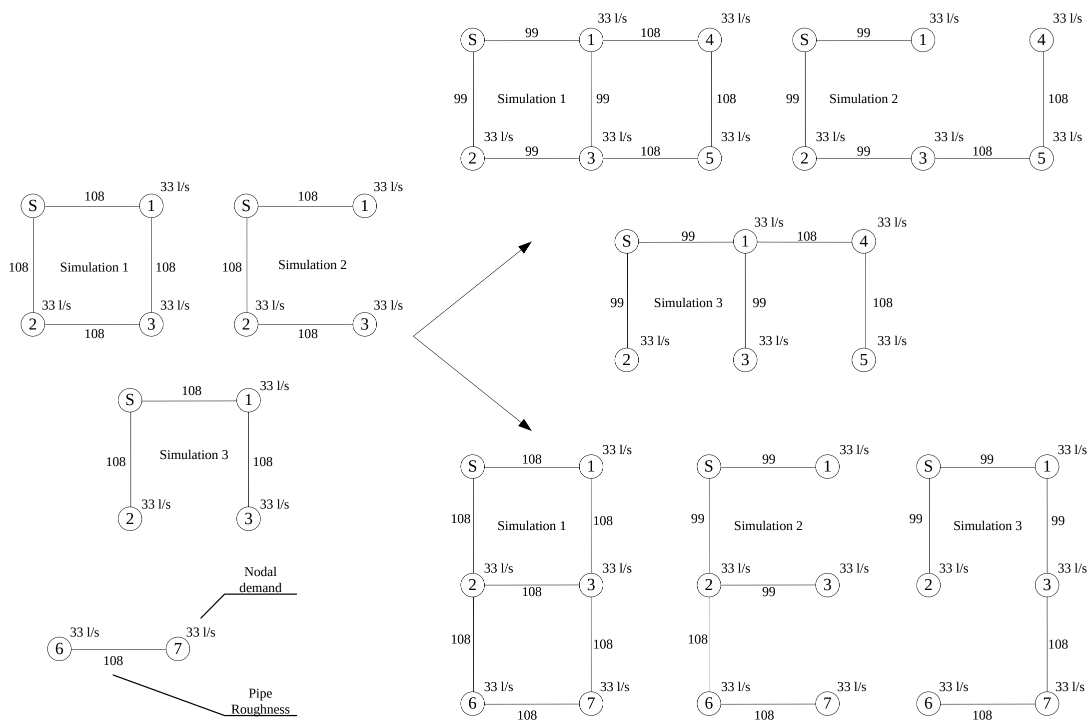

Figure 5-5 The integral uncertainty model for the example network

Total penalty for flexible design of UWDS can be expressed as:

$$Penalty = \sum_{k=1}^{3} Penalty_k^{state} / 3 \tag{5.11}$$

where $Penalty_k^{state}$ is state penalty under the state k.

The choice of penalty coefficient influences the performance of GA. A large penalty coefficient prevents the GA from using the good features of slightly infeasible solutions to effectively reach an optimal solution, while a small penalty coefficient misleads the GA to treat an infeasible solution as similar to the feasible solution (Wu and Walski 2005). Therefore, a self penalty function is applied in the thesis to compute the penalty coefficient W_p, which is self-adjust during the search process of GA. The function is expressed as:

W_p = cost (5.12)

Finally, the fitness function for one solution can be computed as:

$$Fitness = \left(\sum_{i=1}^{I_0} U(D_i^0) L_i^0 + \sum_{t=1}^{NT} \sum_{i=1}^{I_t} R_i^t \frac{U(D_i^t) L_i^t}{(1+r)^{t\Delta t}} \right) \left(1 + \sum_{k=1}^{3} Penalty_k^{state} \right) \quad (5.13)$$

5.3.4 Selection

According to its fitness, a chromosome may be chosen into a pool for reproduction, and this process in GA is called ‘selection’. The fitter the chromosome is, the more chance it has to be selected. *Roulette-wheel* is one of fitness-proportionate selection. Each chromosome is assigned a slice of a circular “roulette wheel”. The size of the slice is proportional to the individual’s fitness. The wheel is spun N times, where N is the size of the population. On each spin, the chromosome under the wheel’s marker is selected to be in the pool of parents for reproducing.

One of main drawbacks of *Roulette-wheel* is prematurity. Small number of chromosomes with high fitness would occupy most of the Roulette-wheel. As a result, the diversity in the pool of parents is weak. Therefore, *Tournament* is chosen as the selection operator in the thesis because it performs better at preventing prematurity than *Roulette-wheel*. Two chromosomes are picked up randomly from the population, the fitter one is put into the pool for reproducing, and then the two are returned to the population and can be picked up again. This procedure is repeated until the size of a new population has been obtained.

5.3.5 Crossover

The selection does not create a new population, but rather generates a pool of parents for crossover. The crossover is applied with a probability p_c. Two chromosomes are selected from the group of parents, and then an integer k is chosen randomly, between 1 and l-1 (l is the string length of the chromosomes), where k is the position of crossover. Two new chromosomes (called the *offsprings*) are created by swapping all bits between positions $k + 1$ and l inclusively. A simple example is illustrated in Figure 5-6.

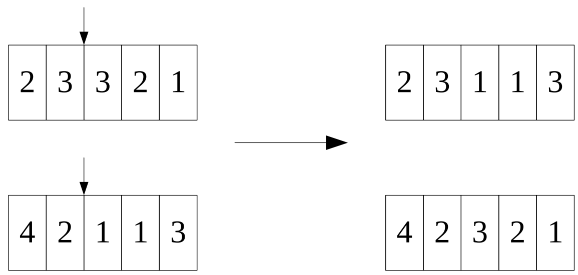

Figure 5-6 One-point Crossover

5.3.6 Mutation

The mutation operator changes genes in each chromosome of new population with a small probability. As a result, all decision variables are subject to low probability random changes. If the decision variable of pipe diameter is under mutation, it can randomly select a new value from a vector of available decisions. If the decision variable of pipe replacement is under mutation, it becomes either 0 from 1 or 1 from 0.

5.3.7 Computational framework of the proposed method

The uncertain nodal demands and pipe failures were modelled by the integral uncertainty modelling in Chapter 3, which can be represented as one scenario tree. A scenario tree is a collection of scenarios with a specific estimated probability within a time period. One scenario is one realisation of uncertainties, which represents one possible future. An example scenario tree, modelling uncertain nodal demands and pipe failures in UWDS is illustrated in Figure 5-7. Refer to Chapter 3 for detailed construction of the scenario tree. It was found that more hydraulic simulations are required as more stages or more states in each stage are considered. Therefore, to improve computational efficiency it is important to control the number of stages and the number of states for each stage for flexible design in UWDS, by using the proposed method.

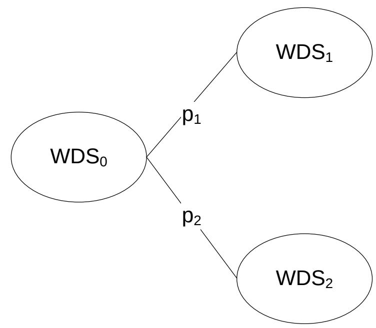

Figure 5-7 An illustrative scenario tree

where WDS_i represents future system state. Within each WDS_i, three simulations are run. One is with whole system configuration and full nodal demands (expected value + safety margin). The other two are with the system configuration of two spanning trees and partial nodal demands. p_j represents the occurrence probability of the transition between two states.

A two loops computational framework of the proposed method to identify the optimal solution of flexible design in UWDS is shown in Figure 5-8. The internal loop optimises the current system development (ready to be implemented) over its design period. Although the useful output is just the current optimal system development, to achieve cost-effectiveness the optimisation model also includes possible future system development under different scenarios. The model tries to generate the best current solution for its lifecycle, which requires evaluating all the current solutions together with the future unimplemented solutions within the decision space. The inner loop is solved by GA to search the optimal current system development. The external loop shows a shift on the current time. Its main function is to update the information about current existing system condition, and the environmental condition on a new lifecycle.

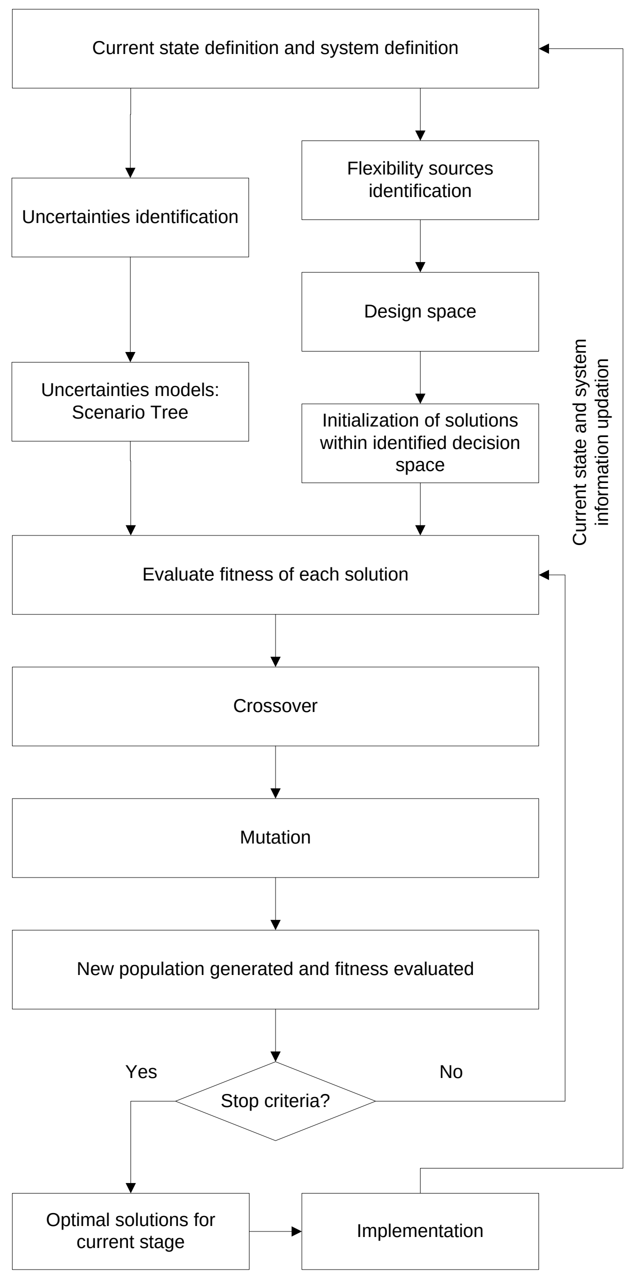

Figure 5-8 Computational framework of flexibility-based optimisation model

5.4 Chapter Summary

This chapter developed a flexibility-based optimisation model based on GA process to identity flexible design in UWDS. For this purpose, it reviewed the basic components of GA and also its successful applications for solving the problems of design and operation in WDS. It then interpreted the problem as a GA process. Initial population was generated from the design space, which were based on the flexibility sources identified in Chapter 4. Evaluation was undertaken by incorporating the uncertainties modelling, which was proposed in Chapter 3. Finally, a computational framework for flexibility-based optimisation modelling was developed. This method can help water engineers achieve optimal solutions efficiently. The optimisation model generates optimal current system development (flexible design), to respond to uncertain nodal demands and pipe failures in a cost-effective way.

Chapter 6 Case Study

6.1 Case description

The proposed flexibility-based optimisation method is used to identify flexible design for a hypothetical network “anytown”, firstly introduced by Walski et al. (1987). This network was chosen as the case study, because it was well characterised. The system layout is shown in Figure 6-1. The source is located in the lower-right side, where water is treated at a central plant. A pumping station near the source lifts treated water and pumps it into the system. Three tanks are planned near the node 21, 22, and 23, which are used to balance the difference between supply and demand. The network has a total of 19 demand nodes and 42 pipes.

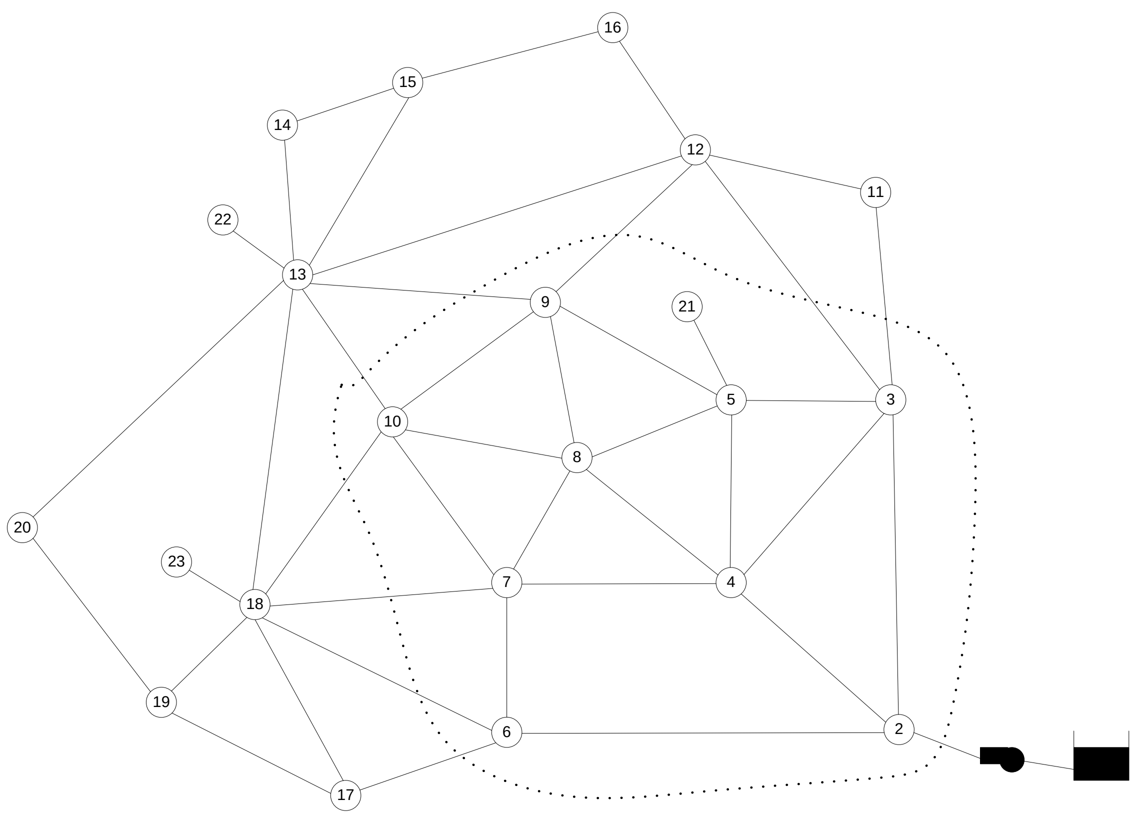

Figure 6-1 Network layout for “anytown”

Node properties for the network are given in Table 6-1, and average daily water use at each node is listed under column 2 to column 4, which are treated as expected values. The elevation of each node is listed under column 5.

Table 6-1 Nodal properties for "anytown"

Node	Average Daily Use			Elevation (m)
	2030 (l/s)	2050 North (l/s)	2050 West (l/s)	
1	Treatment works	Treatment works	Treatment works	82.4
2	31.5	31.5	31.5	6.1
3	12.6	12.6	12.6	15.3
4	31.5	31.5	31.5	15.3
5	31.5	31.5	31.5	15.3
6	31.5	31.5	31.5	15.3
7	31.5	31.5	31.5	15.3
8	63.1	63.1	63.1	15.3
9	31.5	31.5	31.5	15.3
10	12.6	25.2	25.2	36.6
11	-	12.6	-	15.3
12	-	37.9	-	15.3
13	-	25.2	25.2	24.4
14	-	37.9	-	24.4
15	-	37.9	-	24.4
16	-	37.9	-	24.4
17	-	-	25.2	36.6
18	-	-	63.1	36.6
19	-	-	25.2	36.6
20	-	-	25.2	36.6
21	Tank	Tank	Tank	15.3
22	Tank	Tank	Tank	24.4
23	Tank	Tank	Tank	36.6
Peak day: average flow = 1.3; Instantaneous peak: average flow = 1.8.				

The water use variation within a day is given in Table 6-2. For example, the value of 1.3 times average use for 9-12 means that water use is 1.3 times the average use during those hours.

Table 6-2 Water use pattern for "anytown"

Time of day	Actual average use
0-3	0.7
3-6	0.6
6-9	1.2
9-12	1.3
12-15	1.2
15-18	1.1
18-21	1.0
21-24	0.9

The unit costs to lay new pipes and to replace old pipes are summarised in Table 6-3. Replacing a pipe is more expensive than the initially installation of a pipe of similar size.

Table 6-3 Unit Costs for pipe laying (Walski et al. 1987)

Pipe Diameter (mm)	New ($/m)	Urban ($/m)
152.4	42.0	85.9
203.2	58.4	91.1
254	73.8	111.8
304.8	95.7	135.7
355.6	118.7	164.6
406.4	143.0	191.8
457.2	168.9	217.0
508	197.0	251.8
609.6	252.5	358.0
762	345.9	467.2
863.6[a]	418.0	583.3
1016[a]	535.1	766.9
[a]Added since original problem.		

Pipe properties are given in Table 6-4. The initial roughness height is recommended by Sharp and Walski (1988), which gives reasonable results for new metal pipes.

Table 6-4 Pipe properties for "anytown"

Pipe		Length (m)	C-factor
1	2	30.5	0.18
2	3	3660	0.18
2	4	3660	0.18
2	6	3660	0.18
3	4	2745	0.18
3	5	1830	0.18
3	11	1830	0.18
3	12	2745	0.18
4	5	1830	0.18
4	7	1830	0.18
4	8	1830	0.18
5	8	1830	0.18
5	9	1830	0.18
6	7	1830	0.18
6	17	1830	0.18
6	18	1830	0.18
7	8	1830	0.18
7	10	1830	0.18
7	18	1830	0.18
8	9	1830	0.18
8	10	1830	0.18
9	10	1830	0.18
9	12	1830	0.18
9	13	1830	0.18
10	13	1830	0.18
10	18	1830	0.18
11	12	1830	0.18
12	13	3660	0.18
12	16	1830	0.18
13	14	1830	0.18
13	15	1830	0.18
13	18	1830	0.18
13	20	3660	0.18
14	15	1830	0.18
15	16	1830	0.18
17	18	2745	0.18
17	19	1830	0.18
18	19	1830	0.18
19	20	1830	0.18
5	21	30.5	0.18
13	22	30.5	0.18
18	23	30.5	0.18

The Hazen-Williams C-factor in pipes with time can be described by a mathematical equation, proposed by Sharp and Walski (1988):

$$C = 18.0 - 37.2\log\left(\frac{e_0 + at}{D}\right) \tag{6.1}$$

where C = Hazen-Williams, C-factor; D = diameter, ft; e = absolute roughness height, L; e_0 = roughness height at time zero, L; a = growth rate in roughness height, L/T; t = time, T.

Growth rate in roughness height a is a case-based coefficient. Here it is assumed to be 0.1 mm/yr. The Hazen-Williams C-factor values on initial year, after 20 years, and after 40 years are then calculated, and given in Table 6-5.

Table 6-5 The Hazen-Williams C-Factor value with the time

Pipe Diameter (mm)	C-factor with time		
	Initial	20 years	40 years
152.4	126.9	86.6	76.1
203.2	131.6	91.3	80.7
254	135.2	94.9	84.4
304.8	138.1	97.8	87.3
355.6	140.6	100.3	89.8
406.4	142.8	102.5	91.9
457.2	144.7	104.4	93.8
508	146.4	106.1	95.6
609.6	149.3	109.0	98.5
762	153.9	112.6	102.1
863.6[a]	154.9	114.6	104.1
1016[a]	157.6	117.3	106.7

[a]Added since original problem.

6.2 Flexible design development

6.2.1 Introduction

The total design period for this case study is 40 years, beginning in year 2010 and ending in year 2050. To control the number of stages, the total planning period is divided into two stages of 20 years each. Three designs will be developed based on the different methods. Inflexible design comes from a least cost design under expected scenario, where uncertain parameters are taken as their expected values, and pipe failure is not included. The network includes numerous decision variables from pipes, which is complex enough to illustrate the applicability and the efficiency of the proposed flexibility-based optimization model to produce flexible design. Therefore, for simplicity, in this model the pumping station is treated as a reservoir with fixed head. The network inside the dashed area will be developed in the first stage. Then the network is expected to expand to the north in the second stage, and besides installing new pipes, some old ones may require replacement. Flexible design 1 and Flexible design 2 are developed by applying the proposed flexibility-based optimisation method, where uncertain water demand and pipe failure are considered. However, Flexible design 1 is a system designed without tanks, while Flexible design 2 has tanks. Capital costs for installing pumps and tanks, and energy costs for operating pumps are not formulated into the objective function. For these two flexible designs, the pumping station is also treated as a reservoir with fixed head and tanks are treated as demand nodes with known demand. During high demand period, the tank provides water to the system and is treated as a supply source, and during low demand period, the tank stores water from the system and is treated as a demand node.

6.2.2 Inflexible design

6.2.2.1 Model preparation

The model uses deterministic values for the uncertain nodal demands and does not consider pipe failures. Inflexible design is generated by finding the least cost solution under the expected condition. The network is first developed within the dashed line until year 2030, and then is expected to expand to the north. The network layout of this inflexible design is shown in Figure 6-2. There are 9 demand nodes in the first stage and 15 demand nodes in the second stage.

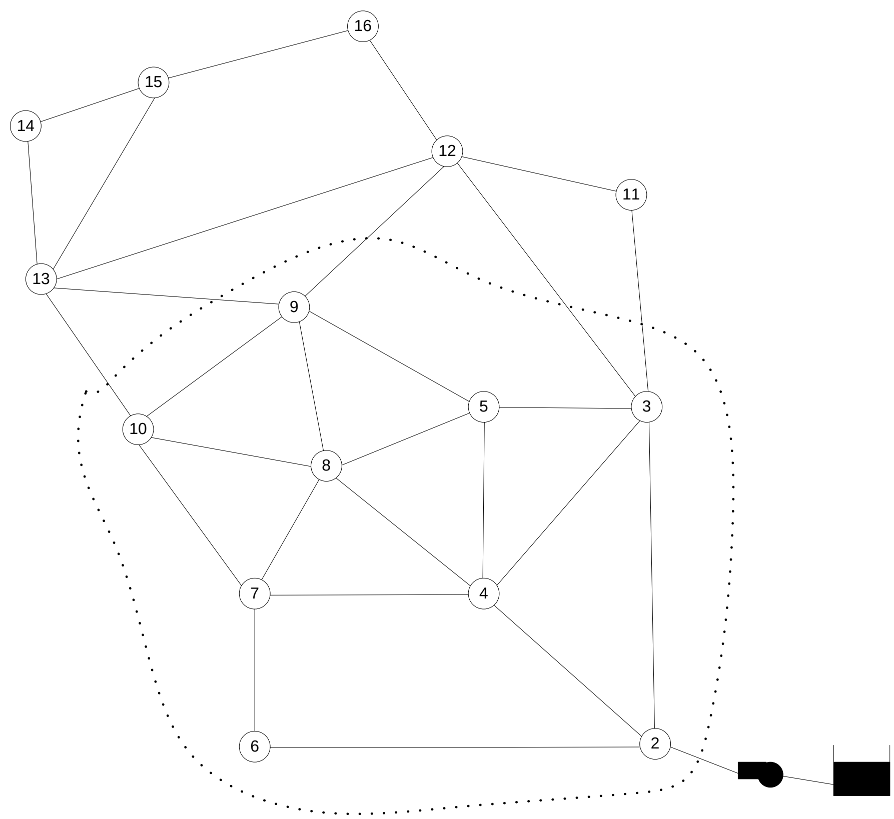

Figure 6-2 Network layout of "inflexible design"

6.2.2.2 Model formulation

The general mathematical formulation of the optimal design for a water distribution system was originally presented for one period (Shamir and Howard 1968; Quindry et al. 1981; Savic and Walters 1997), but here, is extended into multi-period. The objective of this inflexible design is to minimise the present value of total capital cost for laying pipes when satisfying minimum pressure on node under the expected condition. Hence, the objective function for the problem is defined as a function of pipe diameters and lengths:

Minimise $$f(D)=\sum_{i=1}^{PN_0}U(D_i^0)L_i^0+\sum_{i=1}^{PN_t}R_i^1\frac{U(D_i^1)L_i^1}{(1+r)^{20}} \quad (6.2)$$

where D_i^t = pipe diameter for pipe *i* in stage *t*; $U(D_i^t)$ = unit cost for the pipe *i* with the diameter D_i^t; R_i^t = replacement status for pipe *i* in stage *t*; L_i^t is the length of the pipe *i*; PN_t = number of pipes in stage *t*; *r* = discount rate, taking 15% in this case.

This least cost problem is also subject to the following constraints:

Mass and energy balance constraints:

For each junction node: $\sum Q_{in}-\sum Q_{out}=\overline{Q}$ (6.3)

For each of the basic loop: $\sum h_f-\sum E_p=0$ (6.4)

where Q_{in} = flow into the junction; Q_{out} = flow out of the junction; and $\overline{Q}$ = external inflow or demand at the junction node, taking expected values. E_p = energy input for each loop. The Hazen-Williams factor is used to express the head-loss term h_f.

This optimisation uses EPANET (Rossman 2000) to simulate the network hydraulic, where mass and energy balance constraints are met automatically.

The minimum head constraint for each node:

$$H_j \geq H_j^{\min};\ j=1,\ \dots,\ N \quad (6.5)$$

where H_j = head at node j; $H_j^{\min}$ = minimum required head at the node j; and N = total number of demand nodes in the system.

Available pipe diameters:

$$D_i^t \in \{D_{\min}, \cdots, D_{\max}\} \tag{6.6}$$

Replacement status for each pipe:

$$R_i^1 \in [0, 1] \tag{6.7}$$

6.2.2.3 Model solution

The optimisation model is solved by using Genetic Algorithms and run for several times with different initial seed. The least-cost option is chosen as the solution. Its total capital cost is $ 4.68 million, which includes the initial investment on the first stage, and additional investment in the second stage. The nodal pressure on two stages for the least cost solution is presented in Table 6-6, and the result of the system configuration on the two stages are shown in Table 6-7.

Table 6-6 Nodal pressure of "inflexible design"

Node	Pressure (psi)	
	2030	2050
1	-	-
2	71.2	71.0
3	32.7	58.2
4	51.5	51.5
5	32.0	37.5
6	32.9	27.0
7	33.2	27.8
8	48.8	48.4
9	35.0	44.3
10	27.3	26.5
11	-	42.9
12	-	50.5
13	-	29.6
14	-	26.4
15	-	29.8
16	-	34.4
Note: H_{min} = 26.3 m		

Table 6-7 System configuration of "inflexible design"

Pipe		System configuration on 2030		System configuration on 2050	
Start Node	End Node	Pipe Diameter (mm)	C-factor	Pipe Diameter (mm)	C-factor
1	2	762	112.6	762	102.1
2	3	152.4	86.6	762	112.6
2	4	609.6	109.0	609.6	98.5
2	6	254	94.9	254	84.4
3	4	152.4	86.6	152.4	76.1
3	5	152.4	86.6	152.4	76.1
3	11	-	-	152.4	86.6
3	12	-	-	609.6	109.0
4	5	203.2	91.3	203.2	80.7
4	7	152.4	86.6	152.4	76.1
4	8	609.6	109.0	609.6	98.5
5	8	152.4	86.6	152.4	76.1
5	9	152.4	86.6	152.4	76.1
6	7	152.4	86.6	152.4	76.1
7	8	203.2	91.3	203.2	80.7
7	10	152.4	86.6	152.4	76.1
8	9	152.4	86.6	152.4	76.1
8	10	457.2	104.4	457.2	93.8
9	10	254	94.9	254	84.4
9	12	-	-	406.4	102.5
9	13	-	-	355.6	100.3
10	13	-	-	152.4	86.6
11	12	-	-	152.4	86.6
12	13	-	-	152.4	86.6
12	16	-	-	406.4	102.5
13	14	-	-	355.6	100.3
13	15	-	-	152.4	86.6
14	15	-	-	152.4	86.6
15	16	-	-	355.6	100.3

6.2.2.4 Performance of "inflexible design" under uncertainties

Inflexible design was generated by finding the least cost solution under expected condition, which treated uncertain nodal demands as deterministic, by applying their expected values and did not consider pipe failures. However, this expected condition is almost always wrong in reality. Nodal pressures for inflexible design under uncertain nodal demands and pipe failures are simulated. It is assumed that the range of nodal demand is between 0.8—1.2. The nodal pressures under two extreme demand scenarios are displayed in Table 6-8. These two extreme demand scenarios apply multiplier of 0.8 and 1.2 on expected nodal demand for each node, respectively.

Table 6-8 Nodal pressures of inflexible design under two extreme demand scenarios

Node	Pressure (m)			
	2030		2050	
	-20%	+20%	-20%	+20%
1	-	-	-	
2	71.2	71.1	71.1	71.0
3	42.8	**20.7**	59.7	56.5
4	55.3	47.0	55.3	47.0
5	42.4	**19.6**	46.0	27.3
6	43.0	**21.0**	39.1	**12.7**
7	43.1	**21.3**	39.6	**13.9**
8	53.5	43.2	53.2	42.7
9	44.4	**24.0**	50.5	36.9
10	32.5	**21.0**	32.0	**20.0**
11	-	-	49.6	34.9
12	-	-	54.6	45.7
13	-	-	37.9	**19.7**
14	-	-	35.8	**15.2**
15	-	-	38.0	**20.0**
16	-	-	41.1	26.5
Note: H_{min} = 26.3 m				

Under low demand scenario, nodal pressure on each node is above the required minimum pressure and is higher than that under expected demand scenario. Under high demand scenario, nodal pressures on some nodes did not change very much or at least did not fall below the required minimum pressure (e.g. node 2 and node 4) while some others dropped significantly and could not satisfy the required minimum pressure (e.g. node 10 and node 14). Therefore, it is concluded that pressure on some nodes are very sensitive to the change on the nodal demand, which has been discussed by Babayan et al. (2003). Based on the result in Table 6-8, the advantages and disadvantages of inflexible design are discussed. The advantages of inflexible design are: 1) meet the required minimum pressure on each node under low and expected demand scenario; 2) have surplus head on each node under low demand scenario which may enable the required supply capacity even when some pipes are out of service; and 3) may save some investment if the high demand scenario does not happen. The disadvantages of inflexible design include: 1) cause low pressure on some nodes under high demand scenario; and 2) may need large additional investment if the high demand scenario occurs. In general, water engineers are more concerned about the possible risks of being system deficiency when high demand scenario happens. As a result, to improve its performance under different demand scenarios, the system has to be designed to meet the required minimum pressure within a reasonable demand range.

The second considered uncertain source is pipe failure. Pipes in the system have two modes: operational and non-operational. Operational pipe means that its designed function can be achieved while non-operational pipe means that it is taken out of service for some reasons (e.g. accident or maintenance). A system failure may be caused by one component out of service, or several components together out of service, which result in the system capacity falling during a period of time, and consumers on some nodes may not get sufficient water. When the pipe is in non-operational mode, the status of pipe in the EPANET (Rossman 2000) is set as closed. Thus, it does not allow any flow through the pipe. Table 6-9 and Table 6-10 show nodal pressure of inflexible design on year 2030 and 2050 respectively, under the scenarios of maximum demand and one pipe out of the service.

Table 6-9 Nodal pressure of inflexible design under one pipe failure on year 2030

Node	Pressure (m)															
	2030															
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 4-5	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9	Pipe 6-7	Pipe 7-8	Pipe 7-10	Pipe 8-9	Pipe 8-10	Pipe 9-10
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2
3	**21.1**	**-3047.0**	29.6	**22.3**	36.9	**13.0**	32.8	**-61.8**	27.4	30.4	32.8	33.3	33.0	31.2	20.9	**20.3**
4	50.8	**-3442.1**	48.3	51.7	51.5	51.8	51.8	55.5	51.6	51.6	51.6	52.2	51.8	51.5	52.2	51.7
5	**26.1**	**-3441.4**	28.5	27.0	30.6	**-0.4**	32.1	**-168.9**	**24.4**	28.8	32.0	32.7	32.3	30.0	**13.6**	**12.7**
6	32.5	**-533.8**	**-230.7**	32.9	32.9	32.8	27.7	**-60.5**	33.0	33.0	31.6	**19.5**	28.4	32.9	**21.4**	33.3
7	32.6	**-3331.0**	**-9.2**	33.2	33.1	33.0	26.3	**-328.7**	33.3	33.2	33.9	**8.9**	27.4	33.1	**13.4**	33.7
8	48.0	**-3442.8**	44.7	48.8	48.7	48.5	48.9	**-378.7**	49.0	48.9	48.9	49.8	49.1	48.9	50.2	49.3
9	33.0	**-3450.0**	30.9	33.9	34.6	29.0	35.1	**-378.7**	33.5	37.3	35.1	35.8	35.7	30.4	**-28.9**	**-30.9**
10	26.4	**-3462.5**	**22.7**	27.2	27.2	26.6	27.2	**-399.0**	27.4	27.5	27.4	28.0	28.0	27.0	**-49.3**	29.1
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Note: H_{min} = 26.3 m																

Table 6-10 Nodal pressure of inflexible design under one pipe failure on year 2050

Node	Pressure (m)													
	2050													
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 3-11	Pipe 3-12	Pipe 4-5	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9	Pipe 6-7	Pipe 7-8
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3	**-231.4**	50.7	58.0	58.3	58.4	58.3	62.1	58.0	58.2	54.5	58.2	58.3	58.3	58.3
4	**15.7**	**-101.2**	48.9	51.2	50.9	51.4	28.5	52.1	51.8	60.2	51.6	50.0	51.6	52.1
5	**-121.6**	**-98.6**	35.3	37.3	29.3	37.3	**-22.4**	**13.1**	37.6	**8.6**	31.9	32.9	37.6	38.0
6	**4.9**	**-21.0**	**-304.4**	26.9	26.7	26.9	**9.8**	27.2	**20.3**	**-2.6**	27.1	27.0	**23.9**	**9.4**
7	**-15.1**	**-105.2**	**-23.7**	27.7	27.4	27.8	**-2.0**	28.1	**19.2**	**-39.4**	28.0	27.8	29.6	**-3.3**
8	**2.9**	**-101.2**	45.1	48.1	47.8	48.3	**16.7**	48.7	48.5	**-38.8**	48.7	48.3	48.5	49.5
9	**-223.5**	**-7.9**	42.6	44.2	43.9	43.9	**-196.6**	43.5	44.3	**13.0**	44.1	44.8	44.3	44.6
10	**-36.8**	**-117.7**	**23.1**	26.3	**26.0**	26.4	**-22.4**	26.7	26.5	**-57.9**	26.8	26.5	26.7	27.1
11	**-243.2**	27.1	42.3	42.9	42.9	**9.5**	**-134.8**	42.5	42.9	34.0	42.8	43.0	42.9	43.0
12	**-232.1**	30.3	49.8	50.6	50.5	50.1	**-205.1**	50.2	50.6	38.6	50.5	50.8	50.6	50.7
13	**-237.3**	**-23.0**	28.0	29.5	29.3	29.2	**-210.4**	29.0	29.6	**-2.6**	29.5	30.0	29.6	29.8
14	**-241.9**	**-25.0**	**24.8**	26.3	**26.1**	**26.0**	**-215.0**	**25.7**	26.4	**-4.6**	26.3	26.8	26.4	26.6
15	**-247.8**	**2.6**	28.7	29.8	29.6	29.4	**-220.9**	29.3	29.8	**13.0**	29.7	30.1	29.8	30.0
16	**-245.9**	**11.0**	33.5	34.4	34.3	34.0	**-218.9**	34.0	34.4	**20.3**	34.3	34.7	34.4	34.6

Note: H_{min} = 26.3 m

Conti.

Node	Pressure (m)													
	2050													
	Pipe 7-10	Pipe 8-9	Pipe 8-10	Pipe 9-10	Pipe 9-12	Pipe 9-13	Pipe 10-13	Pipe 11-12	Pipe 12-13	Pipe 12-16	Pipe 13-14	Pipe 13-15	Pipe 14-15	Pipe 15-16
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3	58.3	58.2	57.1	58.0	59.7	58.1	58.2	58.2	58.3	58.9	58.1	58.2	58.3	58.6
4	51.6	51.6	54.8	52.2	46.2	51.9	51.7	51.5	51.4	49.4	52.0	51.5	51.4	50.4
5	37.6	37.5	35.5	37.4	**21.5**	38.6	37.5	37.6	37.3	33.3	38.3	37.4	37.4	35.6
6	**21.0**	27.1	**24.1**	27.5	**22.7**	27.3	27.2	27.0	26.9	**25.4**	27.4	27.0	27.0	**26.2**
7	**20.3**	28.0	**24.1**	28.6	**22.5**	28.3	28.1	27.9	27.8	**25.7**	28.4	27.8	27.8	26.7
8	48.7	48.6	53.1	49.4	41.3	49.0	48.8	48.5	48.3	45.5	49.2	48.4	48.3	47.0
9	44.6	43.9	35.5	42.5	**9.0**	47.9	43.8	44.5	44.0	34.8	46.3	44.2	44.1	39.9
10	27.2	26.7	**4.9**	28.1	**16.3**	27.2	27.1	26.6	26.3	**22.3**	27.6	26.5	26.4	**24.4**
11	42.9	42.7	40.2	42.3	46.1	42.5	42.7	**17.7**	42.9	44.3	42.4	42.9	42.9	43.6
12	50.7	50.4	46.9	49.8	48.6	50.1	50.3	50.9	50.6	52.6	50.0	50.6	50.6	51.6
13	29.8	29.2	**20.0**	28.2	**-0.7**	**-43.4**	28.2	29.8	28.5	**-3.9**	35.7	29.4	29.0	**14.3**
14	26.6	**26.0**	**17.1**	**25.0**	**-2.6**	**-45.4**	25.0	26.6	25.3	**-17.7**	**-292.5**	**26.2**	**25.2**	**6.4**
15	30.0	29.5	**24.3**	28.8	27.1	**16.7**	29.1	30.1	29.4	**-321.5**	**17.6**	30.0	30.6	**-75.6**
16	34.6	34.2	29.9	33.5	35.7	28.4	33.9	34.7	34.3	**-324.8**	28.7	34.5	34.8	41.1
Note: H_{min} = 26.3 m														

From the results in the tables, it is obvious that the effect of pipe failure on nodal pressure differs from one pipe to the other. Some pipe failures are critical to nodal pressure decreasing while others have minor effects on nodal pressure, for example, failure of pipe 2-4 or pipe 4-8 in Table 6-9 results in unsatisfactory supply on most demand nodes. On the contrary, the implication of failure of pipe 3-5 or pipe 4-7 in Table 6-9 on the system pressure changing is very small. It is also found that different nodes would be differently affected. Some nodal pressures are very sensitive to pipe failure. For example, node 14 in Table 6-10 is the most sensitive to pipe failure. However, it can not be concluded which pipes or nodes are always important or critical, because they are highly associated with the specific system configuration. That is the reason why it is not useful to fix some flexible components, before the optimal system configuration is identified by GA. During GA process, the collection of solutions (population) is always changing from one generation to the other. Accordingly, important components and critical nodes are also changing from one generation to the other. Therefore, the flexible component in a water distribution system will only become clear after the system configuration has been derived.

The third uncertain source is future expansion. The expected expansion is to the north of the existing system. As a result, there are some pipe routes to the north, which will be designed with large capacity to allow for this expansion. However, in reality there is a high possibility that the system will not follow the original plan and expand differently. If this happens, some modifications on the existing system have to be made, to achieve the required minimum pressure on each node. Otherwise, the required minimum pressures on some nodes become difficult to meet, because the capacity embedded in the system is designed for an expected expansion and not for others. The modification on initial design will be very expensive, since the cost of replacing a pipe is much higher than the cost of installing a pipe of similar size. In some cases, this modification should be avoided, due to high social and environmental cost. Therefore, the system should be well planned and designed for different possible future expansions, so that the capacities of its components are sufficiently sized.

6.2.3 Flexible design 1

6.2.3.1 Model preparation

Flexible design 1 is developed by applying the proposed flexibility-based optimisation method, where uncertain water demand and pipe failure are considered. Flexible design 1 is a system designed without tank, and thus network capacity should be sized to respond to maximum hourly demands. Capital costs for installing pumps and tanks and energy costs for operating pumps are not formulated into the objective function. Three system layouts are considered in the case. These are WDD_1, WDD_2, and WDD_3. WDD_1 is built out in the first stage, while WDD_2 and WDD_3 are the two possible expansions at the second stage. WDD_2 is the system after its development to the north, while WDD_3 is the system after its development to the west. Then, a scenario tree is built up to present this system development, which is given in Figure 6-3. WDD_i represents system state i and $Tree_j$ presents s-t spanning tree j. The probability for each future expansion is set as 50%.

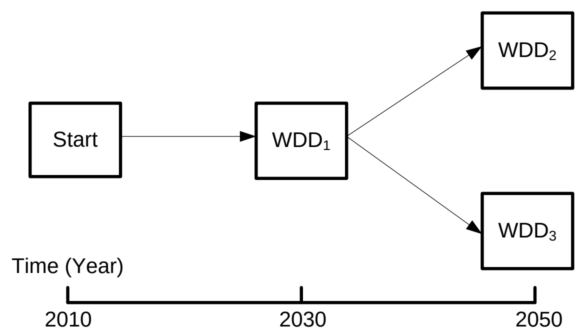

Figure 6-3 Scenario tree for "flexible design 1"

According to the uncertainties modelling in Chapter 3, three simulations are required to approximate system performance under uncertain nodal demands and pipe failures for each state. One is under the system configuration with no pipe failure, and the demand scenario of nodal demand is set as the expected value multiplied by a safety margin coefficient. The other two are under the system configuration of two s-t spanning trees, and the demand scenario of nodal demand is set as the expected value multiplied by a safety margin coefficient. These are illustrated in Figure 6-4.

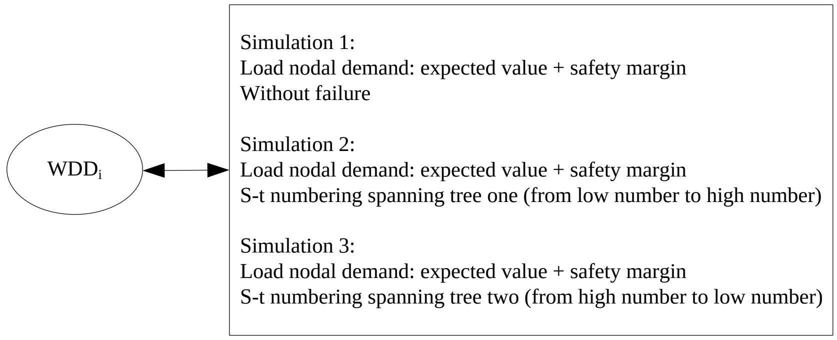

Figure 6-4 Three simulations for each WDD$_i$

For generating two independent spanning trees, an s-t numbering is applied on the WDD$_2$ and WDD$_3$. According to s-t numbering algorithm in Chapter 3, the s-t numbering is generated for WDD$_2$ and WDD$_3$, which are given in Figure 6-5 and Figure 6-6, respectively. The network in the dashed line was developed in the first stage. There are two possible system extensions in the second stage, and for WDD$_2$, the system was extended into the north, while for WDD$_3$, the system was extended into west.

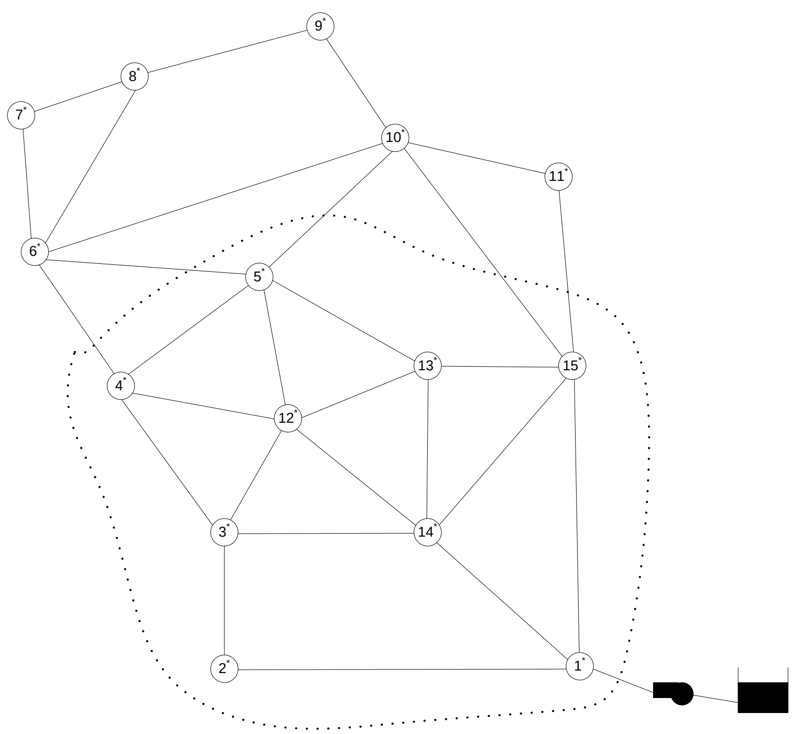

Figure 6-5 S-t numbering for WDD$_2$ in "flexible design 1"

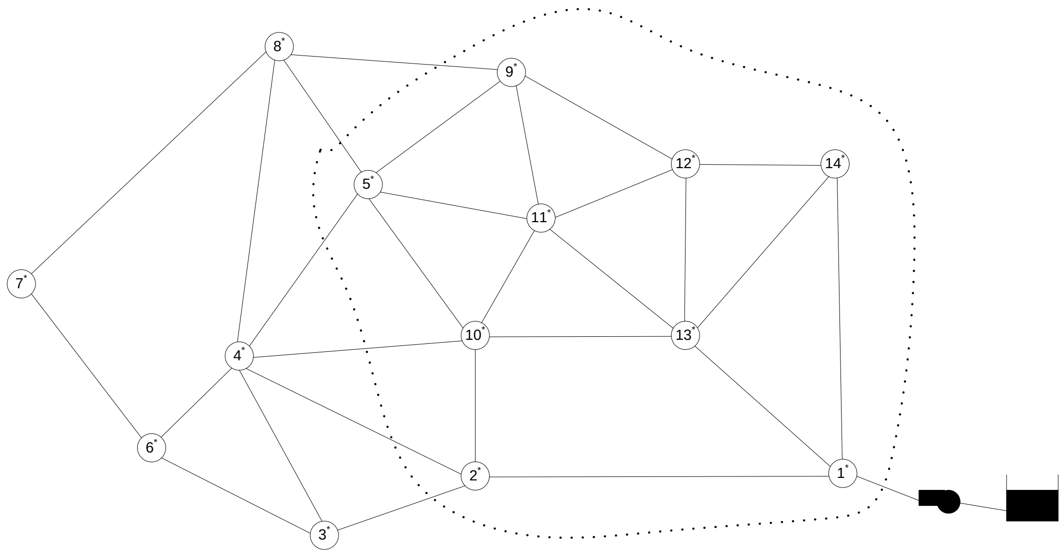

Figure 6-6 S-t numbering for WDD_3 in "flexible design 1"

When we have the s-t numbering for the two system configurations, two overlapping spanning trees for each system can be generated. Two trees for WDD_1 choose the sub-part of the trees in WDD_2 and WDD_3 as the components. Two trees for WDD_1 are presented in Figure 6-7 and Figure 6-8 respectively.

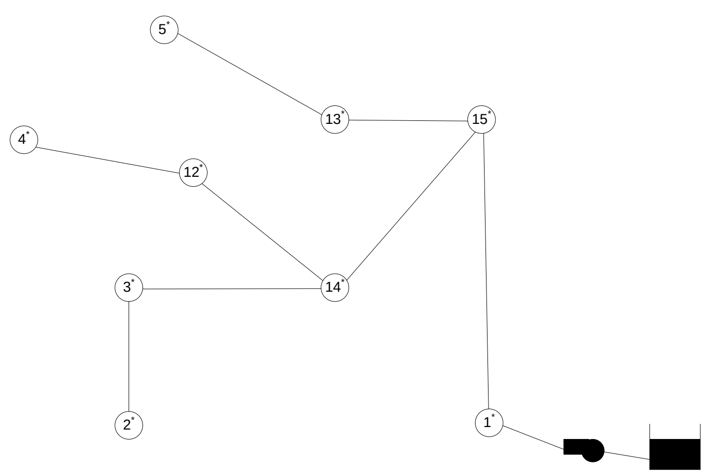

Figure 6-7 Spanning tree 1 for WDD_1 in "flexible design 1"

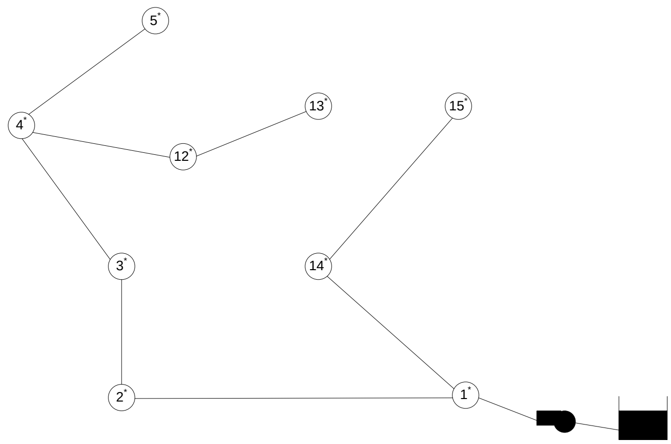

Figure 6-8 Spanning tree 2 for WDD_1 in "flexible design 1"

Two trees for WDD_2 are presented in Figure 6-9 and Figure 6-10, respectively.

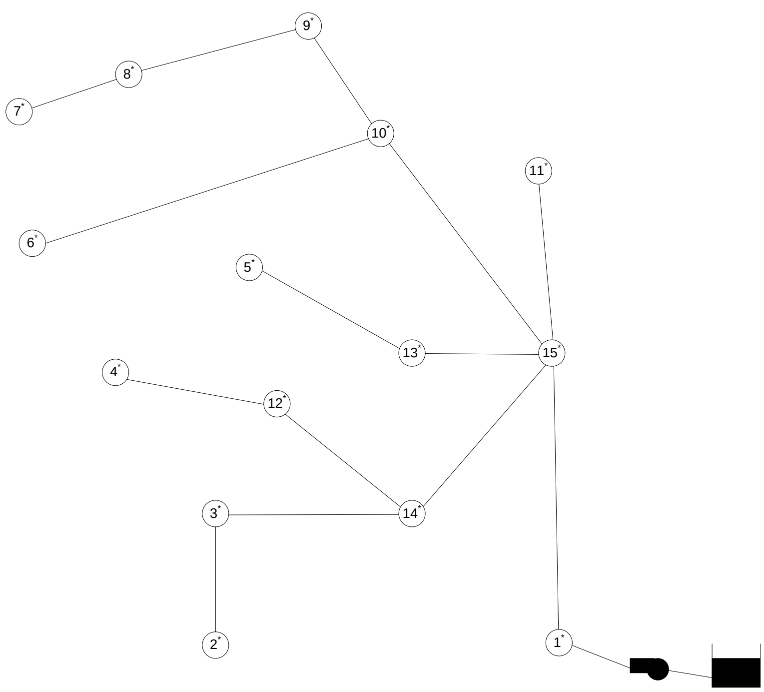

Figure 6-9 Spanning tree 1 for WDD_2 in "flexible design 1"

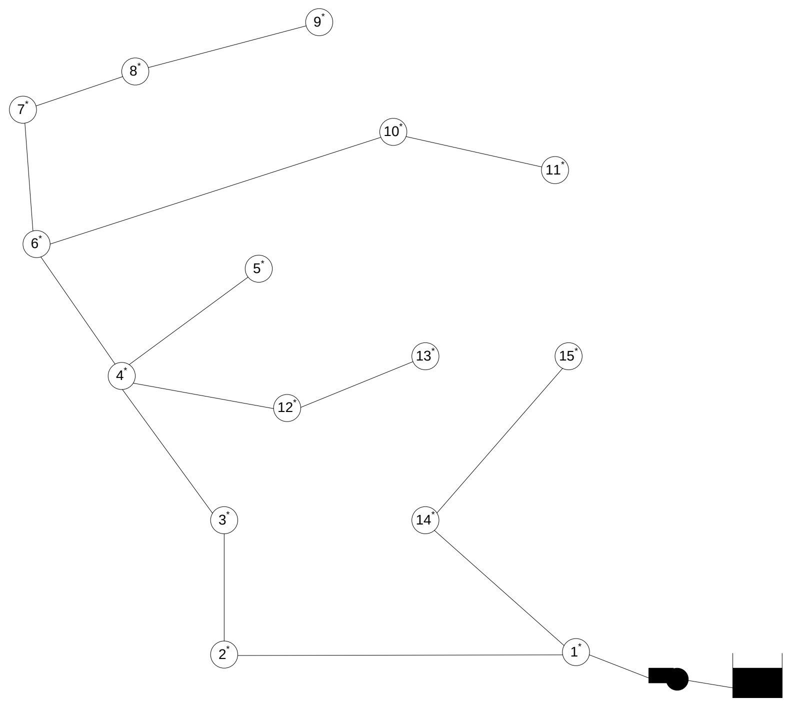

Figure 6-10 Spanning tree 2 for WDD_2 in "flexible design 1"

Two trees for WDD_3 are presented in Figure 6-11 and Figure 6-12, respectively.

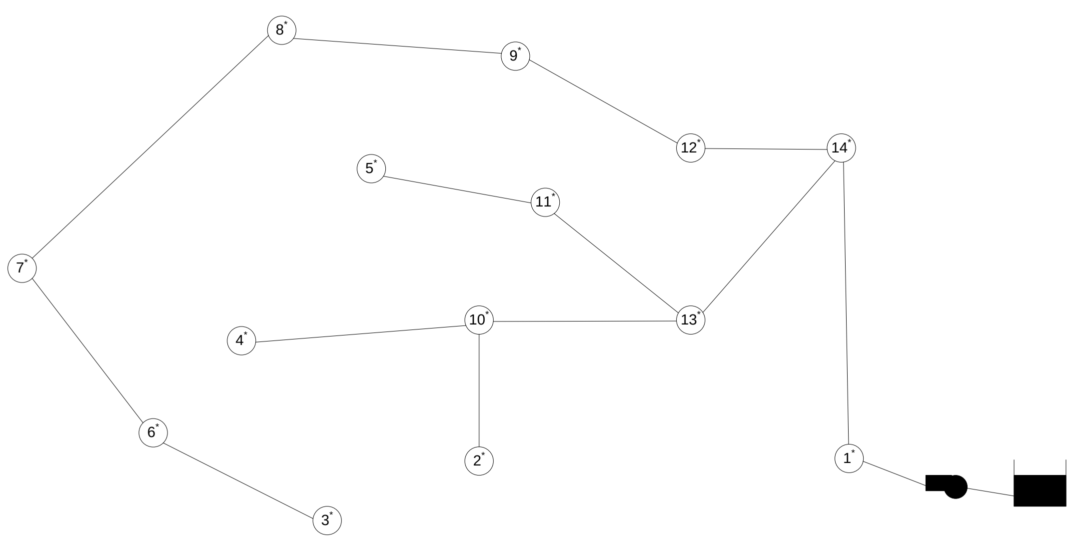

Figure 6-11 Spanning tree 1 for WDD_3 in "flexible design 1"

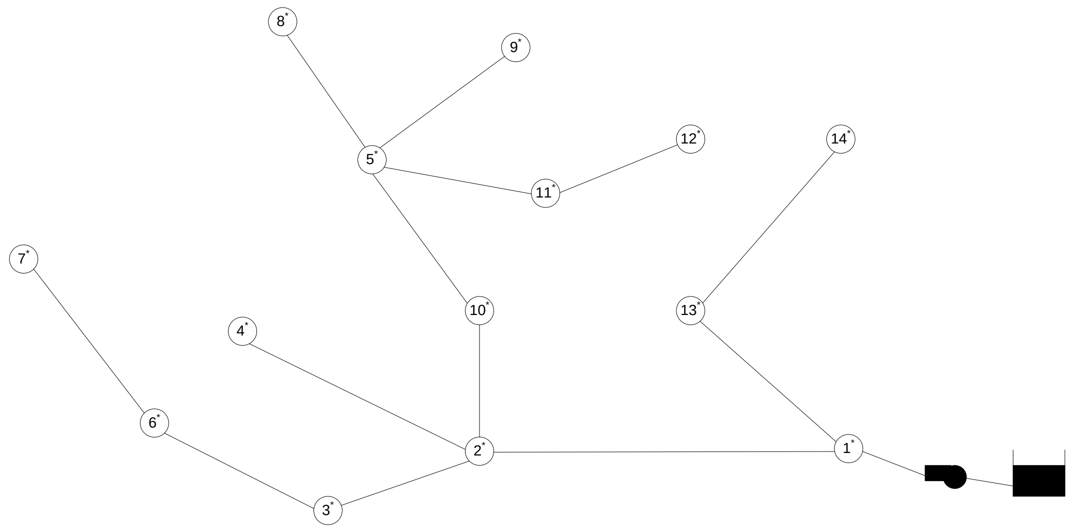

Figure 6-12 Spanning tree 2 for WDD_3 in "flexible design 1"

Designing a water distribution system under uncertainty requires trade-off among different objectives, for example cost and risk. The model control parameters discussed here illustrate the trade-off between economics and risk. The first control parameter is the minimum pressure at all demand nodes during peak flow, when all system components are functional. This pressure shows the available energy to supply the sub-system. High available energy has more capacity to respond to the variation in water demand, and component failure in the sub-system. Also, it can make system solutions less sensitive to the errors from the simplification of the network model. The minimum pressure for "flexible design 1" is set as 40 psi (257.8 kPa).

The second control parameter is the safety margin coefficient for each node, which shows the additional capacity available to enable the system with the ability to deliver required water with sufficient pressure despite some excess on the designed demand. It is a complex task to set this coefficient properly. Babayan et al. (2007) developed an iteration method to determine the values of the safety margins to respond to the required range of uncertainties. However, they also showed some concerns about the method. For example, before network configuration becomes known, it is difficult if not impossible to find more "influential" nodes, i.e., where demand fluctuation affects network robustness the most. Research in this direction should be inspired, but this is not within the scope of this thesis. Here, we simply assign a similar safety margin coefficient to all demand nodes, which is 1.2.

The third control parameter is the multiplier coefficient for the spanning tree, which shows the capacity from each independent route. This value shows capacity contribution from each route to supply consumers, and also the ability to respond to the component failure directly, and the variation in the water demand indirectly. High values mean high delivery capacity for each spanning tree, and has more capacity to respond to uncertainties. For "flexible design 1", the value is chosen as 1.0 for each tree. All these three control parameters are summarised in Table 6-11.

Table 6-11 Control parameters in "flexible design 1"

Model Component	Control Parameter	Chosen value
Spanning Tree (1)	Multiplier Coefficient	1.0
Spanning Tree (2)		1.0
Spanning Tree (3)		1.0
Spanning Tree (4)		1.0
Spanning Tree (5)		1.0
Spanning Tree (6)		1.0
Demand Node	Safety Margin Coefficient	1.2
	Minimum pressure	26.3m

6.2.3.2 Model formulation

The objective of "flexible design 1" is to minimise the expected system life cycle cost on different designs under uncertain water demand and pipe failure, while at the same time meet the specifications for providing enough water with sufficient pressure under the pre-defined uncertain level. The life cycle refers to planning period in the thesis. The mathematical formulation for "flexible design 1" is shown as:

$$\text{Minimise} \quad f(D) = \sum_{i=1}^{PN_1} U(D_i^1)L_i^1 + 0.5\sum_{i=1}^{PN_2} R_i^2 \frac{U(D_i^2)L_i^2}{(1+r)^{20}} + 0.5\sum_{i=1}^{PN_3} R_i^3 \frac{U(D_i^3)L_i^3}{(1+r)^{20}} \tag{6.8}$$

where D_i^j = pipe diameter of pipe *i* for WDD_j; $U(D_i^j)$ = unit cost for the pipe *i* with the diameter D_i^j; R_i^j = replacement status of pipe *i* for WDD_j; L_i^j is the length for the pipe *i*; PN_j = number of pipes for WDD_j; *r* = discount rate, taking 15% in this case.

This least cost problem also subjects to the following constraints:

Mass and energy balance constraints:

For each network *j* and $j \in \{1,2,3\}$

$$\sum Q_{in} - \sum Q_{out} = Q_{WDD_j} \tag{6.9}$$

$$\sum h_f - \sum E_p = 0 \tag{6.10}$$

For each tree *j* and $j \in \{1,2,3,4,5,6\}$

$$\sum Q_{in} - \sum Q_{out} = Q_{TREE_j} \tag{6.11}$$

$$\sum h_f - \sum E_p = 0 \tag{6.12}$$

where Q_{in} = flow into the junction; Q_{out} = flow out of the junction; and Q_{WDD_j} and Q_{TREE_j} = external inflow or demand at the junction node, taking expected values + safety margin. E_p = energy input for each loop. The Hazen-Williams factor is used to express the head-loss term h_f.

This optimisation uses EPANET (Rossman 2000) to simulate the network hydraulic, where mass and energy balance constraints are met automatically.

The minimum head constraint for each node:

$$H_i \geq H_i^{\min};\ i = 1, \ldots, N_j \tag{6.13}$$

where H_i = head at node i; $H_i^{\min}$ = minimum required head at the node i; and N_j = number of demand nodes in WDD_j.

Available pipe diameters:

$$D_i^j \in \{D_{\min}, \cdots, D_{\max}\} \tag{6.14}$$

Replacement status for each pipe:

$$R_i^j \in [0, 1] \tag{6.15}$$

6.2.3.3 Model solution

The optimisation model is solved by using Genetic Algorithms and run for several times with different initial seed. The least-cost option is chosen as the solution. Its total capital cost is $ 10.07 million. The result of the system configuration on the two stages is shown in Table 6-12.

Table 6-12 System configuration of "flexible design 1"

Pipe		Pipe Diameter at year 2030 (mm)	Pipe Diameter at year 2050 (mm)	
Start Node	End Node		North	West
1	2	304.8	1016	863.6
2	3	1016	1016	1016
2	4	355.6	355.6	355.6
2	6	863.6	863.6	863.6
3	4	762	762	762
3	5	355.6	355.6	762
3	11	-	203.2	-
3	12	-	609.6	-
4	5	-	-	-
4	7	355.6	355.6	609.6
4	8	609.6	609.6	609.6
5	8	304.8	304.8	304.8
5	9	304.8	304.8	609.6
6	7	609.6	1016	762
6	17	-	-	457.2
6	18	-	-	406.4
7	8	-	-	-
7	10	863.6	863.6	863.6
7	18	-	-	508
8	9	-	-	-
8	10	508	508	508
9	10	304.8	304.8	304.8
9	12	-	-	-
9	13	-	-	609.6
10	13	-	609.6	254
10	18	-	-	-
11	12	-	254	-
12	13	-	406.4	-
12	16	-	508	-
13	14	-	609.6	-
13	15	-	-	-
13	18	-	-	-
13	20	-	-	762
14	15	-	609.6	-
15	16	-	508	-
17	18	-	-	-
17	19	-	-	609.6
18	19	-	-	-
19	20	-	-	457.2

The cost is much higher (about one time more) than that of the inflexible design under the expected scenario. The difference between these two costs is the cost of providing flexibility, to reduce the risk of being in supply deficiency, when the real water demand exceeds the designed delivery capacity and one pipe is taken out of the service. Comparing the system configuration in the first 20 years between the inflexible design and flexible design 1, it can be seen that the average capacity of each component is much larger in "flexible design 1" than in "inflexible design". As a result, this enables the system to respond to uncertainties from water demand and pipe failure. The embedded additional capacity in pipes for flexible design creates value for the system, which is illustrated as nodal pressure improvement when the system operates in an uncertain environment.

6.2.3.4 Performance of "flexible design 1" under uncertainties

Flexible design 1 was generated by finding the least cost solution, considering uncertain nodal demands and pipe failures. Nodal pressures for flexible design 1 under uncertain nodal demands and pipe failures were simulated, and it was assumed that the range of nodal demand is between 0.8—1.2. The nodal pressures under three demand scenarios where no pipe failure happens are given in Table 6-13. One is expected demand scenario, and the other two apply multipliers of 0.8 and 1.2 on expected nodal demand for each node respectively.

Under each demand scenario, nodal pressure on each node is above the required minimum pressure, and is much higher than the required minimum pressure. Based on the results in Table 6-13, the advantages and disadvantages of flexible design 1 are discussed. The advantages of flexible design 1 are: 1) meet the required minimum pressure on each node under each demand scenario; 2) have surplus head on each node under each demand scenario, which enables the required supply capacity even when some pipes are out of service. Flexible design 1 might cause some investment waste, but this is paid to avoid the risk of supply deficiency if the required capacity becomes larger than the designed capacity. In general, water engineers are more concerned about the possible risks of system deficiency, when high demand scenario happens. Therefore, it is worth the additional investment to reduce the risk.

Table 6-13 Nodal pressure under three water demand scenarios of "flexible design 1"

Node	Pressure (m)								
	2030			2050 (North)			2050 (West)		
	-20%	0	+20%	-20%	0	+20%	-20%	0	+20%
1	-	-	-	-	-	-	-	-	-
2	67.5	65.6	63.3	71.2	71.2	71.2	71.2	71.1	71.1
3	58.7	56.7	54.3	61.8	61.4	60.9	61.9	61.5	61.0
4	58.3	56.1	53.5	61.4	60.7	59.9	61.4	60.7	60.0
5	57.1	54.2	50.9	59.8	58.3	56.6	61.5	60.9	60.2
6	58.6	56.5	54.1	61.4	60.7	59.9	61.5	60.9	60.1
7	58.1	55.8	53.0	61.2	60.5	59.6	61.3	60.5	59.7
8	58.0	55.6	52.7	60.8	59.9	58.8	61.2	60.4	59.4
9	56.4	53.2	49.4	58.9	57.0	54.7	60.9	60.0	59.0
10	38.1	35.8	33.0	40.9	40.0	38.9	41.3	40.5	39.6
11	-	-	-	59.9	58.5	56.9	-	-	-
12	-	-	-	60.4	59.2	57.8	-	-	-
13	-	-	-	51.7	50.4	49.0	52.1	51.1	49.9
14	-	-	-	51.3	49.8	48.0	-	-	-
15	-	-	-	51.2	49.7	47.9	-	-	-
16	-	-	-	51.2	49.7	48.0	-	-	-
17	-	-	-	-	-	-	40.6	39.6	38.3
18	-	-	-	-	-	-	40.9	40.0	38.9
19	-	-	-	-	-	-	40.6	39.5	38.2
20	-	-	-	-	-	-	40.6	39.6	38.3
Note: H_{min} = 26.3 m									

Performance of flexible design 1 was also checked under different pipe failure scenarios when one pipe is out of service. Table 6-14 to Table 6-16 present the nodal pressure in the system when there is one pipe failure under high water demand scenario. It is found that almost all the nodes can meet the minimum pressure requirement.

Table 6-14 Nodal pressure of flexible design 1 under one pipe failure on year 2030

Node	Pressure (m)												
	2030												
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9	Pipe 6-7	Pipe 7-10	Pipe 8-10	Pipe 9-10
1	-	-	-	-	-	-	-	-	-	-	-	-	-
2	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3
3	43.0	54.2	53.5	54.7	54.3	54.3	54.4	54.2	54.3	53.7	54.1	54.2	54.2
4	43.1	53.3	50.9	48.3	53.3	53.6	54.2	53.6	53.5	51.8	53.0	53.3	53.5
5	40.9	50.7	47.2	48.1	43.8	50.8	48.6	48.6	52.0	48.6	49.6	50.7	48.2
6	52.2	54.0	45.8	53.1	53.9	54.0	53.6	54.1	54.0	54.7	54.3	54.1	54.1
7	46.5	52.9	46.2	49.8	52.5	52.8	51.4	53.1	52.9	48.9	53.9	53.3	53.3
8	43.1	52.6	47.9	48.2	52.1	52.7	48.7	52.9	52.7	49.6	50.8	52.1	52.7
9	40.5	49.3	44.3	46.5	43.8	49.4	47.3	48.0	44.3	46.4	47.6	49.5	39.7
10	26.2	32.8	26.3	29.6	32.4	32.8	31.1	33.1	32.8	29.0	30.4	33.3	33.3
Note: H_{min} = 26.3 m													

Table 6-15 Nodal pressure of flexible design 1 under one pipe failure on year 2050 (North)

Node	Pressure (m)										
	2050										
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 3-11	Pipe 3-12	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9
1	-	-	-	-	-	-	-	-	-	-	-
2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2
3	41.4	60.7	57.7	61.6	61.0	60.9	61.5	60.9	61.2	60.8	60.9
4	42.1	59.6	54.0	55.4	59.8	59.9	59.6	53.5	61.0	60.0	59.9
5	39.5	56.4	48.7	54.8	47.9	56.5	55.8	56.6	54.3	53.7	58.0
6	52.2	59.8	45.6	58.5	59.7	59.9	58.6	59.9	59.1	60.0	59.9
7	50.6	59.4	45.6	57.9	59.3	59.6	58.1	59.5	58.6	59.7	59.5
8	42.2	58.5	49.2	55.3	58.2	58.8	57.2	58.8	54.5	59.0	58.8
9	39.3	54.5	44.1	52.9	47.9	54.7	53.3	54.7	52.8	52.9	48.3
10	27.7	38.8	25.7	37.0	38.5	38.9	36.8	38.9	37.5	39.1	38.8
11	39.3	56.7	50.1	56.7	56.8	53.6	46.4	56.9	56.6	56.9	56.9
12	40.9	57.7	50.4	57.5	57.7	57.6	46.3	55.9	57.4	57.9	57.8
13	35.0	48.8	37.0	47.6	48.6	48.8	42.5	48.9	47.9	49.0	48.9
14	33.2	47.9	36.8	46.9	47.8	47.9	39.9	48.0	47.1	48.1	48.0
15	32.5	47.7	36.8	46.8	47.6	47.8	38.7	47.8	47.0	47.9	47.8
16	32.2	47.8	38.1	47.1	47.7	47.8	37.8	47.9	47.2	48.0	47.9
Note: H_{min} = 26.3 m											

Cont.

Node	Pressure (m)										
	2050										
	Pipe 6-7	Pipe 7-10	Pipe 8-10	Pipe 9-10	Pipe 10-13	Pipe 11-12	Pipe 12-13	Pipe 12-16	Pipe 13-14	Pipe 14-15	Pipe 15-16
1	-	-	-	-	-	-	-	-	-	-	-
2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2	71.2
3	58.3	59.4	60.8	60.8	60.3	60.9	60.9	61.0	60.7	60.8	60.9
4	55.1	57.7	59.8	59.9	60.0	59.9	59.9	59.8	60.0	60.0	59.9
5	50.3	51.9	56.4	53.3	56.8	56.6	56.5	56.4	56.7	56.6	56.5
6	62.5	61.9	60.0	60.1	60.8	60.0	59.9	59.6	60.3	60.0	59.9
7	48.5	61.9	59.7	59.8	60.6	59.6	59.5	59.2	60.0	59.7	59.5
8	51.0	53.1	58.3	58.8	59.5	58.8	58.7	58.3	59.1	58.9	58.7
9	46.4	47.9	54.7	42.8	55.4	54.7	54.7	54.4	55.0	54.8	54.7
10	28.5	29.9	39.1	39.2	40.4	39.0	38.9	38.4	39.5	39.1	38.9
11	51.6	52.8	56.9	56.9	51.4	48.2	57.1	58.0	55.3	56.5	57.1
12	52.0	53.2	57.9	57.9	51.5	58.0	58.1	59.3	55.9	57.3	58.1
13	39.7	41.0	49.1	49.1	36.3	49.1	48.7	47.4	50.3	49.3	48.7
14	39.4	40.7	48.2	48.2	36.2	48.2	47.9	44.9	37.5	49.0	47.5
15	39.4	40.7	48.0	48.0	36.3	48.0	47.8	43.7	37.8	44.9	47.2
16	40.3	41.6	48.0	48.0	38.2	48.1	48.0	42.8	40.9	45.7	48.7
Note: H_{min} = 26.3 m											

Table 6-16 Nodal pressure of flexible design 1 under one pipe failure on year 2050 (West)

Node	Pressure (m)										
	2050										
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9	Pipe 6-7	Pipe 6-17
1	-	-	-	-	-	-	-	-	-	-	-
2	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1
3	47.6	60.9	58.2	61.1	61.7	61.2	61.1	61.1	61.5	60.4	60.8
4	48.2	59.7	54.0	57.3	59.1	60.4	60.3	59.9	59.6	58.5	60.0
5	47.4	60.1	56.4	60.4	49.2	60.3	60.1	60.3	61.3	59.5	59.6
6	53.0	60.0	50.9	58.6	58.7	59.8	60.0	60.1	59.2	61.2	60.5
7	49.8	59.5	51.3	57.5	58.1	59.3	59.5	59.6	58.8	57.7	59.8
8	48.0	59.2	52.3	57.1	57.6	59.3	57.6	59.3	58.7	57.7	59.4
9	47.1	58.8	53.2	58.3	49.2	58.9	58.8	59.0	50.4	58.1	57.4
10	29.5	39.4	31.4	37.5	37.9	39.3	39.2	39.5	38.7	37.7	39.7
13	38.4	49.7	43.2	48.9	40.7	49.8	49.7	49.9	41.9	49.1	47.2
17	28.1	38.2	30.5	37.2	31.7	38.2	38.2	38.3	32.6	38.0	32.4
18	29.6	38.7	30.2	36.9	37.4	38.5	38.7	38.8	38.0	37.5	39.1
19	27.6	38.1	30.5	37.1	30.8	38.1	38.1	38.3	31.8	37.8	32.6
20	27.0	38.1	31.4	37.3	29.3	38.2	38.1	38.3	30.5	37.7	35.1
Note: H_{min} = 26.3 m											

Cont.

Node	Pressure (m)									
	2050									
	Pipe 6-18	Pipe 7-10	Pipe 7-18	Pipe 8-10	Pipe 9-10	Pipe 9-13	Pipe 10-13	Pipe 13-20	Pipe 17-19	Pipe 19-20
1	-	-	-	-	-	-	-	-	-	-
2	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1	71.1
3	61.0	60.9	61.1	61.0	61.0	61.3	61.0	61.2	60.9	61.1
4	59.9	60.0	60.1	59.9	60.0	59.9	60.0	60.0	60.0	60.0
5	60.2	59.9	60.3	60.2	60.1	60.8	60.2	60.5	60.0	60.3
6	60.2	60.3	60.0	60.2	60.2	59.7	60.1	59.9	60.3	60.1
7	59.5	60.0	59.8	59.7	59.7	59.4	59.7	59.6	59.7	59.7
8	59.3	58.5	59.6	59.2	59.5	59.3	59.5	59.5	59.4	59.4
9	58.9	58.4	59.0	59.0	58.8	60.4	58.8	59.7	58.4	59.2
10	39.5	38.2	39.8	39.7	39.7	39.4	39.7	59.3	39.6	39.6
13	49.8	49.4	49.9	49.9	49.7	43.1	49.6	51.0	48.9	50.2
17	38.3	38.0	38.3	38.4	38.2	33.5	38.2	34.7	39.7	37.6
18	37.4	39.2	33.2	39.0	38.9	38.6	38.9	38.8	39.0	38.9
19	38.2	37.9	38.2	38.3	38.1	32.8	38.1	34.1	36.4	37.5
20	38.3	37.9	38.3	38.3	38.2	31.7	38.1	33.4	37.1	38.7
Note: H_{min} = 26.3 m										

6.2.4 Flexible design 2

6.2.4.1 Model preparation

Flexible design 2 is developed by applying the proposed flexibility-based optimisation method, where uncertain water demand and pipe failure are considered. Flexible design 2 is a system designed with tank, and thus the network capacity was sized only to respond to maximum daily demands, and tanks used to respond to demand variation within a day. Like flexible design 1, three system layouts were considered in the case. These are WDD_1, WDD_2, and WDD_3. WDD_1 is built out in the first stage, and WDD_2 and WDD_3 are the two possible expansions in the second stage. WDD_2 is the system after its development to the north, while WDD_3 is the system after its development to the west. Then a scenario tree is built to present this system development, which is given in Figure 6-13. WDD_i represents system state i and $Tree_j$ presents s-t spanning tree j. The probability for each future expansion is set as 50%.

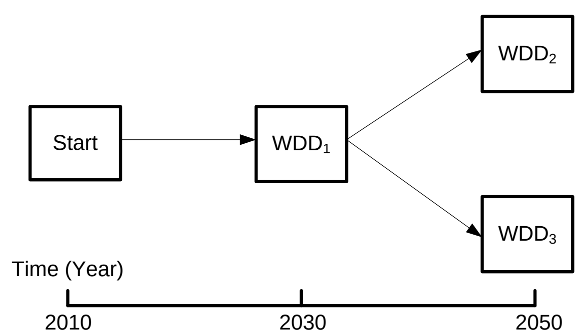

Figure 6-13 Scenario tree for "flexible design 2"

According to the uncertainties modelling in Chapter 3, four simulations are required to approximate system performance under uncertain nodal demands and pipe failures for each state. Two of them are under the system configuration with no pipe failure. And within these two simulations, one of them is under the peak demand period with nodal demand set as the expected value multiplied by a safety margin coefficient, and the other is under the tank refilling period with nodal demand set as the expected value multiplied by a safety margin coefficient. The other two simulations are under the system configuration of two s-t spanning trees, and the demand scenario with nodal demand is set as a fraction of the expected value. These are illustrated in Figure 6-14.

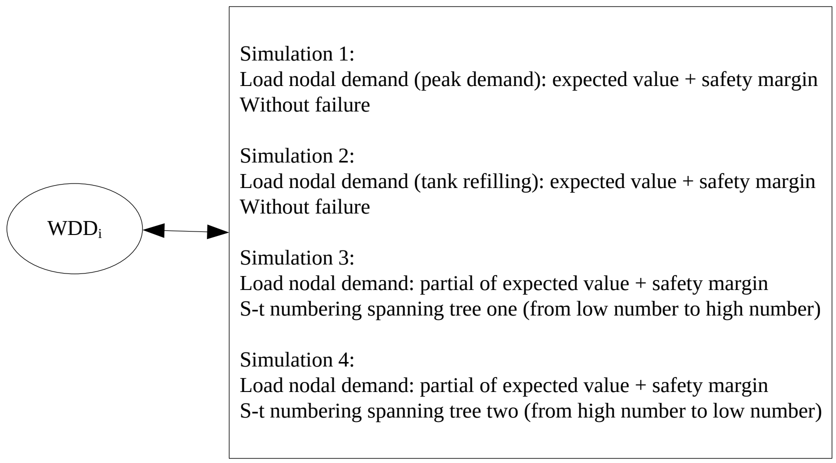

Figure 6-14 Four simulations for each WDD_i

For generating two independent spanning trees, an s-t numbering is applied on the WDD_2 and WDD_3. According to s-t numbering algorithm in Chapter 3, the s-t numbering is generated for WDD_2 and WDD_3, and are given in Figures 6-15 and 6-16 respectively. The network in the dashed line was developed in the first stage. There are two possible system extensions in the second stage, for WDD_2 the system was extended into the north, while for WDD_3 the system was extended to west.

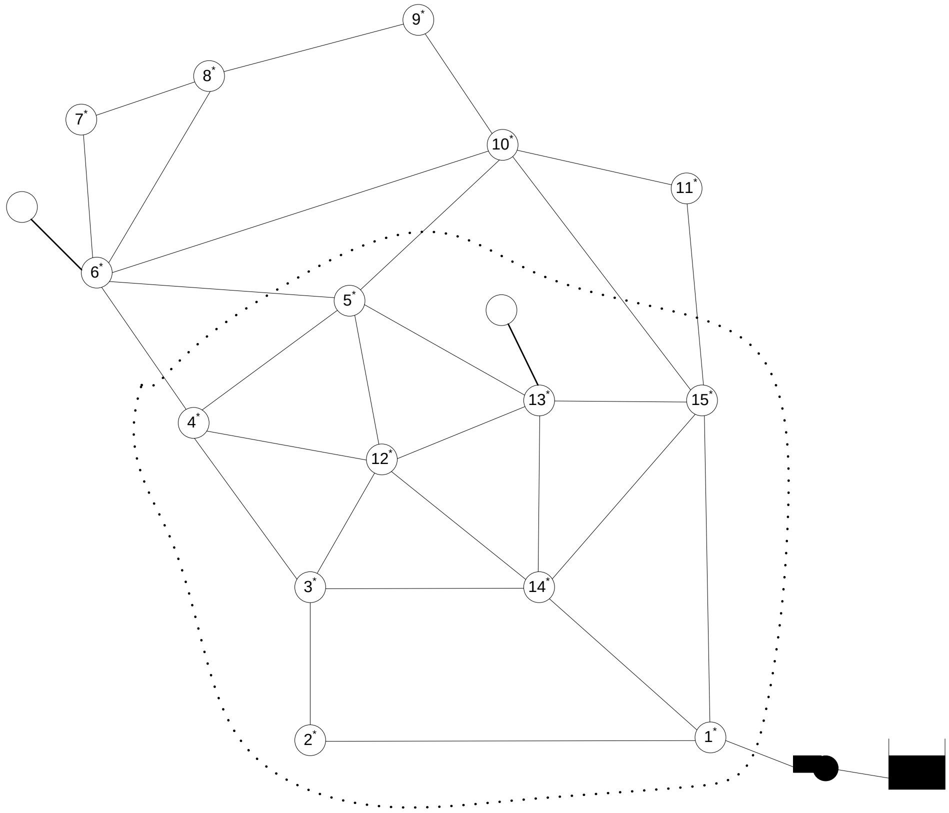

Figure 6-15 S-t numbering of WDD_2 of "flexible design 2"

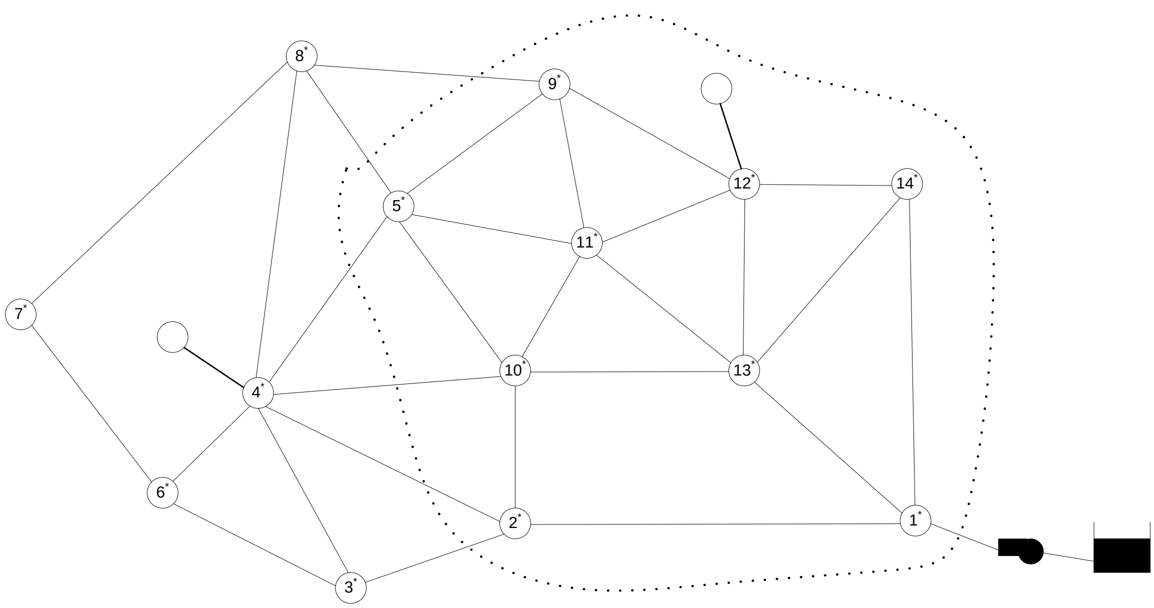

Figure 6-16 S-t numbering of WDD_3 "flexible design 2"

When we have the s-t numbering for the two system configurations, two overlapping spanning trees for each system can be generated. Two trees for WDD_1 choose the sub-part of the trees in WDD_2 and WDD_3 as the components. The two trees for WDD_1 are presented in Figures 6-17 and 6-18.

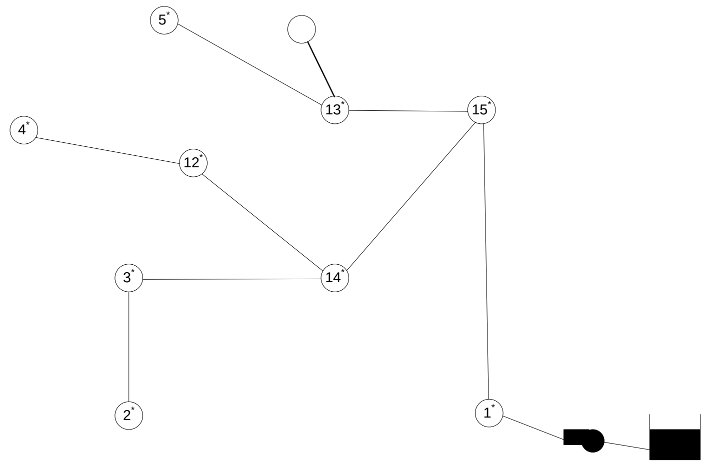

Figure 6-17 Spanning tree 1 for WDD_1 in "flexible design 2"

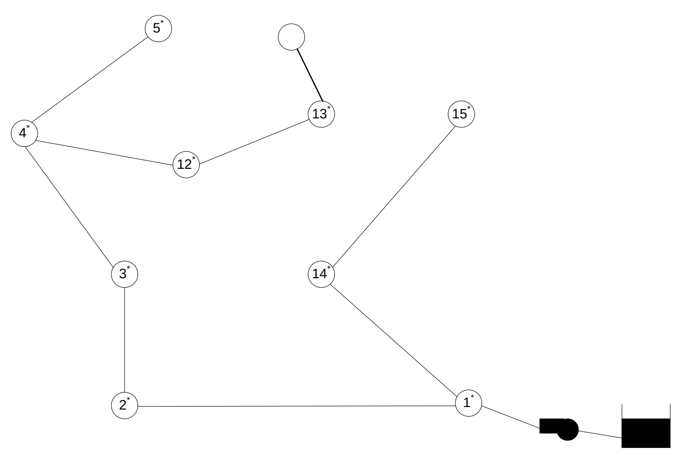

Figure 6-18 Spanning tree 2 for WDD_1 in "flexible design 2"

The two trees for WDD_2 are presented in Figures 6-19 and 6-20.

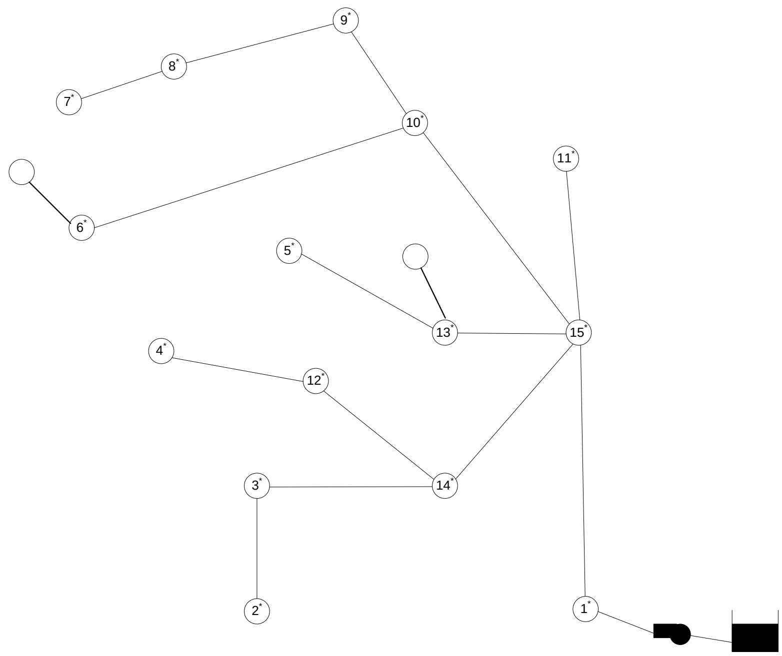

Figure 6-19 Spanning tree 1 for WDD_2 of flexible design 2

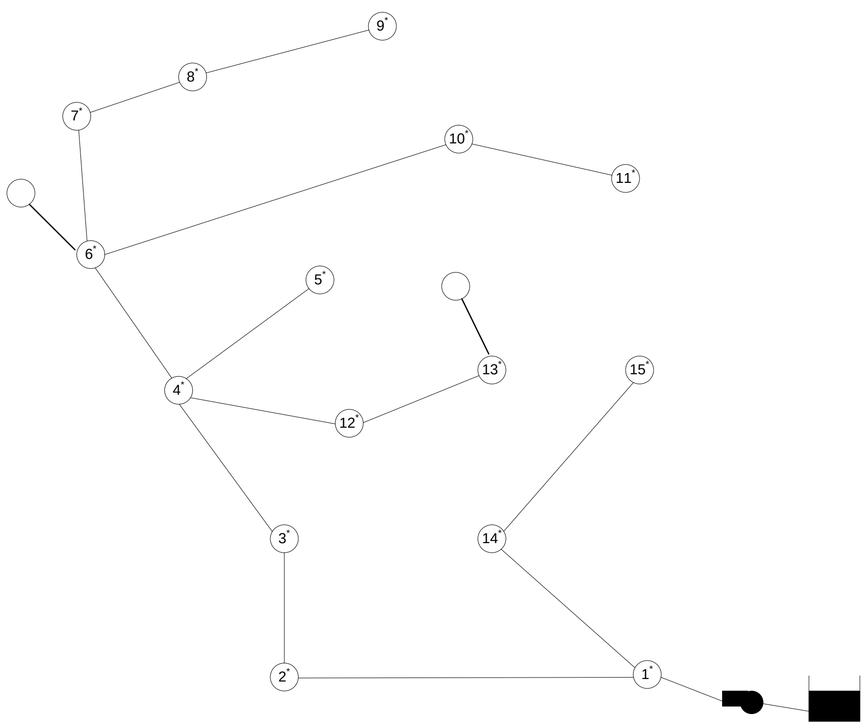

Figure 6-20 Spanning tree 2 for WDD_2 of flexible design 2

The two trees for WDD_2 are presented in Figures 6-21 and 6-22.

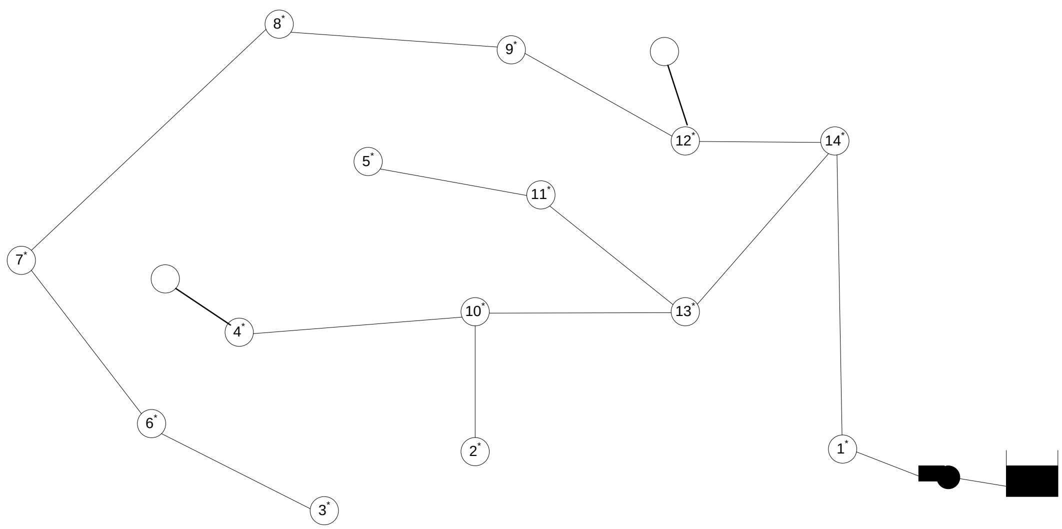

Figure 6-21 Spanning tree 1 for WDD_3 of flexible design 2

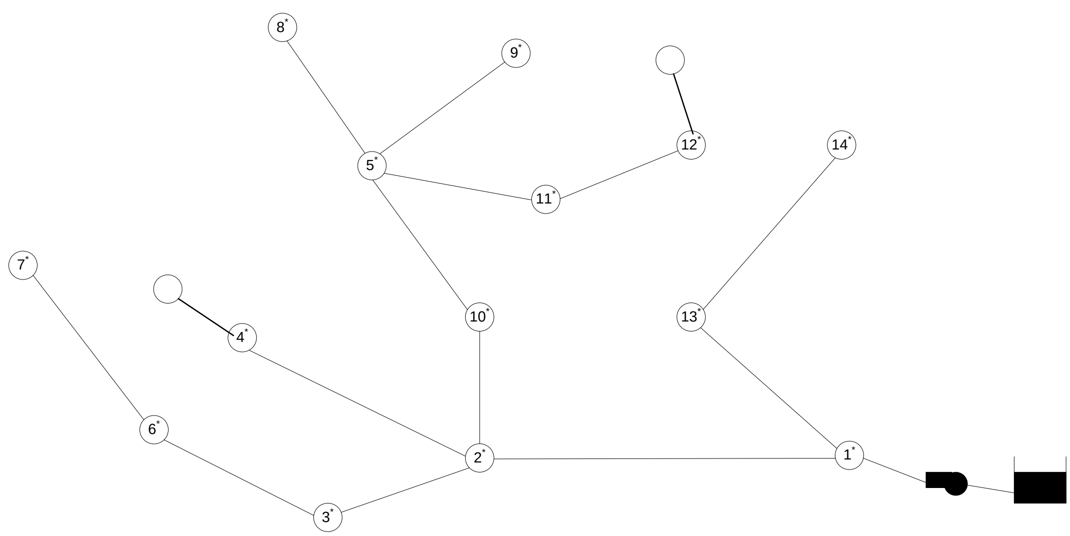

Figure 6-22 Spanning tree 2 for WDD_3 of flexible design 2

Designing a water distribution system under uncertainty requires trade-off among different objectives, for example cost and risk. The model control parameters discussed here illustrates the trade-off between economics and risk. The first control parameter is the minimum pressure at all demand nodes during peak flow when all system components are functional. This pressure shows the available energy to supply the sub-system. High available energy has more capacity to respond to the variation in water demand and component failure in the sub-system. Also it can make system solution less sensitive to the errors from the simplification of the network model. The minimum pressure for the case is set as 40 psi (257.8 kPa).

The second control parameter is the safety margin coefficient for each node, which shows the additional capacity available, to enable the system with the ability to deliver required water with sufficient pressure despite some excess in the designed demand. It is a complex task to set this coefficient properly. Babayan et al. (2007) developed an iteration method to determine the values of the safety margins to respond to the required range of uncertainties. However, meanwhile they also provided some concerns about the method. For example, before network configuration becomes known, it is difficult if not impossible to find more “influential” nodes, i.e., where demand fluctuation affects network robustness the most. Here we simply assign a same safety margin coefficient to all demand nodes, which is 1.2.

The third control parameter is the minimum filling elevation for the tank, which controls the scope of the service area the tank can provide water to. It directly determines the required system capacity to refill the tank, and also shows the available potential energy in the tank to supply the system and respond to uncertainties. During peak demand, excess water is provided by the tank. Nodal pressure near the tank is largely controlled by the water level in the tank, which is indirectly related to the setting of minimum filling elevation. For each tank, the minimum filling elevation can be set dependently or independently. An analysis should be made about the trade-off between economics and risk. Here, it simply assumes that the minimum filling elevation for each tank is equal to its base elevation on connection node + 40 psi (257.8 kPa).

The fourth control parameter is the multiplier coefficient for the spanning tree, which shows the capacity from each independent route. This value shows capacity contribution from each route to supply consumers, and also the ability to respond to the component failure directly, and variation in the water demand indirectly. High values mean high delivery capacity for each spanning tree, and has more capability to respond to uncertainties. For the case, the value is chosen as 0.5 for each tree. All four control parameters are summarised in Table 6-17.

Table 6-17 Control parameters in flexible design 2

Model Component	Control Parameter	Chosen value for the case
Tank (21)	filling elevation	41.6 m
Tank (22)		50.7 m
Tank (23)		62.9 m
Spanning Tree (1)	Multiplier Coefficient	0.5
Spanning Tree (2)		0.5
Spanning Tree (3)		0.5
Spanning Tree (4)		0.5
Spanning Tree (5)		0.5
Spanning Tree (6)		0.5
Node	Safety Margin Coefficient	1.2
	Minimum pressure	26.3 m

6.2.4.2 Model formulation

The objective of "flexible design 2" is to minimise the expected system life cycle cost on different designs under uncertain water demand and pipe failure while at the same time meeting the specification for providing enough water with sufficient pressure under the pre-defined uncertain level. The life cycle refers to planning period in the thesis. The mathematical formulation for "flexible design 2" is shown as:

$$\text{Minimise} \quad f(D) = \sum_{i=1}^{PN_1} U(D_i^1)L_i^1 + 0.5\sum_{i=1}^{PN_2} R_i^2 \frac{U(D_i^2)L_i^2}{(1+r)^{20}} + 0.5\sum_{i=1}^{PN_3} R_i^3 \frac{U(D_i^3)L_i^3}{(1+r)^{20}} \tag{6.16}$$

where D_i^j = pipe diameter of pipe *i* for WDD$_j$; $U\left(D_i^j\right)$ = unit cost for the pipe *i* with the diameter D_i^j; R_i^j = replacement status of pipe *i* for WDD$_j$; L_i^j is the length for the pipe *i*; PN_j = number of pipes for WDD$_j$; *r* = discount rate, taking 15% in this case.

This least cost problem is also subject to the following constraints:

Mass and energy balance constraints:

For each network *j* and $j \in \{1,2,3\}$

$$\sum Q_{in} - \sum Q_{out} = Q_{WDD_j} \tag{6.17}$$

$$\sum h_f - \sum E_p = 0 \tag{6.18}$$

For each tree *j* and $j \in \{1,2,3,4,5,6\}$

$$\sum Q_{in} - \sum Q_{out} = Q_{TREE_j} \tag{6.19}$$

$$\sum h_f - \sum E_p = 0 \tag{6.20}$$

where Q_{in} = flow into the junction; Q_{out} = flow out of the junction; and Q_{WDD_j} and Q_{TREE_j} = external inflow or demand at the junction node, taking expected values + safety margin. E_p = energy input for each loop. The Hazen-Williams is used to express the head-loss term h_f.

This optimisation uses EPANET (Rossman 2000) to simulate the network hydraulic, where mass and energy balance constraints are met automatically.

The minimum head constraint for each demand node:

$$H_{node} \geq H_{node}^{\min} \tag{6.21}$$

Minimum tank filling elevation:

$$H_{\tan k} \geq H_{\tan k}^{\min} \tag{6.22}$$

where H_{node} and $H_{node}^{\min}$ are pressure and minimum pressure requirement on the node. $H_{\tan k}$ and $H_{\tan k}^{\min}$ are tank filling elevation and minimum tank filling elevation.

Available pipe diameters:

$$D_i^j \in \{D_{\min}, \cdots, D_{\max}\} \tag{6.23}$$

Replacement status for each pipe:

$$R_i^j \in [0, 1] \tag{6.24}$$

6.2.4.3 Model solution

The optimisation model is solved by using Genetic Algorithms and run for several times with different initial seed. The least-cost option is chosen as the solution. Its total capital cost is $ 6.80 million, and the result of the system configuration for the two stages is shown in Table 6-18.

Table 6-18 System configuration of flexible design 2

Pipe		Pipe Diameter at year 2030 (mm)	Pipe Diameter at year 2050 (mm)	
Start Node	End Node		North	West
1	2	762	762	762
2	3	762	762	762
2	4	254	254	254
2	6	762	762	762
3	4	609.6	609.6	762
3	5	406.4	406.4	406.4
3	11	-	152.4	-
3	12	-	406.4	-
4	5	-	-	-
4	7	254	254	508
4	8	406.4	406.4	406.4
5	8	254	254	254
5	9	203.2	203.2	609.6
6	7	609.6	609.6	609.6
6	17	-	-	355.6
6	18	-	-	508
7	8	-	-	-
7	10	304.8	508	355.6
7	18	-	-	355.6
8	9	-	-	-
8	10	254	254	254
9	10	254	254	254
9	12	-	-	-
9	13	-	-	508
10	13	-	508	203.2
10	18	-	-	-
11	12	-	203.2	-
12	13	-	304.8	-
12	16	-	406.4	-
13	14	-	406.4	-
13	15	-	-	-
13	18	-	-	-
13	20	-	-	508
14	15	-	355.6	-
15	16	-	355.6	-
17	18	-	-	-
17	19	-	-	355.6
18	19	-	-	-
19	20	-	-	355.6
5	21	304.8	304.8	304.8
13	22	-	304.8	-
18	23	-	-	355.6

6.2.4.4 Performance of "flexible design 2" under uncertainties

Flexible design 2 was generated by finding the least cost solution, considering uncertain nodal demands and pipe failures. Nodal pressures for flexible design 2 under uncertain nodal demands and pipe failures are simulated. The nodal pressures during the period of peak demand and tank refilling when no pipe failure happens are given in Table 6-19.

Table 6-19 Nodal pressure of flexible design 2 under maximum water demand scenario

Node	Pressure (m)					
	2030		2050 (North)		2050 (West)	
	Max_Hour	Tank_Refill	Max_Hour	Tank_Refill	Max_Hour	Tank_Refill
1	Treatment	Treatment	Treatment	Treatment	Treatment	Treatment
2	71.2	71.2	71.1	71.1	71.1	71.1
3	61.8	60.6	58.5	56.9	59.2	58.9
4	60.1	59.9	56.2	55.8	58.4	58.4
5	61.8	49.6	58.5	42.9	53.6	46.5
6	61.5	62.1	59.0	59.7	59.0	58.6
7	60.7	61.6	55.3	56.0	58.3	58.0
8	55.4	56.4	50.7	50.6	52.3	53.6
9	47.2	50.0	40.6	43.0	52.3	46.5
10	34.8	36.5	30.3	30.1	33.0	33.6
11	-	-		47.7	-	-
12	-	-	43.9	47.8	-	-
13	-	-	39.8	37.6		38.0
14	-	-	32.3	36.7	-	-
15	-	-	30.8	36.6	-	-
16	-	-	31.2	37.4	-	-
17	-	-	-	-	31.5	31.9
18	-	-	-	-	38.6	36.5
19	-	-	-	-	29.7	28.2
20	-	-	-	-	29.9	26.7
21	Tank	Tank	Tank	Tank	Tank	Tank
22	-	-	Tank	Tank	-	-
23	-	-	-	-	Tank	Tank
Note: H_{min} = 40 psi						

The pressures on all demand nodes at both stages meet the minimum pressure requirement (40 psi) when no pipe failure happens. The nodal pressure in the state of 2030 is much higher than the minimum pressure requirement. There are two reasons for this. The first one is the additional capacity embedded to respond to pipe failure. When no pipe failure happens, designed capacity is higher than the required capacity. Another one is the additional capacity prepared for the system extension. The embedded capacities for both extensions are higher than the required capacity for one extension. Comparing the minimum nodal pressure for the states of 2050-North and 2050-West, it is also observed that it is more difficult for the system to meet minimum pressure requirement in 2050-West. The reason is the high elevation in that area. As a result, it can be concluded that the additional capacity embedded for different future extensions and pipe failure can enable the system to avoid supply deficiency by uncertain water demand and pipe failure.

Performance of flexible design 2 is also checked under different failure scenarios when one pipe is out of the service. Tables 6-20 to 6-22 present the nodal pressure in the system under high water demand scenario, and when one pipe is taken out of service. It was found that almost all the nodes can meet the minimum pressure requirement, except a few at which the pressure can not meet the minimum pressure requirement under specific failures of some pipes. However, its pressure improvement is more obvious than the inflexible design, and it is much cheaper than flexible design 1. Furthermore, the short period of pressure deficiency can be remedied more cost-effectively by some other strategies, for example, increasing pumping capacity during pipe failure period.

Table 6-20 Nodal pressure of flexible design 2 under one pipe failure on year 2030

Node	Pressure (m)												
	2030												
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9	Pipe 6-7	Pipe 7-10	Pipe 8-10	Pipe 9-10
1	-	-	-	-	-	-	-	-	-	-	-	-	-
2	71.2	71.1	71.1	71.1	71.2	71.1	71.1	71.1	71.1	71.1	71.2	71.1	71.1
3	44.9	59.0	56.9	61.3	61.3	59.0	60.6	59.3	59.2	57.6	44.9	59.0	56.9
4	44.7	56.7	51.0	36.6	59.0	56.7	60.3	57.5	57.2	53.1	44.7	56.7	51.0
5	47.6	49.0	48.8	48.8	48.6	49.0	48.8	48.9	49.0	48.8	47.6	49.0	48.8
6	60.6	61.1	**7.0**	60.2	61.2	61.3	61.0	61.2	61.0	62.4	60.6	61.1	**7.0**
7	58.6	59.8	**7.2**	57.9	60.2	60.4	59.6	60.0	59.7	29.6	58.6	59.8	**7.2**
8	42.0	49.4	40.0	35.5	50.4	49.5	**20.2**	50.6	49.0	43.8	42.0	49.4	40.0
9	35.7	39.5	**8.2**	33.7	39.9	39.6	29.8	40.1	**26.2**	**24.9**	35.7	39.5	**8.2**
10	**24.5**	29.6	**-10.0**	**21.2**	30.4	29.7	**16.0**	30.6	28.0	**9.7**	**24.5**	29.6	**-10.0**
Note: H_{min} = 26.3 m													

Table 6-21 Nodal pressure of flexible design 2 under one pipe failure on year 2050 (North)

Node	Pressure (m)										
	2050										
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 3-11	Pipe 3-12	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9
1	-	-	-	-	-	-	-	-	-	-	-
2	71.1	71.0	71.1	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3	31.7	53.9	52.9	57.6	57.5	54.5	57.0	54.2	56.4	54.5	54.3
4	31.7	51.3	49.2	30.9	54.5	52.3	54.0	51.8	56.0	52.6	52.2
5	39.8	42.1	41.9	41.9	41.7	42.2	42.3	42.1	41.9	42.1	42.3
6	57.2	57.9	37.2	55.3	58.3	58.0	58.1	58.1	58.2	58.0	57.9
7	51.1	52.9	37.5	51.3	53.8	53.1	53.3	53.4	53.4	53.2	52.9
8	30.5	43.6	40.5	30.0	45.3	44.2	45.0	44.0	**16.9**	45.7	44.0
9	30.9	32.8	27.4	32.1	32.9	32.9	32.6	32.9	32.3	33.0	**19.5**
10	**25.2**	26.9	**18.6**	**25.8**	27.3	27.0	26.5	27.1	26.2	27.1	26.5
11	**22.2**	36.9	34.8	38.8	38.9	26.6	**12.3**	37.0	38.1	37.2	37.1
12	27.4	40.1	37.8	41.6	41.8	39.3	**12.6**	40.3	41.1	40.4	40.3
13	35.8	36.7	33.4	36.5	36.9	36.7	35.6	36.8	36.6	36.8	36.6
14	**22.9**	29.0	**26.0**	29.4	29.7	28.7	**16.7**	29.1	29.3	29.1	29.0
15	**18.3**	27.3	**24.6**	28.1	28.3	26.8	**8.1**	27.4	27.9	27.5	27.4
16	**17.6**	27.7	**25.1**	28.7	28.9	27.1	**4.0**	27.8	28.4	27.9	27.8
Note: H_{min} = 26.3 m											

Cont.

Node	Pressure (m)										
	2050										
	Pipe 6-7	Pipe 7-10	Pipe 8-10	Pipe 9-10	Pipe 10-13	Pipe 11-12	Pipe 12-13	Pipe 12-16	Pipe 13-14	Pipe 14-15	Pipe 15-16
1	-	-	-	-	-	-	-	-	-	-	-
2	71.1	71.1	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3	53.2	54.4	54.2	54.4	54.8	54.2	54.0	55.2	52.4	53.6	54.6
4	49.7	52.5	51.9	52.3	53.1	52.1	51.9	52.8	50.7	51.6	52.4
5	42.0	42.1	42.1	41.9	42.2	42.1	42.1	42.2	42.0	42.1	42.2
6	62.4	61.5	58.1	58.2	59.6	58.0	58.0	58.0	57.9	58.0	58.0
7	40.8	60.9	53.2	53.6	56.8	53.1	53.0	53.1	52.9	53.0	53.1
8	41.4	42.5	42.5	44.4	46.0	44.1	44.0	44.4	43.3	43.8	44.2
9	29.0	29.9	33.1	**-45.1**	37.1	32.9	32.9	32.8	32.9	32.9	32.9
10	**21.0**	**22.2**	27.4	28.1	34.4	27.0	27.0	26.8	27.1	27.1	26.9
11	35.3	36.2	37.1	37.2	36.9	**-2.6**	34.0	42.8	**19.6**	30.7	38.7
12	38.4	39.2	40.3	40.4	40.0	41.2	36.7	47.1	**20.6**	32.9	42.2
13	34.2	34.7	36.8	36.9	35.8	36.8	36.8	36.5	37.1	36.9	36.7
14	26.8	27.4	29.1	29.2	28.4	29.4	27.6	**16.0**	**-30.4**	34.3	27.0
15	**25.3**	**25.9**	27.5	27.6	26.9	28.0	**25.2**	**6.3**	**-27.7**	**9.4**	**24.3**
16	**25.7**	26.4	27.8	28.0	27.3	28.5	**25.2**	**1.0**	**-8.4**	**14.7**	31.0
Note: H_{min} = 26.3 m											

Table 6- 22 Nodal pressure of flexible design 2 under one pipe failure on year 2050 (West)

Node	Pressure (psi)										
	2050										
	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-4	Pipe 3-5	Pipe 4-7	Pipe 4-8	Pipe 5-8	Pipe 5-9	Pipe 6-7	Pipe 6-17
1	-	-	-	-	-	-	-	-	-	-	-
2	71.1	71.0	71.1	71.1	71.1	71.0	71.1	71.0	71.0	71.0	71.0
3	46.0	57.2	55.8	61.0	59.5	57.9	58.6	57.5	57.0	56.1	57.5
4	46.2	56.2	54.1	50.3	57.8	57.1	58.1	56.5	55.8	54.6	56.6
5	44.3	45.4	45.2	45.3	44.5	45.4	44.9	45.3	45.6	45.3	44.9
6	55.7	57.2	52.3	56.1	57.6	57.1	57.5	57.3	56.6	58.9	58.2
7	51.2	56.1	52.3	52.9	56.9	55.9	56.7	56.3	55.6	53.3	56.5
8	41.7	47.1	45.6	44.5	47.8	47.6	**17.4**	48.5	45.3	46.0	46.9
9	43.4	44.6	44.2	44.4	43.8	44.6	43.8	44.6	**16.8**	44.5	42.5
10	**24.3**	28.1	**26.0**	**26.0**	28.3	28.1	**23.9**	28.7	**21.8**	26.7	27.3
13	33.8	35.1	34.3	34.8	34.4	35.1	34.3	35.2	**8.2**	35.1	29.7
17	**25.3**	26.7	**24.1**	**26.0**	26.5	26.6	26.4	26.7	**13.3**	27.4	**0.6**
18	35.8	36.3	35.0	36.0	36.3	36.2	36.3	36.3	36.2	36.3	36.3
19	**21.9**	**23.3**	**22.0**	**22.8**	**22.7**	**23.3**	**22.6**	**23.3**	**1.2**	**23.5**	**3.1**
20	**21.8**	**23.2**	**22.0**	**22.8**	**22.5**	**23.2**	**22.4**	**23.2**	**-3.1**	**23.3**	**12.2**
Note: H_{min} = 26.3 m											

Cont.

Node	Pressure (m)									
	2050									
	Pipe 6-18	Pipe 7-10	Pipe 7-18	Pipe 8-10	Pipe 9-10	Pipe 9-13	Pipe 10-13	Pipe 13-20	Pipe 17-19	Pipe 19-20
1	-	-	-	-	-	-	-	-	-	-
2	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3	57.6	57.8	57.4	57.4	57.4	57.2	57.4	57.3	57.5	57.4
4	56.7	56.9	56.4	56.3	56.5	56.1	56.4	56.3	56.5	56.4
5	45.4	45.1	45.4	45.4	45.3	45.5	45.3	45.4	45.2	45.3
6	58.4	57.6	57.3	57.3	57.3	56.8	57.3	56.9	57.8	57.4
7	56.7	57.0	56.2	56.2	56.3	55.9	56.3	56.1	56.4	56.2
8	47.5	45.1	47.3	46.5	47.8	46.5	47.6	47.3	47.1	47.2
9	44.6	43.5	44.6	44.6	44.3	45.3	44.5	45.0	43.6	44.5
10	28.4	**20.7**	28.1	29.0	30.0	26.6	29.2	28.3	27.7	28.1
13	35.3	33.7	35.2	35.2	35.0	**10.8**	34.7	36.2	32.6	34.8
17	27.3	**26.1**	26.7	26.7	26.6	**14.5**	26.5	**17.7**	35.3	28.3
18	36.1	36.3	36.3	36.3	36.3	36.2	36.3	36.2	36.3	36.3
19	**23.6**	**22.1**	**23.3**	**23.4**	**23.2**	**3.3**	**22.9**	**8.6**	**15.8**	**25.8**
20	**23.4**	**21.8**	**23.2**	**23.3**	**23.0**	**-0.5**	**22.8**	**6.1**	**18.4**	**22.6**
Note: H_{min} = 26.3 m										

Some post-optimisation modifications can be applied to improve network performance under pipe failure. The first is to increase the diameters of some pipes. This strategy requires additional capital investment on pipes, and may also cause some water quality problems because of the excess capacity. It has been found that in the first stage, the most significant component is pipe 2-6, and node 10 is the most difficult node to meet the minimum pressure requirement due to the high elevation. Diameter of Pipe 5-9 is changed from (203.2 mm) to (254 mm) and diameter of Pipe 4-7 is changed from (254 mm) to (304.8 mm). After these modifications, the minimum nodal pressure in the system is 14.62 and is at node 10, while all other nodes are above the minimum pressure. The second is to increase the available energy by installing back-up pump in the source, in the tank or somewhere in the system. The additional capital investment is the cost for installing the back-up pumps. There is also operational cost for the pump which can be ignored, since it is small compared with the total lifecycle cost. It has also been found hat the most economical option is to install a boost pump near node 10. There are more strategies than these, which can be applied to improve the performance of the final solution. However, more comprehensive analysis of these strategies should be undertaken before the final solution is chosen. It is necessary to compare the costs and benefits with each other, the final solution is chosen after some trade-offs are made. The final strategy may be one of them or a combination of them.

6.2.5 Comparison study of three designs

Inflexible design comes from a least cost design under expected scenario, where uncertain parameters are taken as their expected values and pipe failure is not included. Flexible design 1 and Flexible design 2 are developed by applying the proposed flexibility-based optimisation method, where uncertain water demand and pipe failure are considered. However, Flexible design 1 is a system designed without tanks, while Flexible design 2 has tanks. System configurations for these three designs are summarised in Table 6-23.

Table 6-23 System configurations of inflexible design, flexible design 1, and flexible design 2

Pipe		Inflexible design		Flexible design 1			Flexible design 2		
Start Node	End Node	2030	2050	2030	2050 North	2050 West	2030	2050 North	2050 West
1	2	762	762	304.8	1016	863.6	762	762	762
2	3	152.4	762	1016	1016	1016	762	762	762
2	4	609.6	609.6	355.6	355.6	355.6	254	254	254
2	6	254	254	863.6	863.6	863.6	762	762	762
3	4	152.4	152.4	762	762	762	609.6	609.6	762
3	5	152.4	152.4	355.6	355.6	762	406.4	406.4	406.4
3	11	-	152.4	-	203.2	-	-	152.4	-
3	12	-	609.6	-	609.6	-	-	406.4	-
4	5	203.2	203.2	-	-	-	-	-	-
4	7	152.4	152.4	355.6	355.6	609.6	254	254	508
4	8	609.6	609.6	609.6	609.6	609.6	406.4	406.4	406.4
5	8	152.4	152.4	304.8	304.8	304.8	254	254	254
5	9	152.4	152.4	304.8	304.8	609.6	203.2	203.2	609.6
6	7	152.4	152.4	609.6	1016	762	609.6	609.6	609.6
6	17	-	-	-	-	457.2	-	-	355.6
6	18	-	-	-	-	406.4	-	-	508
7	8	203.2	203.2	-	-	-	-	-	-
7	10	152.4	152.4	863.6	863.6	863.6	304.8	508	355.6
7	18	-	-	-	-	508	-	-	355.8
8	9		152.4	-	-	-	-	-	-
8	10	457.2	457.2	508	508	508	254	254	254
9	10	254	254	304.8	304.8	304.8	254	254	254
9	12	-	406.4	-	-	-	-	-	-
9	13	-	355.6	-	-	609.6	-	-	508
10	13	-	152.4	-	609.6	254	-	508	203.2
10	18	-	-	-	-	-	-	-	-
11	12	-	152.4	-	254	-	-	203.2	-
12	13	-	152.4	-	406.4	-	-	304.8	-
12	16	-	406.4	-	508	-	-	406.4	-
13	14	-	355.6	-	609.6	-	-	406.4	-
13	15	-	152.4	-	-	-	-	-	-
13	18	-	-	-	-	-	-	-	-
13	20	-	-	-	-	762	-	-	508
14	15	-		-	609.6	-	-	355.6	-
15	16	-	355.6	-	508	-	-	355.6	-
17	18	-	-	-	-	-	-	-	-
17	19	-	-	-	-	609.6	-	-	355.6
18	19	-	-	-	-	-	-	-	-
19	20	-	-	-	-	457.2	-	-	355.6
5	21	-	-	-	-	-		304.8	304.8
13	22	-	-	-	-	-	-	304.8	-
18	23	-	-	-	-	-	-	-	355.6

Lifecycle costs for inflexible design, flexible design 1, and flexible design 2 are \$4.68 million, \$10.07 million, and \$6.80 million respectively. The difference in cost between inflexible design and flexible designs is the cost to provide flexibility to reduce the risk of supply deficiency when the real water demand exceeds the designed delivery capacity and one pipe is taken out of the service. It was found that network capacity in the first stage was smallest in the inflexible design and largest in flexible design 1. The additional network capacity in the two flexible designs enables the system to cost-effectively respond to uncertainties from water demand and pipe failure. The cost difference between flexible design 1 and flexible design 2 is the benefit for incorporating tanks in the system. Network capacity in flexible design 2 was only required to respond to a designed demand, which was equal to the expected daily maximum demand, multiplied by a safety margin coefficient. The network capacity in flexible design 1 was required to respond to a designed demand which was equal to the expected maximum hourly demand, multiplied by a safety margin. The later one was much higher than the former. As a result, the designed capacity in the network was much larger in flexible design without tank than that in flexible design with tank. It is recommended that the required additional capacity to reduce the risk from uncertainties should be distributed to network capacity, tank, and pumping station.

Performances of three designs were checked under different demand scenarios and pipe failure. Table 6-24 shows the nodal pressures of the three designs at peak hour under maximum water demand scenario, when no pipe failure happens. Table 6-25 shows the nodal pressures of inflexible design at peak hour under maximum water demand scenario under one pipe failure. Table 6-26 shows nodal pressures of two flexible designs at peak hour under maximum water demand scenario under one pipe failure. Tables 6-25 and 6-26 only list the worst results for nodal pressures under pipe failure.

Table 6-24 Nodal Pressure under Maximum Water Demand Scenario (m)

Node	Inflexible design		Flexible design 1			Flexible design 2		
	2030	2050	2030	2050 North	2050 West	2030	2050 North	2050 West
1	Source	Source	Source	Source	Source	Source	Source	Source
2	71.1	71.0	63.3	71.2	71.1	71.2	71.1	71.1
3	**20.7**	56.5	54.3	60.9	61.0	61.8	58.5	59.2
4	47.0	47.0	53.5	59.9	60.0	60.1	56.2	58.4
5	**19.6**	27.3	50.9	56.6	60.2	61.8	58.5	53.6
6	**21.0**	**12.7**	54.1	59.9	60.1	61.5	59.0	59.0
7	**21.3**	**13.9**	53.0	59.6	59.7	60.7	55.3	58.3
8	43.2	42.7	52.7	58.8	59.4	55.4	50.7	52.3
9	24.0	36.9	49.4	54.7	59.0	47.2	40.6	52.3
10	**21.0**	**20.0**	33.0	38.9	39.6	34.8	30.3	33.0
11	-	34.9	-	56.9	-	-	40.8	-
12	-	45.7	-	57.8	-	-	43.9	-
13	-	**19.7**	-	49.0	49.9	-	39.8	42.3
14	-	**15.2**	-	48.0	-	-	32.3	-
15	-	**20.0**	-	47.9	-	-	30.8	-
16	-	26.5	-	48.0	-	-	31.2	-
17	-	-	-	-	38.3	-	-	31.5
18	-	-	-	-	38.9	-	-	38.6
19	-	-	-	-	38.2	-	-	29.7
20	-	-	-	-	38.3	-	-	29.9
21	-	-				Tank	Tank	Tank
22	-	-				-	Tank	-
23	-	-				-	-	Tank

Note: H_{min} = 26.3 m

Table 6-25 Nodal Pressure of inflexible design under One Pipe Failure (m)

Node	2030						2050										
	Pipe 2-4	Pipe 2-6	Pipe 4-5	Pipe 4-8	Pipe 8-10	Pipe 9-10	Pipe 2-3	Pipe 2-4	Pipe 2-6	Pipe 3-12	Pipe 4-8	Pipe 7-8	Pipe 9-12	Pipe 9-13	Pipe 12-16	Pipe 13-14	Pipe 15-16
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	71.2	71.2	71.2	71.2	71.2	71.2	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3	**-3047.0**	29.6	**13.0**	**-61.8**	**20.9**	**20.3**	**-231.4**	50.7	58.0	62.1	54.5	58.3	59.7	58.1	58.9	58.1	58.6
4	**-3442.1**	48.3	51.8	55.5	52.2	51.7	**15.7**	**-101.2**	48.9	28.5	60.2	52.1	46.2	51.9	49.4	52.0	50.4
5	**-3441.4**	28.5	**-0.4**	**-168.9**	**13.6**	**12.7**	**-121.6**	**-98.6**	35.3	**-22.4**	**8.6**	38.0	**21.5**	38.6	33.3	38.3	35.6
6	**-533.8**	**-230.7**	32.8	**-60.5**	**21.4**	33.3	**4.9**	**-21.0**	**-304.4**	**9.8**	**-2.6**	**9.4**	**22.7**	27.3	**25.4**	27.4	**26.2**
7	**-3331.0**	**-9.2**	33.0	**-328.7**	**13.4**	33.7	**-15.1**	**-105.2**	**-23.7**	**-2.0**	**-39.4**	**-3.3**	**22.5**	28.3	**25.7**	28.4	26.7
8	**-3442.8**	44.7	48.5	**-378.7**	50.2	49.3	**2.9**	**-101.2**	45.1	**16.7**	**-38.8**	49.5	41.3	49.0	45.5	49.2	47.0
9	**-3450.0**	30.9	29.0	**-378.7**	**-28.9**	**-30.9**	**-223.5**	**-7.9**	42.6	**-196.6**	**13.0**	44.6	**9.0**	47.9	34.8	46.3	39.9
10	**-3462.5**	**22.7**	26.6	**-399.0**	**-49.3**	29.1	**-36.8**	**-117.7**	**23.1**	**-22.4**	**-57.9**	27.1	**16.3**	27.2	**22.3**	27.6	**24.4**
11	-	-	-	-	-	-	**-243.2**	27.1	42.3	**-134.8**	34.0	43.0	46.1	42.5	44.3	42.4	43.6
12	-	-	-	-	-	-	**-232.1**	30.3	49.8	**-205.1**	38.6	50.7	48.6	50.1	52.6	50.0	51.6
13	-	-	-	-	-	-	**-237.3**	**-23.0**	28.0	**-210.4**	**-2.6**	29.8	**-0.7**	**-43.4**	**-3.9**	35.7	**14.3**
14	-	-	-	-	-	-	**-241.9**	**-25.0**	**24.8**	**-215.0**	**-4.6**	26.6	**-2.6**	**-45.4**	**-17.7**	**-292.5**	**6.4**
15	-	-	-	-	-	-	**-247.8**	**2.6**	28.7	**-220.9**	**13.0**	30.0	27.1	**16.7**	**-321.5**	**17.6**	**-75.6**
16	-	-	-	-	-	-	**-245.9**	**11.0**	33.5	**-218.9**	**20.3**	34.6	35.7	28.4	**-324.8**	28.7	41.1

Note: H_{min} = 26.3 m

Table 6-26 Nodal Pressure of flexible design 1 and flexible design 2 under One Pipe Failure (m)

Node	Flexible design 1				Flexible design 2						
	2030		2050 North	2050 West	2030		2050 North			2050 West	
	Pipe 2-3	Pipe 2-6	Pipe 2-6	Pipe 2-3	Pipe 2-6	Pipe 9-10	Pipe 9-10	Pipe 11-12	Pipe 13-14	Pipe 5-9	Pipe 9-13
1	-	-	-	-	-	-	-	-	-	-	-
2	63.3	63.3	71.2	71.1	71.1	71.1	71.0	71.0	71.0	71.0	71.0
3	43.0	53.5	57.7	47.6	56.9	59.4	54.4	54.2	52.4	57.0	57.2
4	43.1	50.9	54.0	48.2	51.0	57.7	52.3	52.1	50.7	55.8	56.1
5	40.9	47.2	48.7	47.4	48.8	48.9	41.9	42.1	42.0	45.6	45.5
6	52.2	45.8	45.6	53.0	**7.0**	61.4	58.2	58.0	57.9	56.6	56.8
7	46.5	46.2	45.6	49.8	**7.2**	60.4	53.6	53.1	52.9	55.6	55.9
8	43.1	47.9	49.2	48.0	40.0	51.3	44.4	44.1	43.3	45.3	46.5
9	40.5	44.3	44.1	47.1	**8.2**	**-20.4**	**-45.1**	32.9	32.9	**16.8**	45.3
10	**26.2**	**26.3**	25.7	29.5	**-10.0**	35.1	28.1	27.0	27.1	**21.8**	26.6
11			50.1				37.2	**-2.6**	**19.6**		
12			50.4				40.4	41.2	**20.6**		
13			37.0	38.4			36.9	36.8	37.1	**8.2**	**10.8**
14			36.8				29.2	29.4	**-30.4**		
15			36.8				27.6	28.0	**-27.7**		
16			38.1				28.0	28.5	**-8.4**		
17				28.1						**13.3**	**14.5**
18				29.6						36.2	36.2
19				27.6						**1.2**	**3.3**
20				27.0						**-3.1**	**-0.5**

Note: H_{min} = 26.3 m

The embedded additional capacity in the network for the two flexible designs creates value for the system, which was illustrated as nodal pressure improvement when the system operates in an uncertain environment. For inflexible design, nodal pressures under numerous scenarios of pipe failure are below the minimum required pressure. For flexible design 1, almost all the nodal pressures meet the minimum pressure requirement. It was found that nodal pressures were much higher than those of flexible design 2 under maximum water demand scenario when no pipe failure happens. It may not be economical to install such large capacity in the network to respond to uncertainties. For flexible design 2, nodal pressures can not meet minimum pressure requirement under a limited number of scenarios of pipe failure and also only at a small number of nodes. However, it was much cheaper than flexible design 1. Only after some strategies were applied did flexible design 2 meet the minimum pressure requirement.

6.2.6 Computational efficiency of the proposed method

The computational efficiency of the proposed method is compared with that of Monte Carlo simulation, Latin Hypercube sampling, and First Order Reliability method. The computational demand is indicated by the required hydraulic simulation time. It was suggested that several thousand hydraulic simulations is required for Monte Carlo simulation and about fifty hydraulic simulations is required for Latin Hypercube sampling (Kapelan et al. 2005). In the case study, there are 42 components in the network. Therefore, 210000 (42*5000) hydraulic simulation time is required for Monte Carlo simulation, 2100 (42*50) hydraulic simulation time is required for Latin Hypercube sampling, and 42 hydraulic simulation time is required for First Order Reliability Method. However, the required hydraulic simulation time of the proposed method is 3 in Flexible Design 1 and 5 in Flexible Design 2. The computational efficiency of the proposed method is obvious. The computational demand of these four method is summarised in Table 6-27.

Table 6-27 Computational demand comparison of the four methods

	Hydraulic Simulation Time
Monte Carlo simulation	210000
Latin Hypercube sampling	2100
First Order Reliability Method	42
Proposed flexibility-based optimisation model	3~5

6.3 Summary

This chapter applied the proposed flexibility-based optimisation model to achieve flexible design of a water distribution system. The purpose of this study was to demonstrate the applicability of the methodology to real system design and also show its computational efficiency to produce flexible design. Flexibility was achieved by embedding additional capacity in the system, which could then be used to reduce the risk of supply deficiency from uncertainties. The level of flexibility was linked to the control parameters for the flexibility-based optimisation model. The optimisation was solved by a Genetic Algorithm. The optimal solution was achieved by minimising the life cycle cost when satisfying all other constraints. The life cycle refers to planning period in the thesis.

Three designs were developed based on the different methods. Inflexible design comes from a least cost design under expected scenario, where uncertain parameters were taken as their expected values and pipe failure was not included. Flexible design 1 and Flexible design 2 were developed by applying the proposed flexibility-based optimisation method, where uncertain water demand and pipe failure were considered. However, Flexible design 1 was a system designed without tanks, while Flexible design 2 included tanks. It was found that flexible design 2 improved the hydraulic performance more than the inflexible design under the expected scenario. Although the hydraulic performance was not as good as that of flexible design 1, flexible design 2 was significantly cheaper. It seemed more economical to distribute the required additional capacity to the network capacity, tank, and pumping station.

Chapter 7 Conclusions and Future works

7.1 Summary

This thesis discussed the concept of flexible design and further developed methodologies for designing flexibility in UWDS for an uncertain environment. The basic components in UWDS and their designs had been widely studied in the literature. Nevertheless, this thesis identified some gaps with regard to flexible design in a water distribution system:

(1) Flexibility in UWDS has not been well studied. Especially, how flexibility is defined and measured in UWDS. Without a clear definition, it is easy to confuse flexible design with other designs (e.g. reliable design). Furthermore, it is difficult to identify flexibility sources. To achieve flexible design in UWDS, there was a need to give a clear definition of flexibility. Different flexible designs can be generated, which deliver different values. Therefore, there was also a need to develop some measures to quantify the value of flexible design, which can then be used to guide water engineers to find the desired flexible designs.

(2) Flexibility sources in UWDS have not been well explored, although there are many successful applications of flexible design in other engineering areas to respond to uncertainties. These applications certainly showed that flexible design can create value because of high uncertainties in the lifecycle. There was a need to analyse different sources in UWDS and their potential to provide flexibility.

(3) To evaluate different flexible designs, it was necessary to firstly develop a method to model uncertainties. There are numerous uncertainties in UWDS, thus it would be computational demanding to model them by the traditional methods (e.g. MCS). As a result, it would also consume huge computational time to evaluate different flexible designs. There was a need to develop a new method, which can efficiently model uncertainties in UWDS.

(4) There are numerous flexibility sources in UWDS, which results in large design space for the problem of flexible design in UWDS. As a result, it is difficult to efficiently compare different flexible designs one by one. There was a need to develop an optimisation model to help water engineers identify the desired flexible designs.

Flexible design for UWDS is motivated by the fact that it is always difficult to make good decisions on system design to enable it give a satisfactory service when there are uncertainties (uncertain water demand and component failure) existing in the life cycle, since these uncertainties are not easily predicted accurately in advance. The life cycle refers to planning period in the thesis. This thesis introduced methodologies that enable water engineers to embed flexibility in the system to respond to uncertainties, thus bridging the gap in the literature and the practice about the availability of an applicable tool for generating flexible design in UWDS.

Numerous definitions for flexibility are found in different systems, until now no definition was fully accepted. The thesis reviewed the definitions from different areas, and discussed their advantages and disadvantages. Based on the discussions, some criteria were summarised, which could then be used to help engineers to check whether a clear definition was given or not. The criteria were:

- Drivers for the change: the reasons flexibility was required
- The mechanism for change: explain the characteristics of the change
- Metrics to measure flexibility: how the flexibility was quantified and compared
- High portability: ease to be applied in other areas
- Good problem representation

According to the criteria, Flexibility in UWDS was defined as:

‘The ability of the system to enable cost-effective changes (configuration or operation) to both internal uncertainties (pipe roughness and component failure) and external uncertainties (nodal demands)’.

This definition clearly stated the drivers of the change, i.e. from both internal (in the system) and external (out of the system). The mechanism for the change was indicated by the required change on configuration or operation. The metrics to measure flexibility were indicated by the cost-effective changes. High portability was achieved by applying some general words, i.e., internal, external, and cost-effective. A good problem representation was achieved by stating the specific uncertainties in UWDS, i.e., nodal demand, pipe roughness, and component failure.

The thesis then discussed different measures to indicate the value of flexible design. They were divided into two classes: indicator-based and performance-based. The indicator-based measures generally did not have strong theoretical foundations. On the contrary they were developed considering practical requirements. The performance-based measures were based on the simulation result of the system. The advantages and disadvantages were also discussed in the thesis.

The thesis reviewed some methods for modelling uncertain nodal demands and component failures in UWDS and developed an efficient method to model these uncertainties. Uncertain nodal demands were handled by incorporating “safety margins” on the expected values for these uncertain parameters. The magnitude of safety margins indicated the capability of the system to respond to uncertain nodal demands. The performance of the system under component failure was approximated by analysing the performance of two independent spanning trees. The magnitude of inputs in nodal demands under these two spanning trees indicated the capability of the system to respond to component failures.

Identification of flexibility sources is a very important part for designing flexibility in the system. With the identified flexibility sources, less computational demanding was required for flexibility evaluation. For UWDS, there are too many components in the system, which make it computational difficult to find optimal combination of different flexibility sources for the system. A method was required to distinguish different flexibility sources. The flexibility sources with high flexibility value can then be screened out for further evaluation. The flexibility identification methodology developed in the thesis consisted of the following four steps:

Step 1: Defining the criteria for network performance and developing a value matrix for evaluating flexibility. When the nodal pressure was above the required minimum pressure, it was assumed that the required flow could be supplied from the node. Also nodal pressures must be above the required minimum pressures not only under the most likely condition, but also under some extreme conditions. These extreme conditions are caused by uncertainties from nodal demands, pipe roughnesses, and component failures. Flexibility measures can be developed for the improvement of the hydraulic performance of the system under these uncertainties. Two flexibility measures were introduced.

Step 2: Identifying the main uncertainties and describing possible future states over time. Major uncertainties in the design of UWDS were nodal demands, pipe roughness coefficients, and component failure. Uncertain nodal demands and uncertain pipe roughness coefficients could be described by some distributions. In this method, only extreme conditions were considered. That was to say that high nodal demands and low pipe roughness coefficients were used to check whether nodal pressures met the required minimum pressures or not. Component failure (mainly pipe) was simulated by setting pipe status as closed. The method only considered the condition where only one pipe was taken out of service.

Step 3: Developing a least cost solution where the expected values were used for nodal demands and pipe roughness coefficients and no component failure occurred in the system. For this least-cost solution, pressure on each node was above the required minimum pressure. Then, high nodal demands, low pipe roughness coefficients, and component failures were applied to the system, and the nodal pressures under these conditions are summarised. This process tried to develop a base design, which can be used to compare its flexibility value with other designs. The least cost solution was then generated by an optimisation model, using expected values as inputs for nodal demands and pipe roughness coefficients and setting status of all pipes as open.

Step 4: Applying different flexibility sources and calculating the flexibility measures after these flexibility sources. The step provided a quantitative view of different flexibility sources within the system to enable it respond to uncertainties in Step 2. This can help water engineers reject some flexibility sources that have low flexibility value while keeping those with high flexibility value for further evaluation and analysis. These high flexibility sources could then be put into a flexibility-based optimisation model, which was introduced in Chapter 5. The optimisation model identifies the optimal design with best combination for these flexibility sources.

The thesis finally developed a flexibility-based optimisation model based on GA process to identify flexible design in UWDS. A two-loop computational flexibility-based optimisation model was developed to provide an applicable tool for flexible design in UWDS (see Figure 7-1). The internal loop optimised the current system development (ready to be implemented) over its lifecycle. The inner loop was solved by Genetic Algorithm to search the optimal current system development. The external loop shows movement on the current time. Its main function was updating the information about current existing system condition and the environment condition in a new lifecycle.

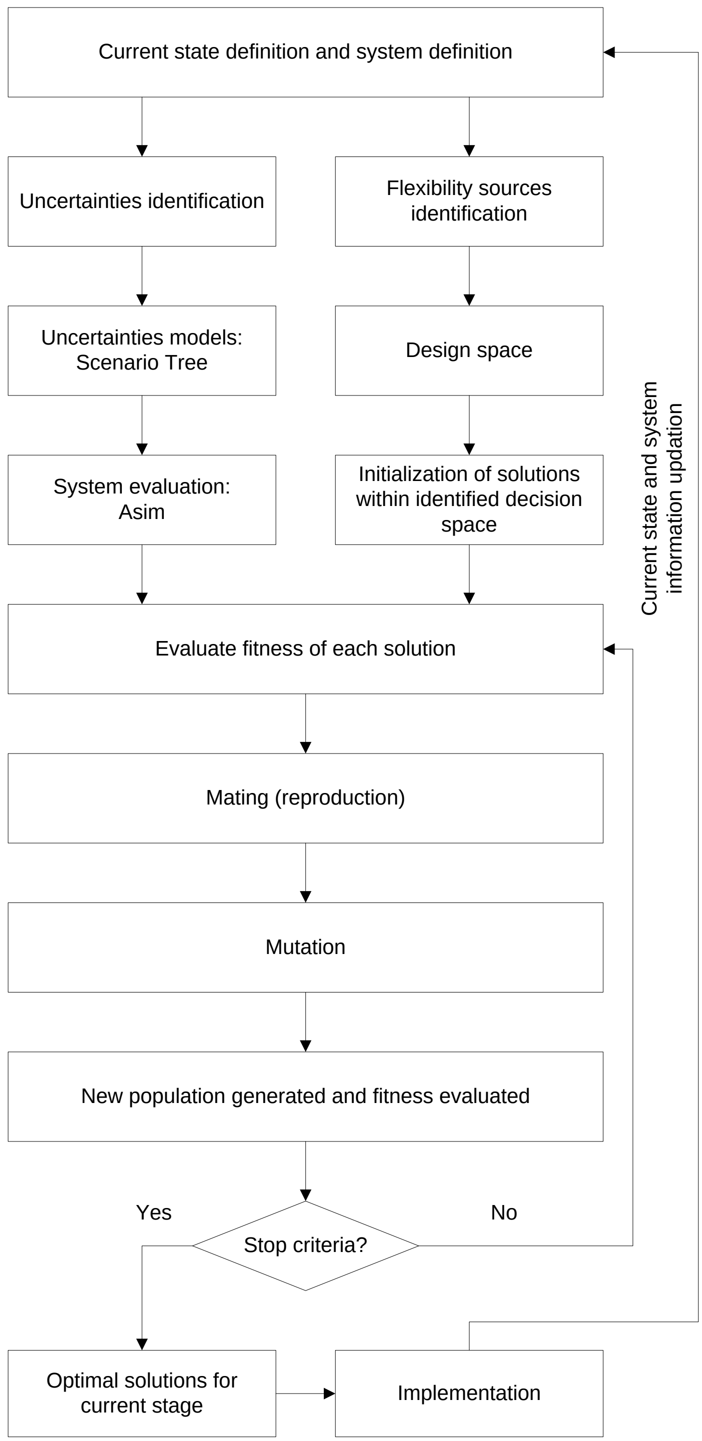

Figure 7-1 Computational framework of the proposed screening model

7.2 Conclusions

Robustness/reliability and resilience refer to the property of the system to meet functionality without changes, while adaptability and flexibility refer to the property of the system to meet functionality with changes. The difference between adaptability and flexibility is that changes for adaptability are from internal while changes for flexibility are from external. Although these could be used to distinguish the specific property of the system to respond to uncertainties, they are essentially similar. They all illustrate the property of the system to respond to uncertainties. In this thesis, flexibility is broadly defined. Any property of the system to respond to uncertainties could be viewed as one kind of flexibility, that is robustness/reliability, resilience, and adaptability are kinds of flexibility.

Ten possible flexibility measures are proposed in this thesis. Connectivity measure, SC and RL are developed based on the practical requirements, which do not require running hydraulic simulation for WDS. However, they do not interpret characteristic of flexibility properly. They may not be suitable flexibility measures for both flexibility identification and flexibility optimisation in UWDS. All others are developed based on pressure on the node or flow in the pipe, which require hydraulic simulation of WDS. Entropy measure, Resilience measure, PDN and PMPN require less hydraulic simulation, while $\sigma(P_i)$, $\sigma(P_{\min})$, and $\sigma(P_{\mathrm{var}})$ require more hydraulic simulation. Entropy measure considers only component failure and Resilience measure may not be suitable for multi sources, therefore they may not be suitable for both flexibility identification and flexibility optimisation in UWDS. Considering their high computational demand, $\sigma(P_i)$, $\sigma(P_{\min})$, and $\sigma(P_{\mathrm{var}})$ are not chosen as flexibility measures for this thesis. Although both PDN and PMPN are computationally efficient, PMPN interprets characteristic of flexibility better.

The proposed integral uncertain modelling is more computational efficient. The computational demand is indicated by the required hydraulic simulation time. It was suggested that several thousand hydraulic simulations is required for Monte Carlo simulation and about fifty hydraulic simulations is required for Latin Hypercube sampling (Kapelan et al. 2005). In the case study, there are 42 components in the network. Therefore, 210000 (42*5000) hydraulic simulation time is required for Monte Carlo simulation, 2100 (42*50) hydraulic simulation time is required for Latin Hypercube sampling, and 42 hydraulic simulation time is required for First Order Reliability Method. However, the required hydraulic simulation time of the proposed method is 3 in Flexible Design 1 and 5 in Flexible Design 2. The computational efficiency of the proposed method is obvious.

The major components in UWDS are pipes, pumps, storages, and valves, which can be divided into energy-generating and energy-consuming components. Flexibility in UWDS has been discussed for each component, along with some basic combinations of these components. Because of uncertainties in UWDS, there are different requirements for energy to supply water to the system. Flexibility is indicated by the capability of the system to adjust the generated or the consumed energy. That is to say that flexibility can be maximised if the energy-generating and energy-consuming components are optimally combined. However, these optimal combinations differ from system to system. Also, since components in UWDS are integrated with each other, optimal system flexibility may not be achieved by only adding optimal flexibility from each component. The inter-relationships between the components have to be considered when identifying flexibility sources for the system. Thus an efficient method is developed to identify flexibility sources for UWDS. It was concluded that high value flexibility sources could be identified by the proposed method. These identified flexibility sources may not be useful for the flexibility-based optimization model to design a system, but it might be a powerful tool to locate the weak points in the system or provide better update options during rehabilitation of the system.

Lifecycle costs for Flexible designs are higher than the inflexible design. The difference in cost between inflexible design and flexible designs is the cost to provide flexibility to reduce the risk of supply deficiency when the real water demand exceeds the designed delivery capacity and one pipe is taken out of the service. It was found that network capacity in the first stage was smallest in the inflexible design and largest in flexible design 1. The additional network capacity in the two flexible designs enables the system to cost-effectively respond to uncertainties from water demand and pipe failure. The cost difference between flexible design 1 and flexible design 2 is the benefit for incorporating tanks in the system. Network capacity in flexible design 2 was only required to respond to a designed demand, which was equal to the expected daily maximum demand, multiplied by a safety margin coefficient. The network capacity in flexible design 1 was required to respond to a designed demand which was equal to the expected maximum hourly demand, multiplied by a safety margin. The later one was much higher than the former. As a result, the designed capacity in the network was much larger in flexible design without tank than that in flexible design with tank.

The embedded additional capacity in the network for the two flexible designs creates value for the system, which was illustrated as nodal pressure improvement when the system operates in an uncertain environment. For inflexible design, nodal pressures under numerous scenarios of pipe failure are below the minimum required pressure. For flexible design 1, almost all the nodal pressures meet the minimum pressure requirement. It was found that nodal pressures were much higher than those of flexible design 2 under maximum water demand scenario when no pipe failure happens. It may not be economical to install such large capacity in the network to respond to uncertainties. For flexible design 2, nodal pressures can not meet minimum pressure requirement under a limited number of scenarios of pipe failure and also only at a small number of nodes. However, it was much cheaper than flexible design 1. Only after some strategies were applied did flexible design 2 meet the minimum pressure requirement. It is recommended that the required additional capacity to reduce the risk from uncertainties should be distributed to network capacity, tank, and pumping station.

7.3 Contributions

The thesis tried to develop a new methodology, which could generate flexible design for UWDS. The resulted flexible design has improved pressure performance under uncertainty. The methodology proposed a design process, which could help water engineers not only consider uncertainties but also identify proper responses to them.

Flexibility was defined in numerous engineering systems. However, there is not a proper definition of flexibility for UWDS. The thesis tried to develop a definition of flexibility for UWDS, not only covering the key properties of flexibility but also interpreting well the characteristics of UWDS.

There were numerous system performance measures for UWDS in the literature. However, their applicability for flexibility identification and flexibility optimisation has not been studied. The thesis proposed different possible flexibility measures and compared them on computational demand and applicability for flexibility identification and flexibility optimisation.

Some methods were developed to model either uncertain nodal demand and pipe roughness or component failure. However, they have not been well handled within one model. The thesis developed an integral uncertainty model to consider all these uncertainties. The model applied "robustness" concept to transfer the stochastic problem into a deterministic one, by incorporating "safety margins" into the uncertain nodal demands. The model also approximated the system performance under component failure, by only checking the performance of two s-t spanning trees with partial or full load demand. As a result, these two techniques generated great computational saving.

Components in UWDS are assigned with their basic functionality, e.g. using pipe to transfer water. However, they have not been studied on their potential to improve pressure performance under uncertainties. In the thesis, major components in UWDS were explored on their potential to provide flexibility under uncertainties.

Components in the UWDS are integrated with each other and with high complexity. It is difficult to analyze flexibility value on the element-level that which component in the system can provide more flexibility. Also this process is computational demanding. The thesis developed an efficient flexibility identification method, which consider inter-connection among the different components.

There are numerous decisions for flexible design in UWDS. It is difficult, if not impossible to compare them one by one. The thesis developed a flexibility-based optimisation model to efficiently compare different designs and generate optimal flexible design. The resulting optimisation model incorporates the uncertainty modelling and identified flexibility sources into a GA process. Water engineers can then use this model to generate flexible design for UWDS. Furthermore, different flexible designs can be produced by simply setting different control parameters in the model. The model could be easily initialised and re-run until the satisfactory solution is obtained.

The thesis finally demonstrated the application of the developed methodologies in one case study for designing flexibility for UWDS. The optimal solution is presented and the performance is analyzed. The purpose is to show the applicability of the methodology and illustrate the advantages and disadvantages. After these discussions, future recommendations are suggested to improve and explore the current methodology.

7.4 Future research

The works done in the thesis is part of an ongoing research stream in engineering system designs, to use flexibility to respond to uncertainties. There are many opportunities to build on the works of this thesis and to further advance this stream of research in the future:

- The cost model used in this work is very rough. It allows quick calculation and does not have high requirement on collecting information to build the real cost model. It will be desirable to use a more sophisticated cost model to generate more accurate system design solutions. Such a more complex cost model has been developed by Clark et al. (2002). Operation costs for pipes should also be included into the model. An estimation of the expected repair cost was given by Kim and Mays (1994). With enough information, the more accurate cost model can be built and then incorporated into flexibility-based optimisation model, which should provide more accuracy to evaluate different flexible designs.

- The work deals with the investment cost only for pipes because it constitutes the majority for parts in UWDS. It does not consider the cost from operation, mainly through energy cost from pump operation. Neglecting cost from operation, the proposed flexibility-based optimisation model may exclude some valuable solutions. General equations for pump construction cost and pump operation cost are given by Ostfeld (2005).

- Capture non-monetary flows: in this thesis, the main objective was to minimise the life-cycle cost while setting other performances as constraints. However, the economic metrics are not the only important aspects for designing a water distribution system. There are many other flows, which may also be very important to stakeholders, such as potential development to the local economy. Multiple types of value metrics (e.g., monetary flow, social-political flow) should be included in future work. The trade-off between these different metrics should be evaluated while incorporating different stakeholders and finally illustrated on the model control parameters to generate desired flexible design for a water distribution system.

- Uncertainty modelling: the uncertainty level for water demand is estimated, which is not based on historical data of similar water distribution systems. One future research area is to develop more realistic uncertain water demand models using historical data. One possible approach is to apply a Bayesian learning framework to update model parameters as actual data becomes available. Ideally, the uncertainty and learning models need to be calibrated against historical data if available.

- Incorporating decision variable for the pumping station: in the current research, the location of pumping station and its power head is pre-determined. In the future research, these parameters should be treated as decision variables. One challenge is to realise automatic modification on the layout of the system when the pumping station is planned in different parts of the system. Currently, it is very difficult to achieve this when the model is on-going. One simple method is to create several alternatives with pumping stations on different locations and then optimise them individually.

- Although the methodologies developed in this research can lead to flexible design, it has the following limitations: (1) the global optimality cannot be guaranteed. The number of stages and the number of state on each stage are limited. For these reasons, the solution from the proposed flexibility-based optimisation model may not be the optimal global solution; (2) the proposed flexibility-based optimisation model will result in different optimal solution when starting with different initial solutions in Genetic Algorithms. Therefore, to guarantee robustness, the model needs to be run several times to choose the best solution; (3) performance of the flexible design can be improved by incorporating some hydraulic simulations under failures of some major components. However, its side effect is the decreasing of computational efficiency.

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Appendix I: Comparison study of different flexibility measures

1. Entropic measure

$$\hat{S} = \sum_{j=1}^{N} \frac{Q_j}{Q_0} S_j - \sum_{j=1}^{N} \frac{Q_j}{Q_0} \ln \frac{Q_j}{Q_0} \tag{I-1}$$

where

$$S_j = -\sum_{i=1}^{n(j)} \left(\frac{q_{ij}}{Q_j} \right) \ln \left(\frac{q_{ij}}{Q_j} \right) \tag{I-2}$$

When the configuration of UWDS is known and demand is distributed to each node, one hydraulic simulation is required to obtain all parameters in the equation (I-1) and (I-2). That is to say it is low computational demand, thus it has potential to be applied for flexibility identification and flexibility optimisation. However, this measure was developed mainly for component failure (Awumah et al. 1991). The applicability of this measure to both uncertain nodal demand and component failure was not approved. Therefore, this measure may not be suitable for flexibility identification and flexibility optimisation in the thesis, considering both uncertain nodal demand and component failure.

2. Resilience measure

Gravity system:

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^* (h_i - h_i^*)}{\sum_{k=1}^{n_r} Q_k H_k - \sum_{i=1}^{n_n} q_i^* h_i^*} \tag{I-3}$$

Pumping system:

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^* (h_i - h_i^*)}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} (P_j / \gamma) - \sum_{i=1}^{n_n} q_i^* h_i^*} \tag{I-4}$$

Similar with entropic measure, only one hydraulic simulation is required to obtain all parameters in the equation (I-3) and (I-4). Thus it is low computational demand. However, it is not suitable to apply for multiple sources (Jayaram and Srinivasan 2008). Also it is just an indicator to show potential of the system to respond to uncertainties, which could not help decision makers know what kind of uncertain level the system could respond to. Thus resilience measure may also not be suitable for flexibility identification and flexibility optimisation in UWDS.

3. Connectivity measure

$$P_c = \sum_{i=1}^{N_c} p_i \tag{I-5}$$

No hydraulic simulation is required to calculate Eq. (I-5). Two efficient algorithms had been developed by Wagner et al. (1988) to calculate connectivity measure. However, for water distribution systems, connection to a source is only a necessary, not a sufficient condition to ensure that water is provided on the nodes. Therefore, this measure may not be suitable for flexibility identification and flexibility optimisation in UWDS.

4. Surplus Capacity

$$SC = \min_{i=1}^{M}\{SC_i\} = \min_{i=1}^{M}\left\{\frac{DP_i - DP_i^{\min}}{DP_i^{\min}}\right\} \tag{I-6}$$

No hydraulic simulation is required to calculate this measure. It implies that the system would have more capacity to respond to uncertainties if it has larger minimum surplus capacity in its components, which may not be applicable to water distribution systems, since they are complex and highly interconnected. Although it is computational efficient, it may not be a proper measure for flexibility identification and flexibility optimisation in UWDS.

5. Reliable Loop

$$RL = \min\{n_i\},\ \mathrm{i} = 1, 2, \ldots, NN \tag{I-7}$$

This measure is simplified from connectivity measure. Also no hydraulic simulation is required. The node is connected to the system, which does not guarantee that sufficient water could be provided from that node. Thus it is also not suitable for flexibility identification and flexibility optimisation in the thesis.

6. Pressure on Demand Node

$$PDN = P_i - P_i^{fix} \tag{I-8}$$

When the configuration of UWDS is known and demand is distributed to each node, one hydraulic simulation is required to obtain nodal pressures. It is low computational demanding. More importantly, it can directly illustrate whether the required demand on one specific node is provided or not. However, there are numerous nodes in the system. The most vulnerable node is not illustrated by this measure. Thus this measure may be an effective flexibility measure for flexibility identification but not for flexibility optimisation in UWDS.

7. Pressure on Minimum Pressure Node

$$PMPN = P_{\min} - P_{\min}^{fix} \tag{I-9}$$

There are numerous demand nodes in a water distribution system. The most vulnerable node is the minimum pressure node, since it could easily drop below the required minimum pressure under emergency. Thus this measure could catch up more characteristic of flexibility in UWDS, compared with the sixth measure. And there is only one hydraulic simulation required. As a result, it is an effective flexibility measure for flexibility identification and flexibility optimisation in UWDS.

8. Variation of nodal pressure

$$F_{P_{\mathrm{var}}} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{i,j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{i,j}^{fix})^2} - \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{i,j} - \frac{1}{n}\sum_{j=1}^{n}P_{i,j})^2} \tag{I-10}$$

This value is calculated to use Monte Carlo (MC) simulation or Latin Hypercube (LH) simulation. It was suggested that several thousand hydraulic simulations is required for MC and about fifty hydraulic simulations is required for LH (Kapelan et al. 2005). More variation there is on the node under uncertainties, more possibility the pressure on the node drops below the required minimum pressure. Thus this measure could illustrate flexibility value. However, considering its high computational demand, this measure may be suitable for flexibility identification but not for flexibility optimisation in UWDS.

9. Variation of nodal pressure on the minimum pressure node

$$F_{P_{\mathrm{var}}} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\min,j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{\min,j}^{fix})^2} - \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\min,j} - \frac{1}{n}\sum_{j=1}^{n}P_{\min,j})^2} \tag{I-11}$$

This measure is a particular value of the eighth measure and its computational demand is same with the eighth measure. The minimum pressure node is more likely to drop below the required minimum pressure, compared with other nodes in the system. Considering its high computational demand, this measure may be suitable for flexibility identification but not for flexibility optimisation in UWDS.

10. Variation of nodal pressure on the most variable node

$$F_{P_{\text{var}}} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\text{var},j}^{fix} - \frac{1}{n}\sum_{j=1}^{n}P_{\text{var},j}^{fix})^2} - \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_{\text{var},j} - \frac{1}{n}\sum_{j=1}^{n}P_{\text{var},j})^2} \tag{I-12}$$

This measure is a particular value of the eighth measure and its computational demand is same with the eighth measure. The node with most variation is also more likely to drop below the required minimum pressure, compared with other nodes in the system. Similar with the eighth and ninth measure, because of its high computational demand, this measure may be suitable for flexibility identification but not for flexibility optimisation in UWDS.

Appendix II: Comparison study of different pairs of spanning tree from one connected network

There can be several different pairs of spanning trees for a given network, and there is no strict rule developed for this decomposition. Here a study was made to show the effect of different numbering by the depth-first search (DFS) on the final pair of spanning tree. The example network was shown in Figure II-1.

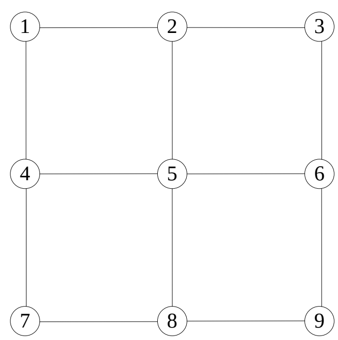


Figure II-1 An example of a connected network

Since DFS does not restrict which next node should be firstly visited, as illustrated in Figure II-2. For node 1, there are two options to search for its next node, either from node 1 to node 2 or from node 1 to node 4. This characteristic is similar on other nodes.

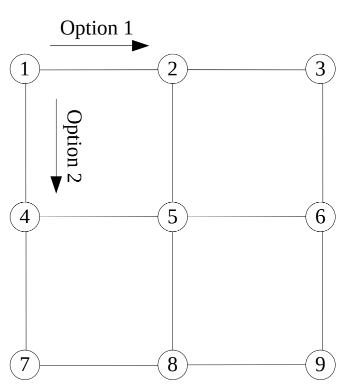
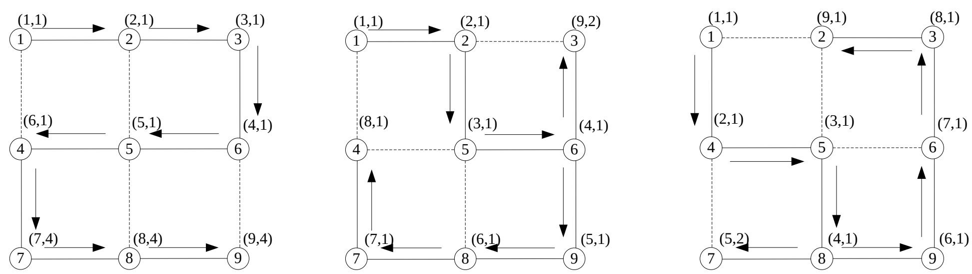


Figure II-2 Search option from node 1

Thus it could generate numerous depth-first search trees from the connected network above. Here we just list three of them, shown in Figure II-3. In the figure, s = 1 and t = 2. Tree edges are indicated by solid lines and each vertex *v* of the tree is labelled by the pair (*pre*(*v*), *low*(*v*)).



a. Tree 1 b. Tree 2 c. Tree 3

Figure II-3 Depth-first search trees

The second process in st-numbering for these three depth-first search trees is illustrated in Figure II-4. The final s-t numbering for them is shown in Figure II-5.

VERTEX ADDED	LIST
	1-,2
3	1-,3,2+
4	1-,4,3+,2+
5	1-,5,4+,3+,2+
6	1-,6,5+,4+,3+,2+
7	1-,6-,7,5+,4+,3+,2+
8	1-,6-,7-,8,5+,4+,3+,2+
9	1-,6-,7-,8-,9,5+,4+,3+,2+

a. Tree 1

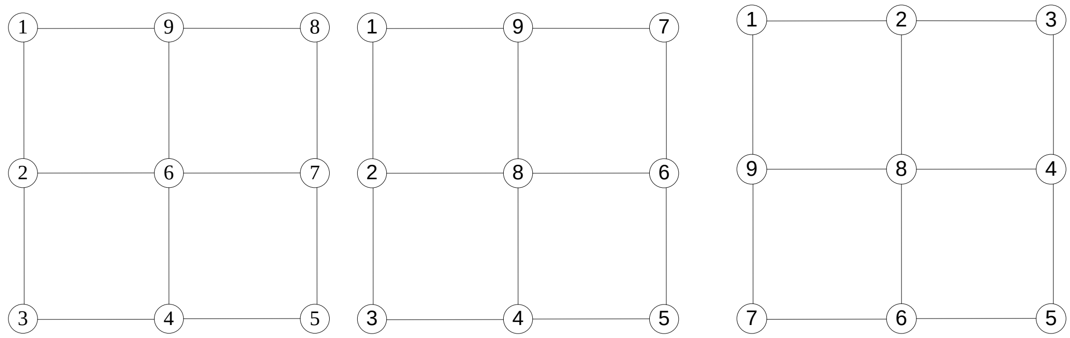
VERTEX ADDED	LIST
	1-,2
3	1-,3,2+
4	1-,4,3+,2+
5	1-,5,4+,3+,2+
6	1-,6,5+,4+,3+,2+
7	1-,7,6+,5+,4+,3+,2+
8	1-,8,7+,6+,5+,4+,3+,2+
9	1-,8,7+,6+,5+,4-,9,3+,2+

b. Tree 2

VERTEX ADDED	LIST
	1-,2
3	1-,3,2+
4	1-,4,3+,2+
5	1-,4-,5,3+,2+
6	1-,6,4+,5,3+,2+
7	1-,7,6+,4+,5,3+,2+
8	1-,8,7+,6+,4+,5,3+,2+
9	1-,9,8+,7+,6+,4+,5,3+,2+

c. Tree 3

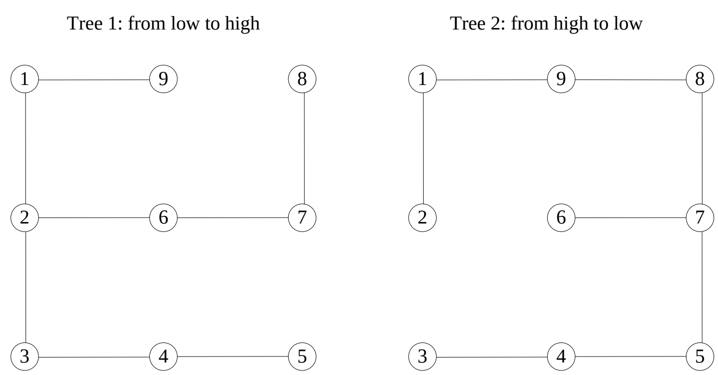
Figure II-4 The list L generated by the second process of the s-t numbering algorithm



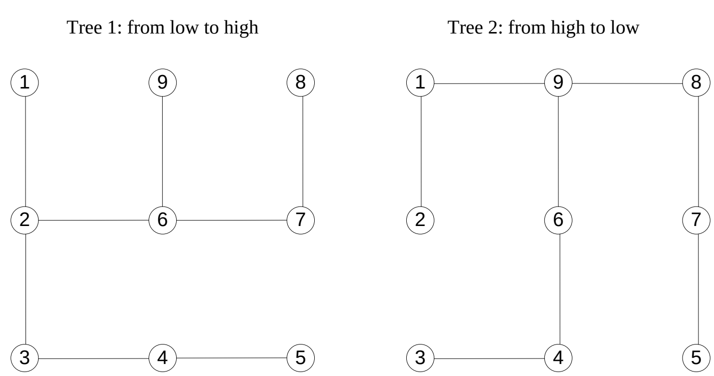
a. Tree 1 b. Tree 2 c. Tree 3

Figure II-5 The resulting s-t numbering for the network

From each network after s-t numbering, there are also several pairs of spanning trees. For example, two pairs of spanning trees for Tree 1, 2, and 3 are illustrated in Figure II-6, II-7, and II-8.

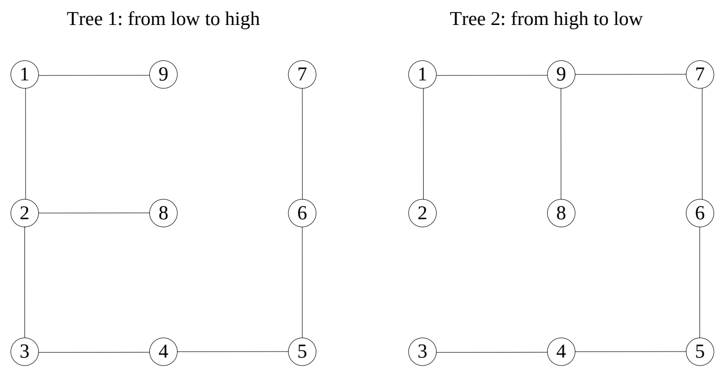


a. Pair 1 of two spanning trees

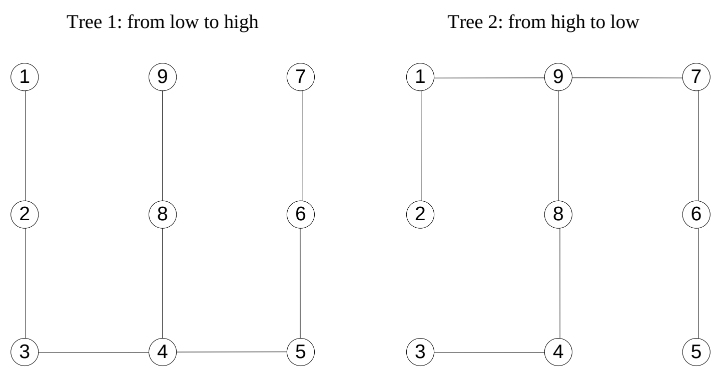


b. Pair 2 of two spanning trees

Figure II-6 Two pairs of spanning trees from Tree 1

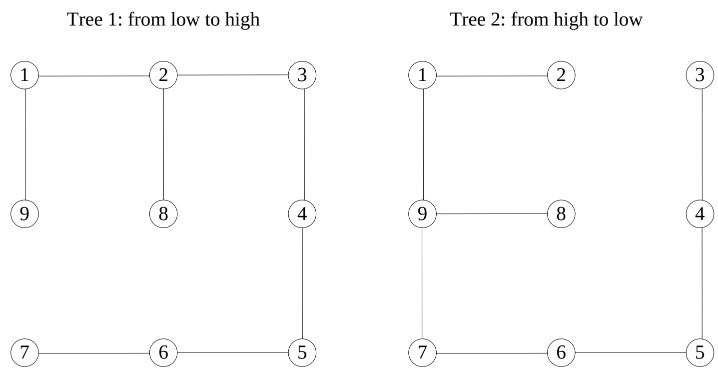


a. Pair 1 of two spanning trees

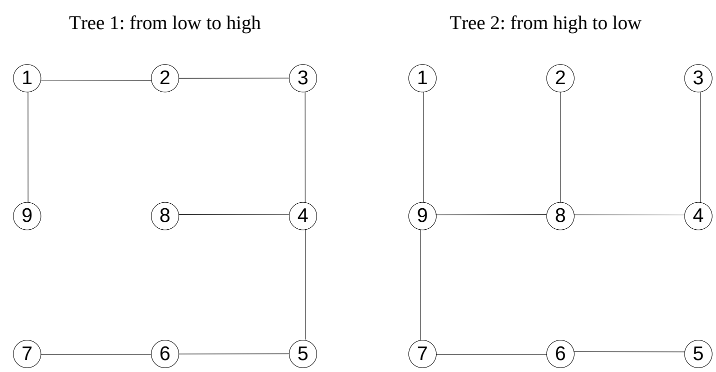


b. Pair 2 of two spanning trees

Figure II-7 Two pairs of spanning trees from Tree 2



a. Pair 1 of two spanning trees



b. Pair 2 of two spanning trees

Figure II-8 Two pairs of spanning trees from Tree 3

A pair of same spanning trees could be generated from different depth-first search trees, for example, pair 1 of spanning trees from Tree 2 is same with pair 1 of spanning trees from Tree 3. There is no strict or approved rule developed for the best choice of a pair of two spanning trees, although Kessler et al. (1990) proposed some general guidences. However, they were not approved. That is to say there is no way to determine the best pair of trees prior to a full hydraulic evaluation of each pair. Thus the thesis just tried to maximise the number of overlapping edges between the two trees.

Appendix III: GA parameters used in the case study

Table III-1 GA parameters of inflexible design

Parameters	Values
Popsize	200
Maxgen	20000
Crossover rate	0.8
Mutation rate	0.01

Table III-2 GA parameters of flexible design 1

Parameters	Values
Popsize	200
Maxgen	20000
Crossover rate	0.8
Mutation rate	0.01

Table III-3GA parameters of flexible design 2

Parameters	Values
Popsize	200
Maxgen	20000
Crossover rate	0.8
Mutation rate	0.01