

**THE PROPOSED RESILIENCE ANALYSIS METHODOLOGY
AND ITS APPLICATION TO THE SASKWATER PUMPING STATION**

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By

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ABSTRACT

Resilience engineering first appeared as a new approach for both system design and system safety in the last decade. One of the first substantive publications on resilience as applied to engineering was “Resilience Engineering: Concepts and Precepts” [Hollnagel et al. 2006]. Hollnagel, Woods, and Leveson developed the basic concepts behind resilience engineering in order to understand and prevent tragedies such as the Columbia Challenger accident and the September 11 terrorist attack.

In its present stage, resilience engineering has several fundamental problems. 1. There is not an appropriate definition for resilience. 2. The differences between resilience and other similar concepts are not clarified. 3. There is no quantitative method which can measure resilience. The three questions need to be addressed in order to advance the concept of resilience engineering and form a theoretical concept to an applied science. These three issues then form the foundation of this thesis.

As a first step, a resilience definition is presented based on the concepts of system function and damage. Then, the differences between resilience and five similar concepts (reliability, robustness, repairing, redundancy, and sustainability) are clearly elaborated. As a last step, a method for quantifying resilience is proposed in the form of a resilience index. This method exclusively measures system resilience by analyzing the system recoverability from two points of view: reconfiguration and replacement of components.

In order to illustrate the approach to and definitions of resilience, an actual application is considered: a water pumping station operated by SaskWater in Saskatoon, Saskatchewan (the Clarence Booster Station). This pumping station is a complicated system consisting of mechanical electrical and chemical subsystems. The resilience of Clarence Booster Station is analyzed using the proposed definition of resilience and resilience index.

This thesis is just an initial step establishing a comprehensive definition (qualitatively and quantitatively) for resilience. The resilience index so defined in this work appears to have potential but much more scrutiny and refinement must be pursued to ensure that it is truly applicable to more universal engineering applications.

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It is a pleasure to thank the many people who helped me to make this thesis possible.

In my time of studying resilience and writing my thesis, the most frequent word appeared in my mind was “struggling” or “suffering”. There was a time (Dec, 2008) I was so desperate. I met the first big challenge in my research. Being a M.Sc. student, I did not change my status from undergraduate who simply depend on answers from professors to “a project manager” who steer the master research. Thank to the talks with my supervisor Dr. Richard Burton and Dr. W.J. Zhang. They helped me grow with their encouragement, sound advice, good teaching, good company, and lots of good ideas. I would have been lost without them.

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In my life in Canada, my family are always caring me in China. My dad and mom bore me, raised me, support me, taught me, and love me. I wish I can back to them soon and they will be healthy and happy.

Dedicated to

My father Junmin Gao and mother Ming Li

My grandfather Jiwen Gao and grandmother Lanfang Zhang

For their constant love and unwavering understanding

Wish them healthy and happy

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ACRONYMS

ARV	Air Release Valve
AWWA	American Water Works Association
CBS	Clarence Booster Station
CTCS	Chemical Test and Control System
EMFM	Electromagnetic Meters
GV	Gate Valve
GPM	Gallon per Minute
LTEU	Landline Telephone Electronic Unit
PSI	Pound Square Inch
PRV	Pressure Relief Valve
PG	Pressure Gauge
PS	Pump System
PPM	Parts Per Million
REC	Resilience Engineering Consortium
SCADA	Supervisory Control and Data Acquisition
VFD	Variable Frequency Drive
WSS	Water Supply System

CHAPTER 1

INTRODUCTION

1.1 General motivation and problem statement

In recent years, the complexity of “systems” has generally increased; this has been accompanied by a tendency for increased interactions between subsystems. As a consequence, details of the system behavior and subsystem interactions cannot be readily observed or controlled by a single operator. Therefore, some systems’ behavior can be unpredictable resulting in catastrophic failures. Building a system which can recover from a failure and reestablish the original system function is a desirable goal. This recovery action is part of a concept which is defined as resilience and the process of designing or analyzing the system is called resilient engineering.

Resilience engineering first appeared as a new approach for both system design and system safety in the early twenty-first century. One of the first substantive publications on resilience as applied to engineering was “Resilience Engineering: Concepts and Precepts” [Hollnagel et al., 2006]. Hollnagel (research interests: cognition and safety), Woods (human factor, cognition), and Leveson (safety, human-computer interaction) developed the basic concepts behind resilience engineering in order to understand and prevent tragedies such as the Columbia Challenger accident and the September 11 terrorist attack.

The concept of resilience has been studied by researchers from various disciplines such as material science, biology and computer science. Several resilience engineering studies have been conducted in recent years. For example, an oil distribution plant in Brazil was examined for resilience [Mata et al., 2002]. This project presented resilience engineering as a safety management approach which focused on human failure analysis. In another application a study in hospital emergency departments [Anders et al., 2006] analyzed how the departments handled patient demands under limited time and resource pressure. The diversity of research areas leads to confusion in understanding resilience. Further, there is confusion over how resilience differs from concepts such as reliability, redundancy, etc. A lack of a formal definition has been an

obstacle in establishing resilience as an acceptable approach in system design. This then has been one of the motivations for the research presented in this thesis.

In 2008, a “Resilience Engineering Consortium” systematically discussed the current research on resilience which attempted to interpret and categorized resilient engineering into four challenges [REC, 2008]:

1. Conception of resilience: understand resilience and explore the characteristics of resilience.
2. Development of performance indicators: develop performance indicators that provide measurement of organization resilience performance.
3. Development of the repository of resilience-related data: develop processes to gather observational data to improve the understanding of resilience processes.
4. Development of tools to understand and interpret data: develop processes to explain the resilience-related data.

In this thesis an attempt is made to analyze some of the challenges by defining a new quantitative index for resilience. In addition, a physical example will be used to demonstrate the application of the index.

1.2 Objectives

Keeping in mind the challenges described above, the following objectives are considered for this study:

Objective 1: propose a new definition for resilience.

Objective 2: differentiate resilience from other similar concepts such as reliability, robustness and redundancy.

Objective 3: develop a new methodology for measuring system's resilience from a quantitative standpoint and apply this methodology to a specific application – the SaskWater Clarence Booster Station (CBS) in Saskatoon.

The first and second objectives are to understand the characteristics of resilience. The third objective is to discuss how to analyze resilience by a quantitative measurement. In Objective 3, the methodology is applied to the pumping station for demonstration purposes but it anticipated that the approach could be applied to any system.

It was recognized from the onset of this study that these objectives were simply a first step in a long process of establishing an all encompassing definition for resilience. It is hoped that the definition and resulting index introduced in this study will provide a basis for further discussion and development.

1.3 General research methodology

As resilience engineering is still in its infant stage, very few studies on this topic have been identified. As a result there is no established systematic analysis for resilience. Therefore, a wide and thorough review on the topic is necessary. Objective 1 is implemented by reviewing various current applications and definitions about resilience, and then providing a new definition for resilience.

Objective 2 is considered as a further step of resilience research. Some researchers have treated resilience as being interchangeable with concepts such as reliability, robustness, redundancy repairing, and sustainability which has lead to great confusion in interpreting the definition. In order to create a more coherent definition, Objective 2 is implemented by analyzing the basic meanings of reliability, robustness, redundancy, repairing, and sustainability, and by differentiating resilience from the five aforementioned concepts.

With Objective 3, the research example (Clarence Booster Station or CBS) is modeled in a descriptive manner and illustrates the operation of CBS. Two questions “How does CBS

operate?” and “Why is CBS operated in this way” are answered. From this descriptive model, the resilience of CBS is measured using the two following steps.

1. A “Failure analysis” is conducted, which aims to find out the relationship between system failure and possible damages. For example, if “maintaining pressure function” is lost in CBS, what are the possible causes (damages)?
2. A “Resilience measure” is developed, which measures the system recoverability (resilience) after certain damage. The recoverability is considered as the number of ways of recovery.

1.4 Structure of the thesis

The thesis will be organized as follows: Since a specific application is used throughout the thesis, Chapter 2 presents the background information about the SaskWater Clarence Booster Station (CBS). This information includes introduction of the water supply system and its subsystems such as the water distribution system, the water treatment system, the pumping station, and the water transmission system, and details of the Station such as the pump system and water quality control system. Chapter 3 analyses the concept of resilience. The current study of resilience is reviewed. A new definition for resilience is proposed from a system design and safety standpoint. The differences between resilience, robustness, reliability, redundancy, repairing, and sustainability are then examined. Several practical examples regarding the water supply system are used to assist the discussion. Chapter 4 is about the “CBS physical model”. This model illustrates the basic operation of CBS in a descriptive form. In Chapter 5, a resilience measurement methodology is described. Resilience is measured and represented as an index. In Chapter 6, the proposed resilience analysis methodology is applied to the SaskWater Clarence Booster Station. Chapter 7 summarizes the research, and provides conclusions and recommendations for future work.

CHAPTER 2

RESEARCH EXAMPLE: THE SASKWATER CLARENCE BOOSTER STATION

2.1 Introduction

This chapter provides detailed information about the research example of this thesis study, the SaskWater Clarence Booster Station (CBS). The objective of this chapter is to provide some background knowledge of the system which will be used as the working example throughout the thesis. Section 2.2 describes the water supply system (WSS). In this section, the subsystems and typical components of the WSS are introduced. In Section 2.3, a descriptive model of the Clarence Booster Station is introduced. Section 2.4 discusses the relationship between SaskWater and the City of Saskatoon Water Treatment Plant.

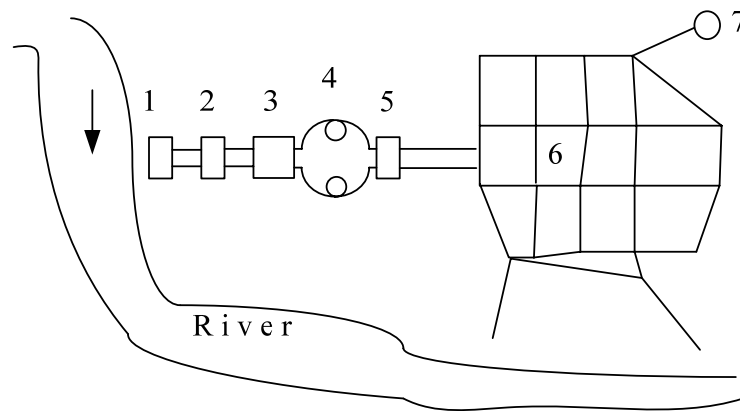
It must be pointed out that whilst the following chapter will provide a fairly detailed description of the CBS, the application to the resilient study in later chapters will concentrate on the pumping systems and the controllers that are directly associated with their operation. It is believed that details pertaining to the whole system operation are necessary to understand the critical nature of the pumps and controllers.

2.2 Introduction to the Water Supply System (WSS)

2.2.1 Water supply system

In general, a water supply system is operated, and maintained to provide water for human consumption or use. The basic function of a water supply system is to obtain water from a source, treat the water to an acceptable quality, and deliver the desired quantity of water to the appropriate place at the appropriate time [AWWA, 1973]. A water supply system can be divided into five major subsystems: water distribution system, water treatment system, water transmission system, pumping station, and water source. The detailed description of these subsystems will be given later.

There are two typical water supply systems based on types of water sources. One type of water supply systems relies on a surface source (SaskWater uses this in Saskatoon) and the second type relies on an underground source. An example of a typical surface source is illustrated in Figure 2.1 and an underground source example is in Figure 2.2. In Figures 2.1 and 2.2, the two water supply systems have a similar structure independent of the water source type. With reference to these figures, the general water delivery obeys the following procedure: raw water first is pumped from the natural source (underground water well or river) by the pumping station, and then passed to a treatment system via a transmission system over long distance pipelines. After treatment, the potable water reaches a certain quality standard and is finally distributed to individual users. SaskWater’s water supply system in Saskatoon is a surface water supply system.



1: Pumping Station 2:Transmission System 3:Treatment System
4:Reservoir 5: Booster Station 6:Distribution System 7:Water Tower

Figure 2.1 Surface source water supply system

2.2.2 Water distribution system

A “generic” water distribution system consists of a network of interconnected pipes to transport water for the consumers. The distribution system differs from application to application in the pipe diameter and number of customers [Mays, 1999].

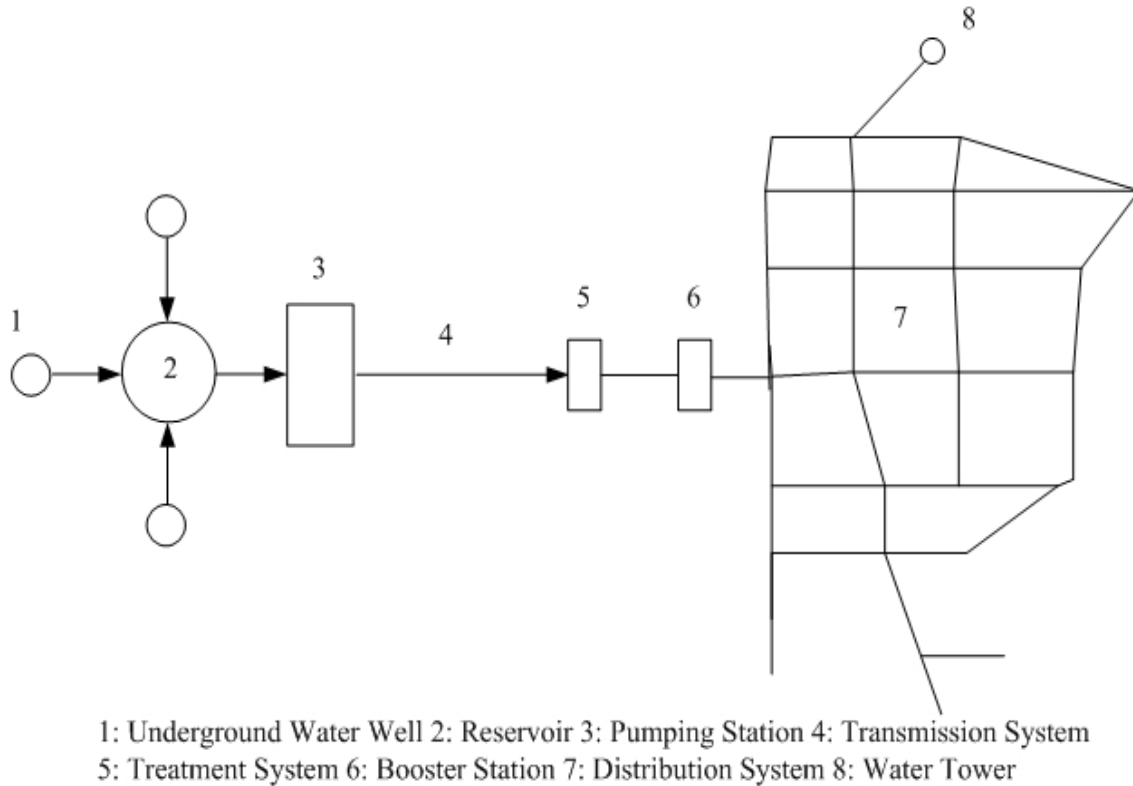


Figure 2.2 Underground source water supply system

The plan and design of an effective water distribution system is developed by following several typical criteria (flowrate, service pressure, storage etc.). These criteria further depend on the service area's geographic location, climate, size of the community, extent of industrialization, and other influencing factors which are unique to a particular customer. For example, hospitals need extremely high quality water for surgeries, devices cleaning, and medicine liquid dilution. Fire-fighting facilities need high pressure, generally at a minimum of 0.14MPa Pa (or 20 PSI) at the fire hydrant [Mays, 1999]. Ensuring safety is a relative high-priority for many big local industrial companies in Saskatoon; e.g. Agrium Potash, P.C.S. Cory, and Sterling Chemicals. Meanwhile, some commercial and farm customers have very large water consumptions; Petrill Golf, Willows Golf, and irrigation of farms are examples.

To summarize, complex customer requirements make it difficult to develop a distribution system which can meet the exact needs of every customer. As the client changes, so does the

requirement and hence so must the distribution system. As an example, SaskWater now is replacing new pipelines in the southeast service area to meet growing and changing demands.

2.2.3 Water treatment system

Water treatment systems are responsible for making water more acceptable for a desired end-use which can include drinking water, industrial processes, medical and many other uses. The goal of a water treatment system is to remove existing contaminants in the water. The expectation is that raw water after treatment can be consumed without concerns for safety. The Saskatoon municipal treatment facilities are located near the SaskWater Queen Elizabeth pumping station. It must be emphasized that SaskWater is not responsible for raw water treatment. Indeed, any potable water that SaskWater distributes is provided by the City.

2.2.4 Water transmission system

The transmission system mainly accommodates the delivery of water over long distances. Because most water sources are far from the customers, large pipes are usually used in comparison with the distribution system. For transmission systems the diameter of the pipe is larger than 400mm [Mays, 1999]. Water pressure and water flow rate are very large. Along the transmission lines, few customers are served as compared to a distribution system where many customers are present.

2.2.5 Pumping station

Pumping stations are facilities which include equipment for pumping water from one place (usually water sources) to another. It is one of the most important parts of the whole water supply system. There are two kinds of pumping stations. One is a “general” pumping station which is responsible for pumping water from natural sources (The SaskWater Queen Elizabeth Pumping Station and River Pumping Station are examples). The second are booster stations (Clarence Booster Station and North Booster Station are examples) which are responsible for increasing the intake water pressure to a desired level for next stage water delivery. This second type of station

is the focus of this study. In addition, certain pumping stations have supplementary functions, such as water quality monitor or control. The CBS is one such pumping station.

2.2.6 Water source

In the SaskWater water supply system, the South Saskatchewan River and the Bradwell reservoir are the two water sources. Most raw water is pumped from this river. For a particular customer, (P.C.S. Allan), the Bradwell reservoir is the raw water source. These two are typical surface water supply systems. It is very important to note that if the river quality is compromised, there is no alternative substitution source for the Saskatoon area (a resilience issue in itself).

2.2.7 Some typical components

As discussed earlier, the SaskWater Clarence Booster Station is the focus of this study. Consequently, a brief introduction to the components of pumping station is very important. A discussion of these typical components is now presented.

2.2.7.1 Pipe

Pipes are the most abundant elements in a water supply system. They are usually constant in diameter and are attached to fittings and other appurtenances, such as valves, storage facilities, and pumps. Pipes connect all the waterworks facilities together. Pipes are manufactured in different sizes and are composed of different materials, such as steel, cast and concrete. In most cases, pipes are the largest capital investment in a distribution system.

2.2.7.2 Valves

Valves are used to regulate the flow rate and pressure in a water supply system. One common valve is the pressure relief valve (PRV). The PRV limits and maintains the pumping station pressure at a desired constant level. In the SaskWater Queen Elizabeth pumping station, every pump is fitted with a PRV. An air-release valve (ARV) is used to release air within the pipe,

because too much air will reduce water delivery efficiency and affect water characteristics such as fluid compressibility. At the CBS, an ARV can be found.

2.2.7.3 Storage

Water storage is needed to save excessive water when the system delivers more water than what is required by the users; in addition a sudden increase in supply might be required for certain emergency applications such as fire-fighting. Near the City of Saskatoon, nearly all the rural communities have their own reservoirs to store water in case of water shortage. It is an easy and efficient way to reduce water outage if the SaskWater's water supply system experiences an unexpected breakdown.

2.2.7.4 Meter (Gauges)

A wide variation of metering devices is installed in every water supply system. They are mainly classified into two categories: pressure gauges and flow meters. Depending on different accuracy and cost constraints, different meters (gauges) are used. In recent years, very sensitive and precise meters have been put into application, such as ultrasonic flow rate meters, electromagnetic flow meters, and capacitor type pressure gauges. In most SaskWater pumping stations, the latest electromagnetic flow rate meters are used.

2.2.7.5 Pump

Pumps are used to deliver water from the source to the user or to increase water pressure in the pipe. There are many types of pumps, e.g. positive displacement pumps, turbine pumps, and gear pumps [Sanks et al., 1989]. The most commonly used pump is a centrifugal pump shown in Figure 2.3. Recently, SaskWater has installed many Variable Frequency Drives (VFD) on their pumps. The VFD is a system which controls the rotational speed of the driving electric motor by controlling the frequency of the electrical power supply. The VFD can offer potential energy savings in a system where the loads vary with time. It is the VFD's most attractive advantage.



Figure 2.3 Centrifugal pump in CBS

2.2.7.6 Supervisory Control and Data Acquisition (SCADA)

SCADA is short for Supervisory Control and Data Acquisition. The SCADA system refers to an industrial control system in which a computer system monitors and controls a process. The process may be industrial, infrastructure, or a pumping station. Figure 2.4 shows the SCADA system at the CBS.

A SCADA system usually consists of the following subsystems [Wallace, 2003]:

- 1). A human-machine interface which processes data to a front-line operator. The operator can monitor and control the process through the interface.
- 2). A data acquisition system which gathers data from the process.
- 3). Remote terminal units which connect to sensors in the process, converting sensor signals to digital data and sending digital data to the supervisory system.
- 4). Communication which is kept with the host computer or remote central control office.



Figure 2.4 SaskWater Clarence Booster Station SCADA

2.2.8 Summary

The section has briefly outlined the basic structure and components of a water supply system. Subsequent sections will expand on some of the components integral to the CBS. A more comprehensive description of the CBS will be now presented.

2.3 Introduction to the Clarence Booster Station

In this section, the physical structure of the CBS is introduced. The CBS is divided into two subsystems (shown in Figure 2.5) which are defined from the two system functions (1. maintaining the CBS in a good operation environment and 2. treating water).

The two subsystems are:

- 1) Chemicals Test and Control System (CTCS).
- 2) Pump System (PS).

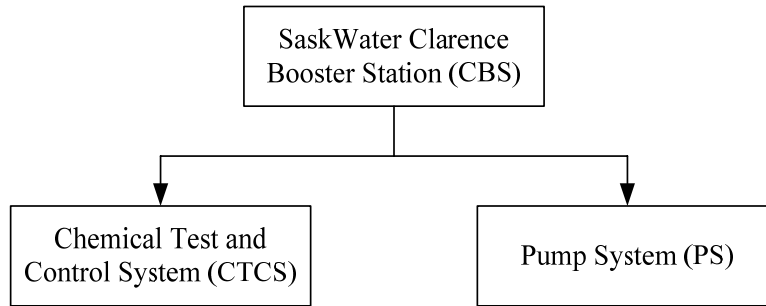


Figure 2.5 The subsystems of the CBS

The two subsystems work together to fulfill the CBS overall function which is providing drinkable water to customers in a timely fashion. This classification of the CBS structure can also help to clearly define the consequences of component failures. For example, when one component fails, the failure may impact the operation of other components leading to so-called cascading failures. Moreover, the two subsystems, to some degree, are not totally exclusive to each other. This is because some components are shared by more than one subsystem.

In the following sections, the CTCS, and the PS are explained.

2.3.1 Chemicals test and control system (CTCS)

The CTCS is the second major subsystem in the CBS. The CBS is one which provides drinkable water for the customers in the southeast area of the City of Saskatoon. The inlet water of the CBS is provided by the City of Saskatoon. The City of Saskatoon Water Treatment Plant treats the water and then delivers the water to the CBS. Due to the temperature variation and long distance pipeline, the chemical concentrations in water may drop down when water is delivered from the City to the CBS. At this point, a secondary water treatment is implemented at the CBS. There are 12 components in the CTCS. First, a sample of the city water is input to vessel A ((1) in Figure 2.6) and vessel B (2), and then tested by the test unit (3). The tested water is then dumped and accumulated into the water tank (11). When a certain volume of water is in the tank occurs, the water pump (12) is turned on and the accumulated water is pumped back to the main pipe. The information of the concentrations of water chemicals from the test unit (3) is sent to the

SCADA (6) and chemical pumps (8, 9). The pump rotation speed and time period of running are directly controlled based on the output signal of the test unit (3).

There are twelve components in the CTCS.

- (1) Vessel A: the water from pipe is stored in the Vessel A at the first step.
- (2) Vessel B: the water from vessel A is stored and tested in the Vessel B.
- (3) Test Unit: the test unit is an important component in the CTCS which is used to test the chemical concentration in the water.
- (4) Junction Box: this junction box connects the test unit, the water tank, the water pump, and the electrical panel together. The junction box performs as a signal/power connection box.
- (5) Electrical Panel: performs as a junction box.
- (6) SCADA: the SCADA is a very important component which is responsible for supervising the CBS operation.
- (7) Tank Cl (Cl stands for Chlorine): the tank Cl is used to store prepared Chlorine solution.
- (8) Pump Cl: the pump Cl is used to pump the Chlorine solution from the tank to the pipe.
- (9) Pump Am (Am stands for Ammonia): the pump Am is used to pump the Ammonia solution from the tank into the pipe.
- (10) Tank Am: the tank Am is used to store prepared Ammonia solution.
- (11) Water Tank: the tested water from the vessels is temporarily accumulated in the water tank.
- (12) Water Pump: the tested water is pumped from the water tank and back to the pipe.

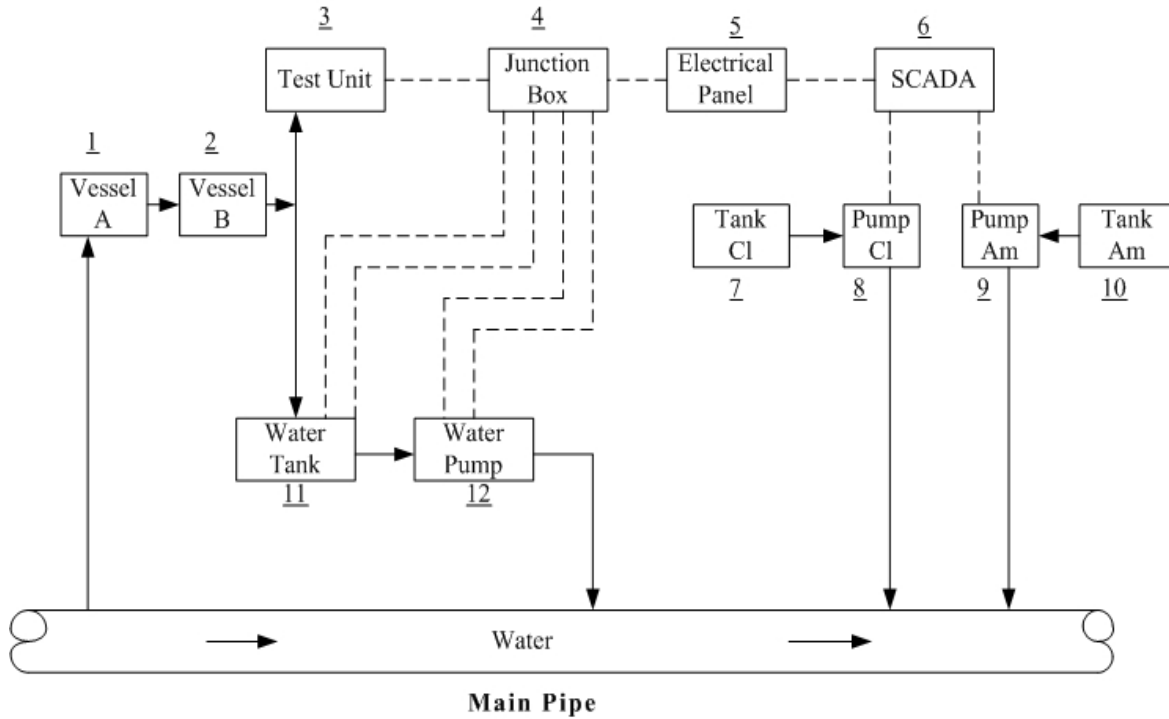


Figure 2.6 Schematic picture of the CTCS

2.3.2 Pump system (PS)

There are three pumps at the CBS and are labeled as: Pump #1, Pump #3 and Pump #4. Section 2.3.2.5 presents the pump system at a holistic level. It should be noted that Pump #2 has been removed from the station. Therefore, Pump #2 will not be discussed. The pump characteristic curve for each pump can be found in the official Aurora Pump Company website [www.aurorapump.com]. Pump #1, Pump #3, and Pump #4 are all centrifugal pumps and the characteristic curves in the following are derived from the Aurora Pump bulletins.

2.3.2.1 Pump #1

The Pump #1 in the CBS is not in service for normal operation, but when necessary it can be manually integrated into the pumping system. Pump #1 has a relatively narrow range of flowrate and pressure as shown in Figure 2.7. The efficiency is also low.

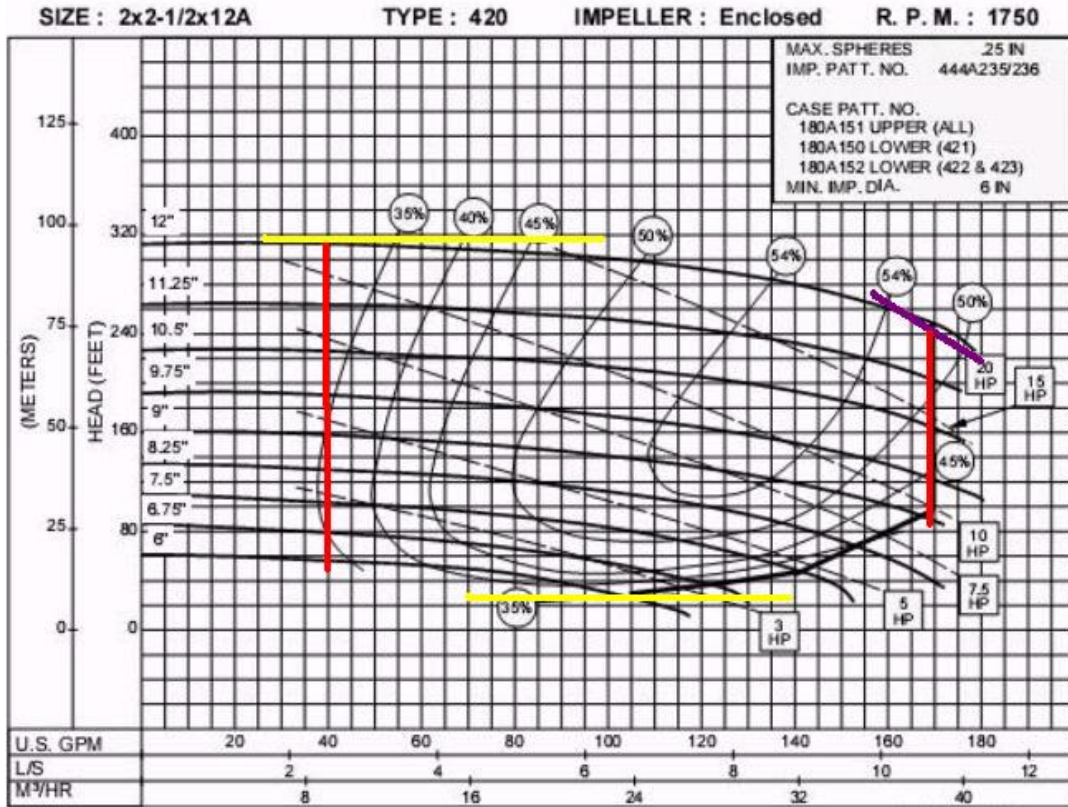


Figure 2.7 Pump #1 characteristic curve [Aurora Bulletin]

The Pump #1 characteristic curve can be observed in Figure 2.7. The maximum power of Pump #1 is limited to 14900 watts (or 20 HP) (the purple line in the Figure 2.7). The available flowrate is located in the zone from 0.0025 m³/s (or 40 GPM) to 0.01 m³/s (or 170 GPM) (the red lines). The available pressure (TDH) lies in the zone from 115.9 Pa (or 30 feet) to 1159 Pa (300 feet) (the yellow lines).

2.3.2.2 Pump #3

Pump #3 is a horizontal centrifugal pump which is controlled by a variable frequency drive (VFD). Using the VFD, Pump #3 can maintain a fairly constant pressure with a varying flowrate under load demand disturbances. The flowrate range is from 0.009 m³/s (or 140 GPM) to 0.033 m³/s (or 525 GPM) (see the yellow lines in the Figure 2.8) while the pressure range is from 174 Pa (or 45 feet) to 1.6K Pa (or 420 feet) (see the red lines).

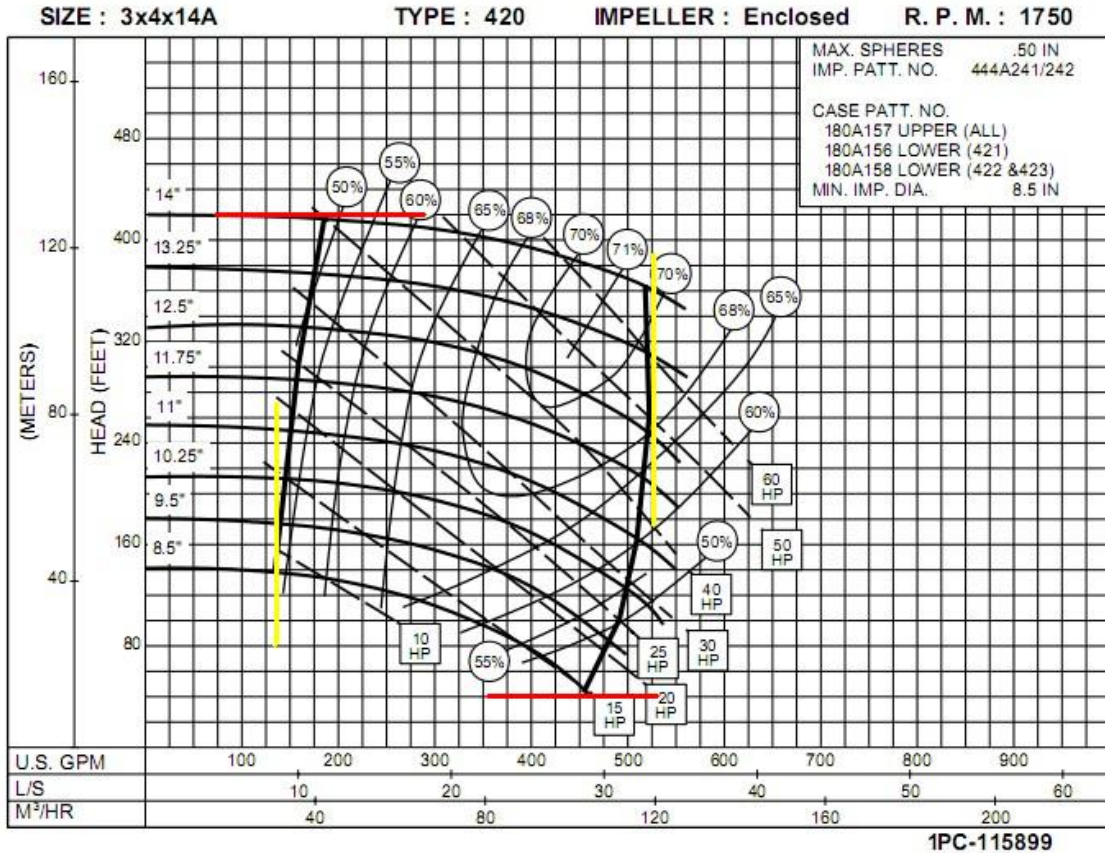


Figure 2.8 Pump #3 characteristic curve [Aurora Bulletin]

2.3.2.3 Pump #3 Control System

As mentioned, Pump #3 is a VFD controlled pump. The control system for Pump #3 is more complicated than for Pumps #1 and #4. Pump #3 is running most of the operation time. Most of the water demand can be met by using Pump #3 alone. The schematic picture of Pump #3 and its control system is shown below in Figure 2.9.

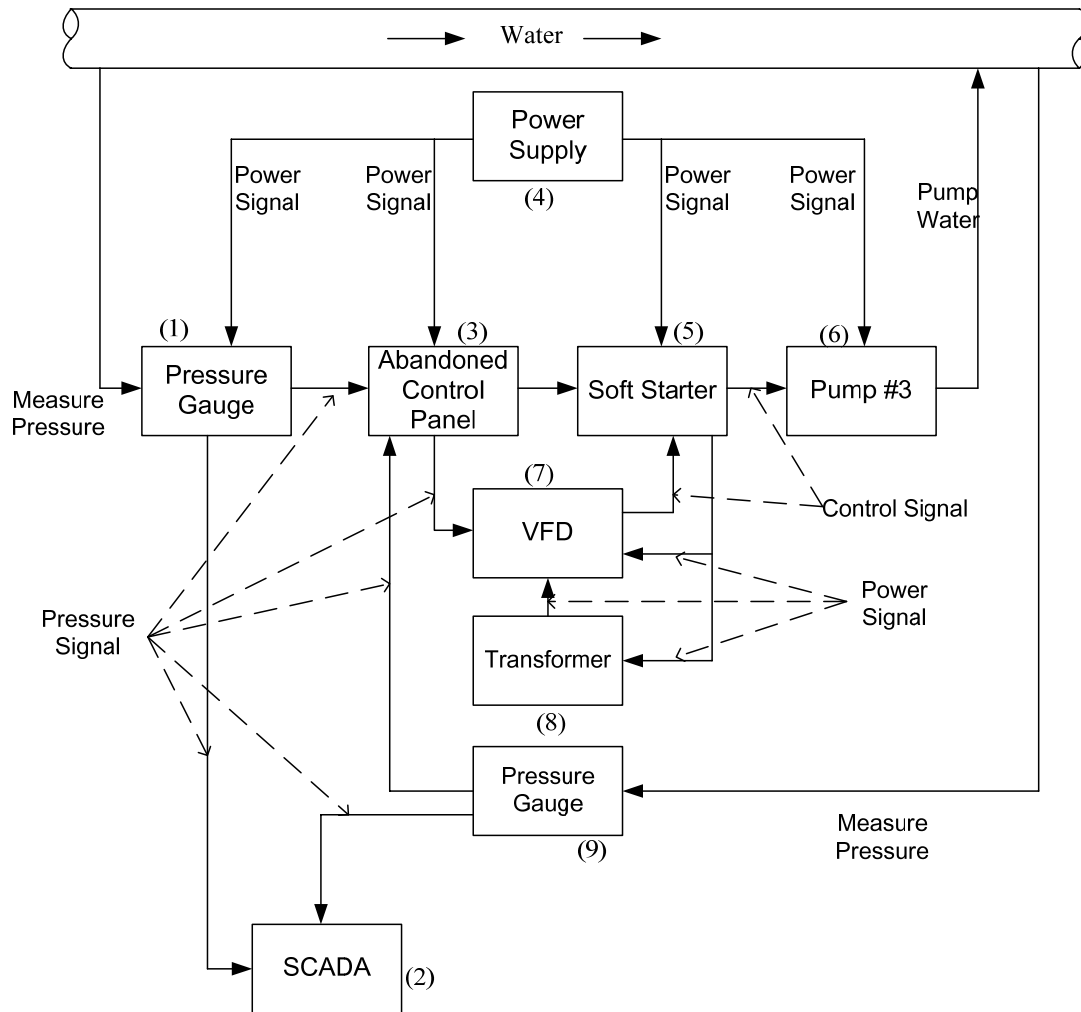


Figure 2.9 Pump #3 and its control system

There are 9 components in Pump #3 control system. The discussion of the nine components starts from the left to the right, and top to the bottom.

(1) Pressure Gauge #1 (PG #1): PG #1 is installed for measuring the inlet water pressure of the CBS.

(2) SCADA: SCADA is the important monitoring unit in the CBS.

(3) Abandoned Control Panel: this panel's original function is abandoned. Now, the panel only performs as a junction box which connects the SCADA, VFD and Pump #3 together.

(4) Power Supply Unit: this unit supplies electrical power to the VFD, the abandoned control panel and the transformer.

(5) Soft Starter: is used to start the pump gradually and avoid producing large initial current which could affect relative circuit voltage stabilization. Since the soft starter is no longer used, it is used as a junction box.

(6) Pump #3: VFD controlled pump.

(7) VFD: The VFD can change the frequency of the electrical power which in turn smoothly changes the voltage magnitude and then controls the speed of pump. The VFD needs two different levels of voltage. The reason is that there are a high voltage circuit and a low voltage circuit in the VFD.

(8) Transformer: because the VFD needs two different levels of voltage to drive the circuit panel, a transformer is required.

(9) Pressure Gauge #2: the pressure gauge #2 measures the discharge water pressure.

2.3.2.4 Pump #4

Pump #4 has a larger maximum flowrate than Pump #3. If the discharge water pressure is too low or the water demand is high, Pump #4 will be started.

Pump #4's characteristic curve can be found in Figure 2.10. The maximum motor power of Pump #4 is limited to 56k watt (or 75 HP) (see the purple lines in Figure 2.10). The available flowrate range is located in the zone from 0.019 m³/s (or 300 GPM) to 0.05 m³/s (or 800 GPM) (the yellow lines). The available pressure range lies in the zone from 950 Pa (or 245 feet) to 1912 Pa (or 495 feet) (the red lines).

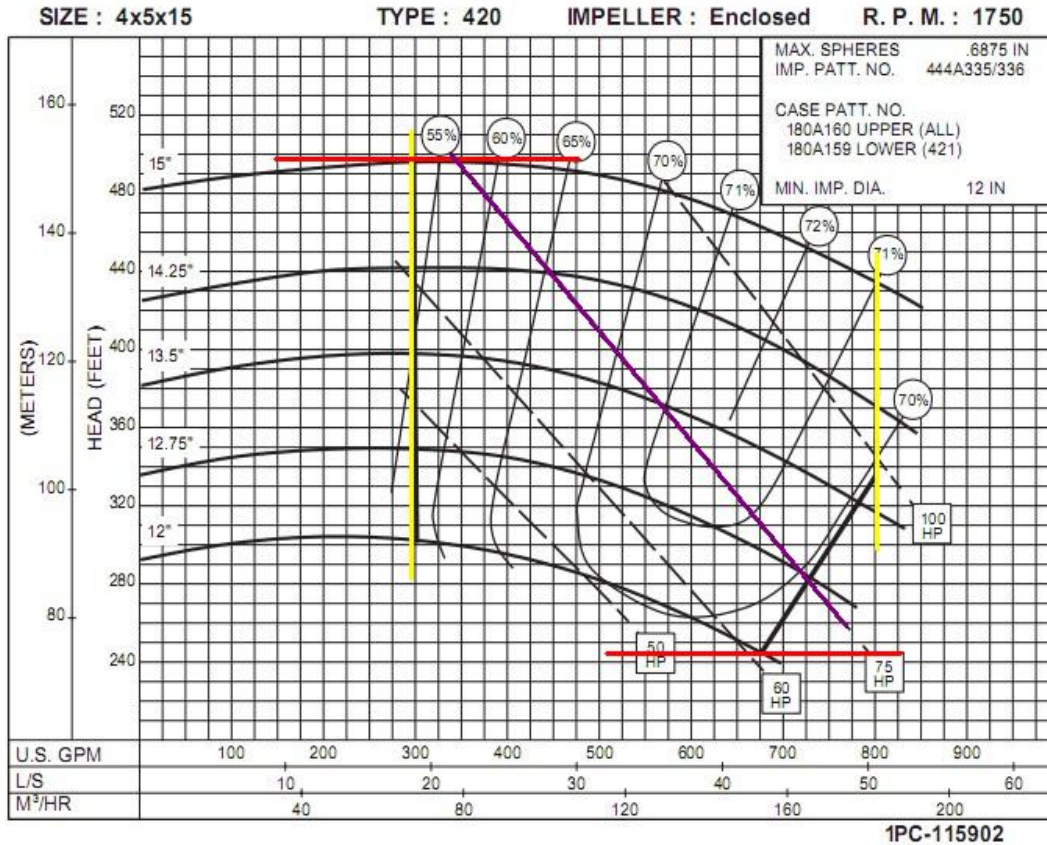


Figure 2.10 Pump #4 characteristic curve [Aurora Bulletin]

2.3.2.5 The general pump system

Figure 2.11 shows the information about the pump system (PS) at an overall level. The dashed line means that this section of pipe is normally closed. No water passes through that pipe. From the information provided by SaskWater, this pipe only is used when the City of Saskatoon changes the flowrate meter. The three pumps are installed in a parallel relationship. Several valves and pressure gauges are used. There are twenty-two components and a brief summary of components are now considered (see Figure 2.11).

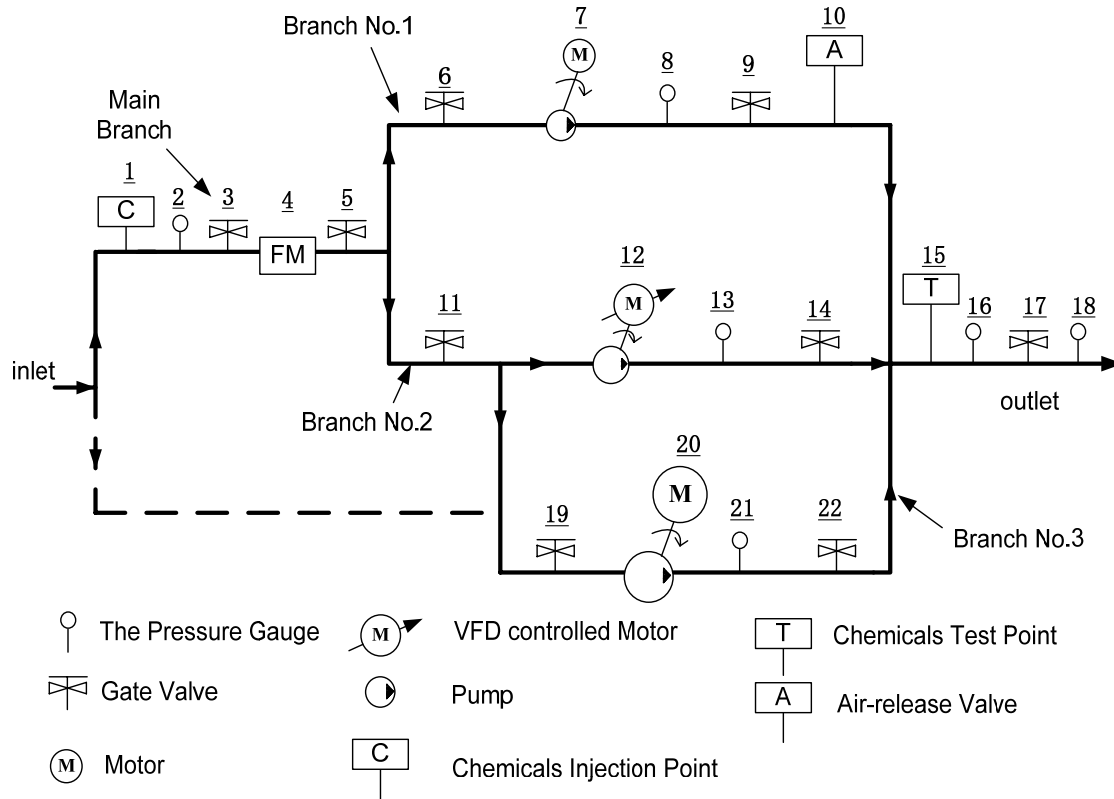


Figure 2.11 Schematic of the general pump system

Numbers in the brackets in the text below refer to the numbers underlined in Figure 2.11.

- (1) Chemicals Injection Unit: Chlorine and Ammonia are injected at this point.
- (2) Pressure Gauge #1 (PG #1): PG #1 is installed to measure the inlet water pressure.
- (3) Gate Valve #1 (GV #1): this GV#1 is fully open normally. The gate valve is known to be very reliable.
- (4) City-installed Flowrate Meter: this flowrate meter is installed by the City of Saskatoon to measure flowrate through the CBS.
- (5) Gate Valve #2 (GV #2): if the City provided water quality is contaminated, the operator can close GV #2.
- (6) Gate Valve #3 (GV #3): GV #3 controls the open/close of Branch No.1 (Branch no.1 is shown in Figure 2.12).
- (7) Pump #1: Pump #1 is a backup pump which is not used during the normal operation.
- (8) Pressure Gauge #2 (PG #2): PG #2 is used to sense the pressure from Pump #1. PG #2 is just a visual pressure gauge and does not send out signals to other units.

- (9) Gate Valve #4 (GV #4): similar as (6).
- (10) Air-Release Valve: the valve can release excessive air from the pipe.
- (11) Gate Valve #5 (GV #5): GV #3 controls the open/close function of Branch No.2.
- (12) Pump #3: Pump #3 is one of the most important pumps in the CBS. A large range of water demand can be met by using the Pump #3.
- (13) Pressure Gauges # 2 and #3: PG #3 is used to sense the pressure from Pump #3, the output signal which is sent to the SCADA system. PG #2 does not send out signals to the SCADA as it is a mechanical gauge instead of electronic one.
- (14) Gate Valve #6 (GV #6): similar as (11).
- (15) Chemicals Test Point: the treated water is sampled at this place.
- (16) Pressure Gauge #4 (PG #4): the PG #4 checks the outlet water pressure and sends the pressure information to the SCADA.
- (17) Gate Valve #7 (GV #7): similar as (3).
- (18) Pressure Gauge #5 (PG #5): the PG #5 senses the outlet water pressure. No signal is sent to the SCADA from PG #5.
- (19) Gate Valve #8 (GV #8): GV #8 controls the open/close function of Branch No.2.
- (20) Pump #4: Pump #4 has the biggest flowrate capacity among the three pumps.
- (21) Pressure Gauge #6 (PG #6): this PG #6 is used to sense the pressure from Pump #3. PG #6 does not send out signals to the SCADA.
- (22) Gate Valve #9 (GV #9): similar as (6).

2.4 Relationship between SaskWater and the City of Saskatoon treatment plant

2.4.1 SaskWater

Although this thesis considers only the CBS, it is important to understand how the CBS relates to SaskWater and the City of Saskatoon water system. SaskWater is a Saskatchewan's Crown water utility service provider, providing potable and non-potable water, wastewater treatment and maintenance services to Saskatchewan municipalities, industry and rural water users. According to the information from the SaskWater website, as of 2007 the SaskWater serves 53 urban and rural municipalities, 60 rural pipeline groups and 41 commercial customers. SaskWater is

dedicated to “making reliable water in quality and quantity, and meet the community’s needs now and into the future” [Jung, 2005].

2.4.2 Overview of the SaskWater waterworks in Saskatoon

A schematic picture of the SaskWater water supply system in the Saskatoon area is shown in Figure 2.12. The SaskWater of Saskatoon mainly operates three water supply branches. They are the North Branch (NB), the Southwest Branch (SWB), and the Southeast Branch (SEB). There is no interconnection amongst the three of them, except that the SWB and the SEB are connected with a pipeline over the South Saskatchewan River. During normal operation, the SWB and the SEB are operated separately. When an emergency happens, engineers can manually open the connection valves to provide water interactively.

The North Branch (NB) is a potable water supply branch. Treated water first is provided by the City of Saskatoon, and delivered to customers via the NB pipelines. Along this branch, there are five communities (Martensville, Warman, Osler, Dalmeny and Hague). There are also two pumping stations: the North Booster Station (NBS) and an unnamed station which is near Dalmeny. Two industrial companies are located near the NBS, Sterling Chemicals and AKZO Nobel. One control meter station (CMS) is near the unnamed station. The CMS is used to record the delivered water volume.

The Southwest Branch (SWB) is a potable and raw water supply branch. Along the potable water line, water is provided by the City of Saskatoon, and delivered to four industrial customers (P.C.S. Cory, United Chemicals, J.Mitchell Holdings, and Royal View Cattle). Along the raw water line, there are two communities, Cedar Villa, Vanscoy and one industrial company, Agrium. One raw water pumping station, the Queen Elizabeth (QE), is built on the South Saskatchewan River’s northern bank which is pumping raw water to pipelines. It is necessary to note that Vanscoy has its own water treatment facilities to treat raw water.

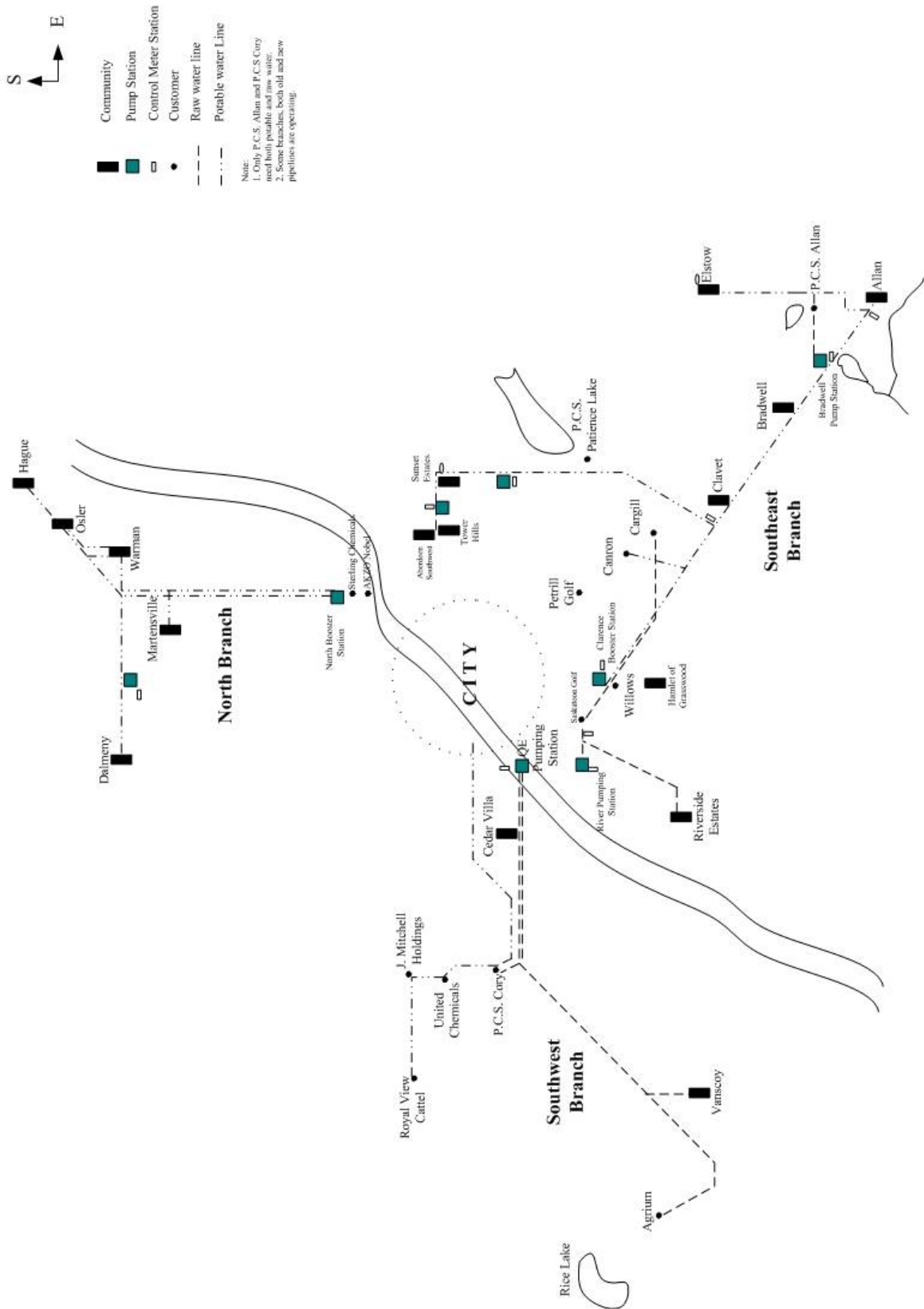


Figure 2.12 Schematic picture of the SaskWater waterworks in Saskatoon

The Southeast Branch is a potable and raw water combination supply branch (two separate lines) and is the most complex one. Along the raw water line, water is pumped from the River Pumping Station to several industrial communities and commercial customers (Riverside Estates, Sask Golf, Grasswood, and Canron etc.). Along the potable water line, water is first provided by the City of Saskatoon and then the pressure is “boosted” to a certain pressure for the four communities (Clavet, Bradwell, Allan, and Elstow). In the SEB, four pumping stations and six control meter stations exist.

Table 2.1 SaskWater facilities in Saskatoon

Facility	Branch	Southwest Branch (SWB)		Southeast Branch (SEB)	
	North Branch (NB)	Raw Line	Potable Line	Raw Line	Potable Line
Pumping Station	2	1	0	1	3
Control Meter Station	1	1	0	2	5
Major Communities	4	2	0	1	7
Major Industrial and Commercial Customer	2	1	4	5	3

It should be noted that the above descriptions only list the major customers along the various branches. Small customers are not listed. Table 2.1 summarizes the various lines and facilities of the SaskWater water supply system in Saskatoon. For example, in the raw water line of the Southwest Branch, there are one pumping station, one control meter station, two major communities and one industrial/commercial customer.

2.4.3 City of Saskatoon waterworks

The City of Saskatoon operates the sole water treatment system in Saskatoon. The major responsibility of the City treatment system is to provide high quality water and wastewater services for users of Saskatoon and northern Saskatchewan. The major water treatment system

includes water treatment sludge handling facility, maintenance facility, water intake & pumping station, filtrations and reservoir storage. The overall picture of the treatment buildings is shown in Figure 2.13.



Figure 2.13 City water treatment plant picture

2.4.4 The Relationship between the City and Clarence Booster Station

In Figure 2.14, the City treatment plant is located on the north side of the South Saskatchewan River. The CBS is at the south side of the South Saskatchewan River. The two places are interconnected by the SaskWater distribution system (long pipelines over the river). Treated water is directly delivered to the CBS from the City treatment plant. In other words, all the water delivered from the CBS is provided by the City. If the City treatment system fails, so does the CBS.

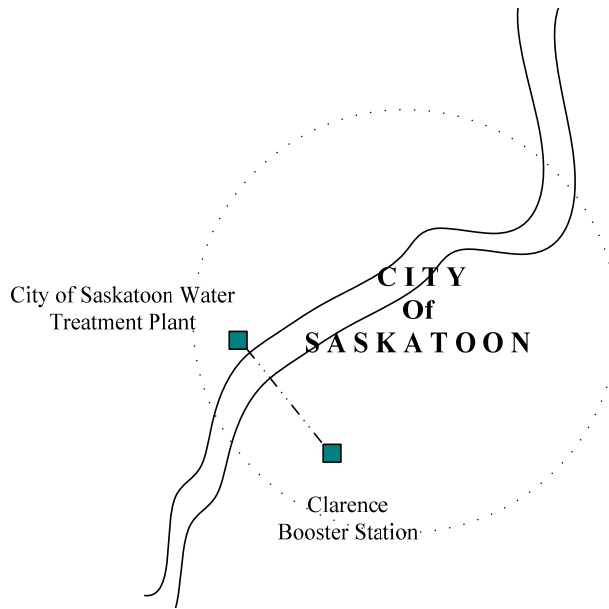


Figure 2.14 Relationship between CBS and city treatment plant

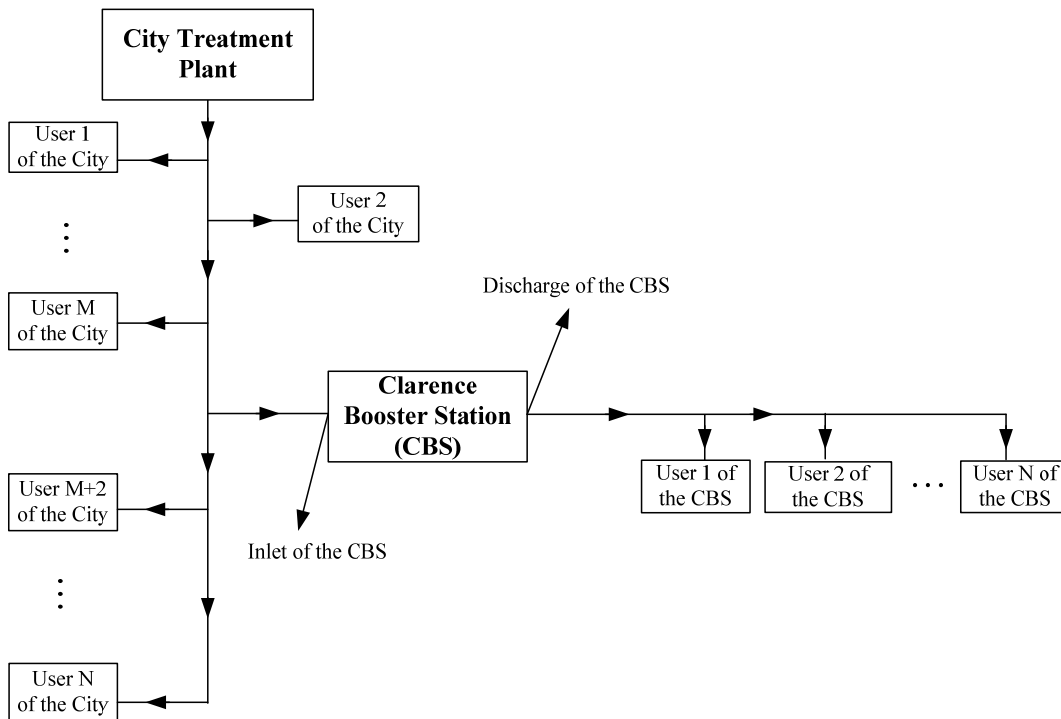


Figure 2.15 Schematic picture for the CBS and city treatment plant

To better demonstrate the relationship between the CBS and the City treatment plant, consider Figure 2.15. It is observed that the CBS is just one of the water clients of the City treatment plant. Other water clients are residents, hospitals, businesses, and public facilities etc. The water

demand of the other clients can directly influence the CBS's inlet water pressure and water supply.

2.5 Summary

This Chapter has briefly summarized the Clarence Water Station, its major components and operation and its relationship to the overall water distribution system and water source. In subsequent Chapters, several of the functions of the CBS will be used to illustrate how the definition of resilience and resilience index will be used. It should be clarified that only a few of the functions will be considered because of the complexity of the station but it was believed that the complete description was necessary to facilitate discussion of the sub-functions so considered.

CHAPTER 3

CONCEPT OF RESILIENCE AND RELATED STUDIES

3.1 Introduction

This chapter will provide information about the concept of resilience and a review of the state-of-the-art literature relevant to resilience. Section 3.2 reviews the existing resilience definitions in the literature and then introduces a new definition for resilience from an engineering design and system safety point of view. Since the study of resilience is very much in its infancy, the newly proposed resilience definition is chosen to be a first step in the study of resilience and its application. Section 3.3 attempts to clarify the difference between resilience and other concepts (such as reliability and robustness) which enhances the newly proposed resilience definition. Section 3.4 provides a brief introduction about the existing resilience measurement methods.

3.2 Resilience

3.2.1 Introduction

In the following sections, three typical examples of resilience from an application point of view are first introduced (resilience in material science, biology, and computer science). This will be followed by outlining several “existing” definitions of resilience. In the end of Section 3.2, a new definition is proposed.

3.2.2 Resilience in other areas

The concept of resilience has been used in several areas such as in material science, biology and computer science. Examples in these areas are introduced to express how traditionally resilience has been applied.

In the material science area, the resilience is related to the ratio of a material's yield strength to its elastic modulus [Hasegawa et al., 1999]. Under an external force on a surface as shown in Figure 3.1, a piece of material will deform to certain degree. If a force is acting on resilient material, the material can fully recover the initial shape elastically after removing the force.



Figure 3.1 Resilience in material science

In biology, humans can suffer from various kinds of diseases. For the same disease, different persons have different levels of “resistance”. A person may survive from the flu after adequate treatment. However, the same flu may be a deadly to others (see Figure 3.2). For example, it has been shown that Asians have a higher resistance than Americans with respect to the fatty liver disease [Walker, 1995]. The resistance to disease can be considered as a human-being's resilience and is often how the term is used in biological applications.

In computer science, the resilience concept has been studied. The computational resilience is considered as the ability to tolerate intrusion under information warfare attack [Lee et al., 2001]. In the highly adverse environments, the resilient system can operate and tolerate attacks and failures by either using replications [Guerraoui et al., 1997] or additional hardware [Schneider, 1990].

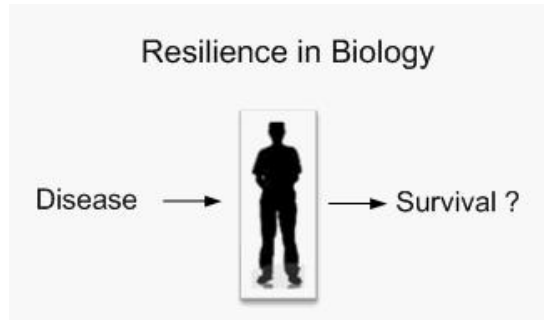


Figure 3.2 Resilience in biology

Resilience has also been considered in areas, such as psychology [Ewart et al., 2002], economics [Perrings, 2006], and education [Jackson et al., 1998]. In this study, the application of resilience in engineering is the focus.

3.2.3 Existing definitions for resilience

A review of the literature has shown that resilience has been studied in many areas for some time. The diversity of the research areas has resulted in a variety of the understanding of resilience. There are three definitions of resilience which illustrates this.

1) Mary Lynn Pulley and Michael Wakefield. 2001. "Building Resiliency: How to Thrive in Times of Change." Center for Creative Leadership:

Resilience provides the ability to recover quickly from change, hardship, or misfortune. It is associated with elasticity, buoyancy, and adaptation. Resilient people demonstrate flexibility, durability, and attitude of optimism, and openness to learning. A lack of resilience is signaled by burnout, fatigue, malaise, depression, defensiveness, and cynicism.

2) Margaret R. Sebescen. 2000. "Resiliency in First Nation's Adults Overcoming the Odds." Thesis Master, University of Manitoba, Canada:

The concept of resilience is one that speaks to the potential of human beings. This potential is exemplified by those who have the capacity to overcome and thrive in the face of

adversity. This capacity to survive in the face of overwhelming odds is perhaps one of the most inspirational aspects of human psyche.

3) John Wreathall. 2006. "Chapter 17 properties of Resilient Organizations: An initial View, Resilience Engineering: Concepts and Precepts." Aldershot UK: Ashgate.

Resilience is the ability of an organization (system) to keep, or recover quickly to, a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses.

The above definitions highlight that the system is under stresses. However, there is no indication of whether the stresses would cause any failure such as beyond the system "yield" or "tensile" strength (borrowing from the terminology of material science). Furthermore, the stresses may come from disturbances. As such, this definition of resilience engineering cannot make a distinction between resilience and robustness for example.

Wreathall [2006] extended the definition of resilience to the inclusion of prevention of failure. Along this line of thinking, resilience engineering should also cover the issue of the prediction of failures to the system. One of the problems with this extended definition is that there is no indication of causes for failures. Failures can be caused by internal system failures and/or external mishaps (natural disasters or terrorist attacks). If the internal failure is meant, the prediction of the failure is similar with reliability analysis. Therefore, it appears that the extended definition cannot distinguish resilience from reliability.

Therefore, a new definition for resilience is needed which not only can explicitly express the identity of resilience but also distinguish resilience from robustness, reliability and other similar concepts.

3.2.4 Working definition for resilience engineering in this thesis

To resolve the issue of various different definitions of resilience and resilience engineering, this thesis proposes a definition based on a revision of Zhang [2008]. The proposed definition is described as follows:

Resilience is a property of a system which measures how the system can still function to a required level by means of its own after the system has experienced partial damage. Resilience engineering is about modeling, analysis, and design of a system for achieving a desired resilience property of the system.

In this thesis, the “recovery” aspect which is implicitly in the phase “still function to a required level by means of its own after the system has experienced partial damage” is the focus of the measurement of resilience which will be introduced in a later chapter.

With this definition, it is possible to distinguish resilience from robustness, reliability, redundancy, sustainability, and repairing. The distinctions are presented in the following.

This new resilience definition implies that a resilient system should recover with its own “source”. There may be some confusion in understanding or defining a “system” (or a system’s own source). Hence, it is important to define what is meant by the term “system” in this study. A system encompasses the physical components (pumps, valves etc), the substances (e.g., water in the context of a water supply system), and human operators who operate or supervise the operation of the physical components. The system has input which includes the substance (e.g., water) and energy (e.g., electric energy). The substance is what to be processed by the system and has a set of characteristics (e.g., pressure, chemical content, etc in the case of water), and the energy is what to drive the system, especially the physical components, and has a set of characteristics (e.g., power, etc.) as well. In this thesis, the energy to human operators is not considered. The system will produce output which is in fact the substance (e.g., water) with a set of “improved” characteristics (e.g., pressure, flow rate, chemical content). In this particular study of resilience, humans (e.g. the SaskWater staff), the physical structures (e.g. pumps, motors in

CBS), available components (e.g. tools, redundant pumps in CBS), and substance (water) are included under the name of the “system”.

As stated above, the definition of resilience implies recovery within the systems’ own sources. What this means physically is that components, states and roles within the system are used to recover from a failure. This makes sense in that recovery can always be accomplished through replacement, and repairing from external sources but at considerable expense and time delays. If one adopts the above stated definition then in essence, every system is resilient. But a truly resilient system can recover using its own resources (planned or by chance) and it is this type of action that this definition encompasses.

3.3 Distinctions between resilience and robustness, reliability, redundancy, sustainability and repairing

3.3.1 Introduction

Resilience engineering stems from the basic philosophy of making a complex system safer. It is related to well-known existing concepts such as reliability and robustness with systems. At first glance, it can be difficult to distinguish between resilience and these existing concepts. But in fact resilience is unique and the following will first attempt to point out the implicit differences as well as define explicitly, what resilience is.

3.3.2 Relationships between resilience and robustness, reliability, redundancy, sustainability and repairing

The five terms (robustness, reliability, redundancy, sustainability and repairing) are chosen to help explain the meaning of resilience. The reason for selecting them is because the five terms are all used to describe system properties. Moreover, some of the five terms are very close to the meaning of resilience. Consequently, many researchers in this area do not clearly define the differences in their meaning. The following section will endeavor to define both the differences and overlaps in the definitions. This section will first briefly introduce the terms and then an

example (Section 3.3.3) will be used to provide greater details and to demonstrate the similarities and differences.

In Figure 3.3, the relationships between the five terms and resilience are illustrated. The resilience is drawn in the centre of Figure 3.3 with the other five terms surrounding it. It can be seen that resilience has intersections with repairing, robustness, and redundancy which implies that these terms do have some common ground in terms of how they are interpreted. The relationships will now be summarized with details for each case as it pertains to a water supply system presented in previous sections.

Consider first the relationship between robustness and resilience; both terms are related to the ability of a system to keep functioning under disturbances (where in this interpretation, disturbance is the alternation or influence to a system). Both a resilient system and a robust system can function in the presence of disturbances. However, for a robust system, the physical structure of the system is still intact whereas for a resilient system, the physical structure is damaged. In essence, a resilient system contains characteristics of a robust system in that it is the magnitude of the disturbance that differentiates between the two properties.



Figure 3.3 Relationship between five terms and resilience

Note: there can be overlaps among the five terms themselves. But these overlaps will not change the relationships between resilience and the five terms.

Consider the relationship between repairing and resilience, both are related to the process of “system recovery”. Resilience focuses on the recovery process of internal means as the priority (e.g. resource relocation and system reconfiguration) whereas repairing emphasizes the recovery process using external means as the priority (e.g. bringing in new components to “heal” the damage). As with robustness, a resilient system has characteristics of repairing because the “end result” is the same.

For the relationship between redundancy and resilience, redundancy can be further classified into two types: physical duplication and function duplication [He, 2008]. The physical duplication means that there are two or more completely similar components or subsystems in an entire system (e.g., duplication of engines in aircraft). The function duplication means that there are two or more different components which enable the same function. In both types of redundancy, two or more redundant components may perform at the same time or may be such that some of them stay spare or idle, while the other functions. Redundancy in a system will improve the system’s resilience; when one component is damaged, its completely duplicated component or partially duplicated component can replace the damaged component to make the system still functional. Redundancy therefore is a means to improve the resilience of a system.

A more difficult property to consider is that of reliability. Reliability implies that the system does not fail in a certain time period. The longer the period the more reliable the system will be. A system can be unreliable yet very resilient given the characteristics associated with resilience discussed above (e.g. redundancy). As such, it is the author’s opinion that the two properties do not overlap well.

The last property is sustainability. Sustainability considers the equilibrium between the system and nature [Harris et al., 2005]. Although all systems should be sustainable, the overlap between the two properties is assumed minimal for this study given that the characteristic of “recovery” is the area of concern. As with reliability, it is the author’s opinion that an overlap is not present but it is equally recognized that this is an area of debate and should be a topic of discussion for future research.

3.3.3 Application of the five terms with respect to a water supply system

In the last section, a brief discussion of the relationships between resilience and robustness, redundancy, repairing, reliability and sustainability was presented. The following sections will expand on this discussion by referring to a water supply system since it is the application of interest in this particular study.

3.3.3.1 Robustness

First, robustness refers to the system quality of being able to function in the presence of disturbances. A system may be said to be “robust” if it is capable of coping well with variations in its operating environment. For example, in pumping stations, the VFD (variable frequency drive) controlled pumps have been gradually replacing the traditional constant speed pumps. The VFD can maintain a fairly constant water discharge pressure independent of load disturbances such as the client water demand (which can vary with time, location, and even temperature) and hence can be considered as a robust component.

However, a robust system is not necessarily a resilient system. Indeed, it is a matter of the size of the disturbance that dictates the difference. The robustness property is usually associated with smaller disturbances (e.g. measurement noise, small perturbations in the loading conditions etc) whereas the resilience property is usually concerned with severe (catastrophic) disturbances such as that which would occur if a pump fails.

3.3.3.2 Repairing

Repairing is just one of the means for system recovery. Repairing implies using external methods or resources to achieve recovery and hence can be an important part of resilience.

Repairing uses external means, instead of the system’s own resources or energy, to heal the damage and recover the system. Resilience stresses the utilization of a system’s own resources or energy. A system which has good access to external resources also contributes to good resilience.

In the Clarence Booster Station, if a pump fails, getting access to parts could be an issue and a substantial delay in getting the pump back on line may occur. If this was the only pump, then the system resilience could be negatively affected. On the other hand if a relay in the power supply to the pump fails, availability of the component from a local supply source is quite high and so repair can be accomplished quickly even if the pump was the only unit in the station. Thus the resilience has improved albeit not as high as if a redundant pump was available (see next section).

3.3.3.3 Redundancy

Redundancy has strong links with resilience because both terms are used to describe system structure and function [Hollnagel et al., 2006]. Redundancy is a system feature, which requires the duplication of critical components as the backup, or systems having an extra unit which can be put into use when necessary. Resilience is more the ability to recover from a failure by reconfiguration and using other means of achieving the required function. For a pumping station two or more pumps are installed. During normal operation, only a few of the pumps are actually working, the other pumps are dormant and can be activated if there is a failure in one of the active units. This pump combination is therefore a reflection of system “structure redundancy”. A second type of redundancy exists which is labeled “function redundancy”. Function redundancy is achieved by using functions of some of the other parts of the systems in a slightly different way than they were intended to operate in the original system in order to maintain the continued use of the system design. Both types of redundancy contribute to resilience.

To demonstrate function redundancy, for the SaskWater Clarence Booster Station, all the operation data is normally transferred to the control centre by a wireless unit, called a “SCADA” (supervisory control and data acquisition) system. There is a landline telephone electronic unit (LTEU) which is used for communications and is located next to the SCADA system. The primary function of the LTEU is not for data transmission. However, function redundancy can be integrated into the LTEU by physically re-connecting certain telecommunication cables to transform the LTEU function from “verbal communication” to the function “data communication” if a failure in the SCADA system occurs.

Redundancy is greatly related to resilience because of the duplication feature. This strategy is often defined as “backup”. In most situations, redundancy is a conventional means to improve system resilience. Having structure and/or function redundancy allows the system to recover quickly and thus ties into the definition of resilience. However, a redundant system is usually a resilient system but a resilient system may not contain redundancy (structural or functional).

3.3.3.4 Reliability

Reliability pertains to the condition that the system does function well in a desired time period. Another way of saying, this is “how long can this system keep working without a problem?” This term is closely related to long term fault free operation (a safety concern in many applications). As an example, in the CBS, electromagnetic flow meters (EMFM) have been installed to replace the propeller flow meters. The EMFM is designed by the Faraday’s law of electromagnetic induction and there are no moving parts. The EMFMs hence can operate fault free for very long periods of time increasing the reliability of the monitoring system.

Reliability is different from resilience. For example, all components in the pumping station may be highly reliable but if a power outage occurs due to an electrical storm, the components’ reliability has not been affected but the system resilience has. If there is a backup power supply, the system is resilient. A reliable system pertains to the condition that the system does not dysfunction or fails within a desired period of time. System reliability is normally calculated using the time period per failure. However, a resilient system could fail anytime during operation. The overlap of the properties is considered to be minimal.

It is recognized that arguments could be forwarded that reliability can increase resilience. In the author’s opinion, this could be true but the association (or overlap) is weak for the application of CBS. Future examination and refinement of resilience definition may be needed to further clarify the possible overlap.

3.3.3.5 Sustainability

The last term to be considered is sustainability. Sustainability is “equilibrium” between social, environmental, and economical concerns. Sustainability has been defined as “the process of change in which the direction of investment, the orientation of technology, the allocation of resources and the development and functioning or organization to meet present needs and aspirations without endangering the capacity of natural system to absorb the effects of human activities and without compromising the ability of future generations to meet their own needs and aspirations” [Harris et al., 2005]. As an example, whenever SaskWater plans to build new pumping stations, nearby communities’ opinions and “environmental circumstance” surveys are carefully considered. In addition, pumping station hardware is updated keeping both energy and economic consideration in mind. As another example, the VFD can offer potential energy saving for pumping stations where the load (or customer water demand) varies a lot. The reason is that motor-driven systems (here pumps) are often designed to handle peak loads as a safety factor. This often leads to energy inefficiency in systems that operate for extended periods at reduced load (such as in the early morning). The ability of the VFD to adjust motor speed can enable a closer matching of the motor output to the load and often results in energy saving. With the VFDs, “soft starters” are no longer required which can result in substantial savings over time. In summary, in this example all the three aspects of sustainability (social, environmental, and economics) are integral to the definition.

The question now becomes one of “is a sustainable system a resilient one?” Just because a pumping station is environmentally friendly now and in the future and can save energy does not necessarily imply that it is resilient unless the action of designing the system to be sustainable results in a system that can recover from failures in an expedient manner. As a result, for the particular application of CBS, the author has assigned minimal overlap of the two properties in the definition of resilience.

In Section 3.3.3.1 to Section 3.3.3.5, robustness, reliability, redundancy, repairing, and sustainability have been discussed in relationship to resilience. Similarities and differences between these terms and resilience have been considered.

3.4 Existing methods for measuring resilience

3.4.1 Introduction

Resilience is clearly a field in the midst of defining itself and its relationships with other terms (e.g., robustness, reliability, etc). In addition, it is required to develop methods to measure resilience. This section is taken as an introduction for providing information about the existing methods developed for resilience measure. Several approaches are introduced, such as defining resilience factor and stress-strain state space.

It is widely perceived that the system resilience usually is manifested during actual operation or actual disturbance. As a result, the possibility for studying resilience in response to disturbances is limited. There are three major reasons for this problem. First, it is not easy to observe system operation detail continuously and completely. Sometimes, the failure of a system results from a small system variation. If the small variation is neglected by operators, it could accumulate and finally become a problem. Second, the consequences of damage may include great destruction to the system. Third, there is still some debate regarding what resilience is and how resilience is different from other concepts. Since the meaning of resilience is still unclear, the means of quantifying it is under development.

Two existing resilience measurement methods are now introduced: defining resilience factor and Stress-Strain State Space.

3.4.2 Defining resilience factor

Some researchers believe that resilience should be concerned with a system's performance at the "boundary of performance" (e.g. the maximum discharge flowrate of a pump, or the maximum flowrate of a pump) under varying demand. As a result, it is believed that a few factors which are related to the system boundary performance can be used as methods for measuring resilience. Mendonca in 2006 proposed a formal discussion about resilience factors. Some of these factors are:

- Flexibility/stiffness: a system’s ability to restructure itself in response to external changes/pressure. A system can maintain its function by slightly changing its physical structure (the restructure is similar to the definition of reconfiguration in this thesis study).
- Margin: performance which is related to a certain boundary. Here, “the system boundary may be said to represent both limits of performance and the border that separates one system from the outside world” [Hollnagel et al., 2006]. Measuring the margin of a system usually requires the study of system limitation.
- Tolerance: Tolerance refers to boundary conditions of a system. Tolerance discusses not the limitations of systems but rather how the limitations are achieved (e.g., the CBS can increase discharge pressure by increasing the pump rotation speed).

Researchers have studied the resilience of some practical cases, such as a power station, and a telecommunication system. A list of the possible factors for the two systems is given in the Table 3.1.

Table 3.1 List of resilience factors of example systems

Factor	Power Station	Telecommunication
Margin/ Tolerance	Transmission capacity Power Network load	Network load
Flexibility/ Stiffness	Development of new procedures Identification of opportunities of renewal	Development of new procedures

The aforementioned factors may be used to measure resilience and even to improve resilience of the system. However, during practical implementation, it is difficult to evaluate system performance and identify system boundary performance. Up to now, the method of defining resilience factor has only been used to study a few cases.

3.4.3 Stress-strain state space

The resilience property often is expressed as how a system adapts to increasing demands (such as the water demand from users). Thus, some researchers suggest that this reaction could characterize and measure a system's resilience based on the similarity from material science which studies the relationship between stress (which means the force on material) and strain (which means the deformation of material under stress). To better understand "system stress-strain relationship" [Hollnagel et al., 2006] developed the stress-strain state space as shown in Figure 3.4. The state space is a representation describing the system input (demand) and output (supply) relationship.

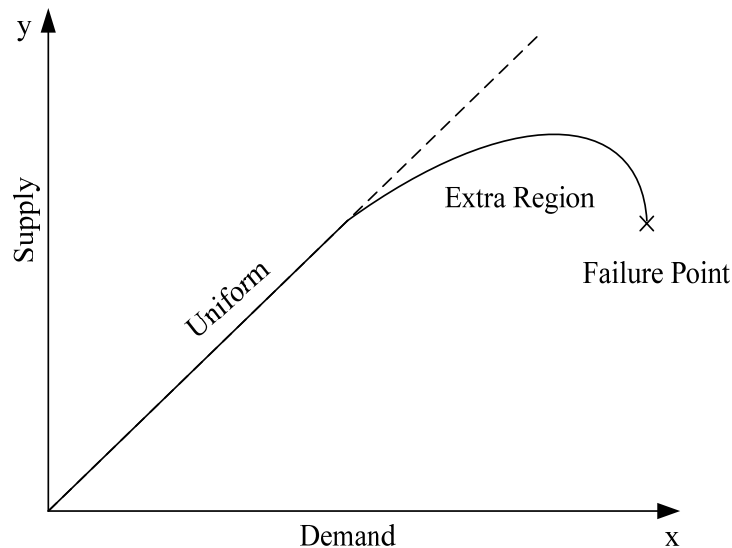


Figure 3.4 Stress-strain state space

In material science, there are two different types of deformation: the elastic one in which the material stretches uniformly (proportionally) under increasing load and the plastic one where the material stretches non-uniformly until the material distorts and a fracture happens. The stress-strain state space method is directly developed based on the above similarity. The stress-strain state space for a system is described by a simple curve. The x-axis is labeled in Figure 3.4 as the demand and the y-axis is the supply or how the system adapts when placed under a given demand.

Similar to the interpretation of material science, the stress-strain state space has two sections. In the first section – defined as the uniform region, the system can “stretch” uniformly as demand varies in this region. This is called the “normal operation performance area”. The system is capable of responding to the demand in a proportional fashion before transitioning to the second region.

In the second non-uniform region, a “gap” (the difference between supply and actual demand) appears as the demand exceeds the ability of the system to adapt. To avoid the gap accumulation which would lead to a system failure, active steps are needed to be taken. The adaption may be provided by a new strategy, resources reallocation, or even structure reconfiguration. This process continues to cope with increasing demands until system failure.

The stress-strain state space usually is obtained based on careful observation about system operation. If a system has a long section of the uniform curve, the system could be a resilient one. However, because the curve representation is simple and only displays the relationship between two variables, some useful information (e.g., adaptation method, time of recovery) is overlooked. This disadvantage limits the development of the stress-strain state space.

3.5 Conclusions

In the aforementioned discussion, some existing studies about resilience are reviewed. Two problems are found. First, the definition of resilience in the current literature is vague, and most definitions fail to make a distinction between resilience and other similar concepts such as reliability and robustness. Second, there is a lack of sound approaches to measure resilience which hinders the further development of resilience modeling, analysis, and design.

CHAPTER 4

THE MODEL OF THE CLARENCE BOOSTER STATION

The following sections will present the details of the CBS operation, which is considered the basis of a “physical” model. In this context, the physical model is one in which the basic operation is described in a verbal form, as opposed to an analytical model. These details include several facets, such as the CBS functions, the normal client’s water requirements, the orifice equation which is basic to fluid flow, typical pump characteristic curves, the operation of the pump system, and the operation of the chemical test and control system. Using these various topics, a physical model of the CBS will be presented.

4.1 The CBS function

The booster station usually is located in the water distribution system for the purpose of increasing water pressure in order to supply water over long distances. In this case, the CBS is responsible for the portable water supply of the southeast area outside the City of Saskatoon. The water users of the CBS consist of both household families and industrial companies. The detailed CBS functions can be described in three aspects (pressure, flowrate and chemical).

Pressure function: to maintain the discharge pressure of the CBS at a fairly constant value. For the winter months, the discharge pressure of the CBS is required to be around 0.9 MPa (130 PSI) whereas in the summer months the pressure is about 1MPa (150 PSI).

Flowrate function: to provide a variable discharge flowrate with a maximum of 0.038 m³/s (or 600 GPM).

Chemical function: to control the Chlorine compound injection dosage rate between 0 PPM and 2 PPM (PPM: parts per million, 2 PPM means two parts of dosage in one million parts of water). The Ammonia dosage rate is four times less than the Chlorine dosage rate. The Ammonia is used to make the Chlorine effective as long as possible. Both the Chlorine and Ammonia solutions are

12% (12 kg chemical in 0.1 m³ water). The actual dosage of a chemical is adjusted depending on the CBS water flowrate and the CBS inlet water chemical concentration. For instance, if the water flowrate is high or the CBS inlet water chemical concentration is low, more Chlorine will be fed into the water.

4.2 User requirement

In this section, the user requirements are discussed. From the customer point of view, the requirement is divided into two different categories. 1. The first category is flow volume where the user requires getting a desired volume of water. 2. The second category is the flow velocity where the user expects to be able to produce high water velocity (pressure) via some controlled orifice or jet such as a sprinkler system.

Requirement of flowrate:

For the users belonging to the first category, the water pressure is not an important concern, because the users may have their own water reservoir and pumping systems. What the users require is whether they can get the desired volume of water on demand. As shown in Figure 4.1 water is delivered into the reservoir and then pumped out for different applications. The water pressure is regulated by the user's own pump system. Examples of the first category users are Clavet, and P.C.S. Allan that are served by SaskWater.

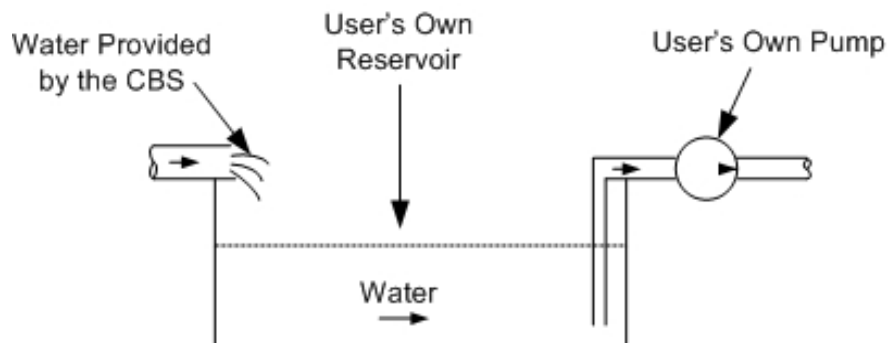


Figure 4.1 User own reservoir and pump system

Requirement of flow velocity:

For the users of the second category requirement, the water velocity from a valve is important, because the users expect to create high velocity water for irrigation, fire-fighting, etc. From a hydraulic point of view, this requirement really translates into having access to a suitable outlet pipeline pressure. This point will be clarified in the next section.

4.3 The orifice equation

In order to achieve high velocity at the outlet, it is necessary to have the discharge pressure before the outlet at some satisfactory value. Although there are various types of valves installed in water supply systems at the user end, the basis of operation of most valves is very similar; that is, the flowrate is controlled by varying the opening area of the valve orifice.

Consider Figure 4.2 (1); water flows from the left to the right through the pipeline. Consider the pipeline pressure at point A which is normally required to be stabilized by the water supplier. The downstream point of the orifice (Point B) is atmospheric pressure (usually assumed to be 0 Pa). Therefore, as the user opens the valve, a pressure difference exists across the valve, and as a result water flows out in a manner that is proportional to the orifice area and the pressure drop.

Consider Figure 4.2 (2); water flows through the small orifice of the valve. If the pressure drop is constant, then the users simply regulate the opening area of the orifice to get the desired flow, as shown by the basic orifice equation (assuming turbulent flow) in the following:

$$Q = C_d A \sqrt{\frac{2}{\rho} (P_u - P_d)} \quad \text{Eq (4.1)}$$

where:

Q is flowrate through orifice.

C_d is the discharge coefficient.

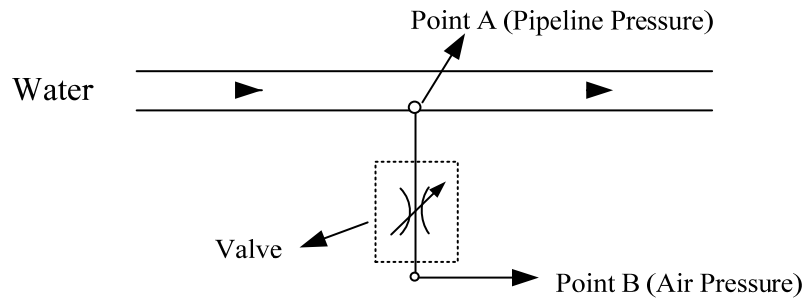
A is the opening area of orifice.

ρ is the fluid density.

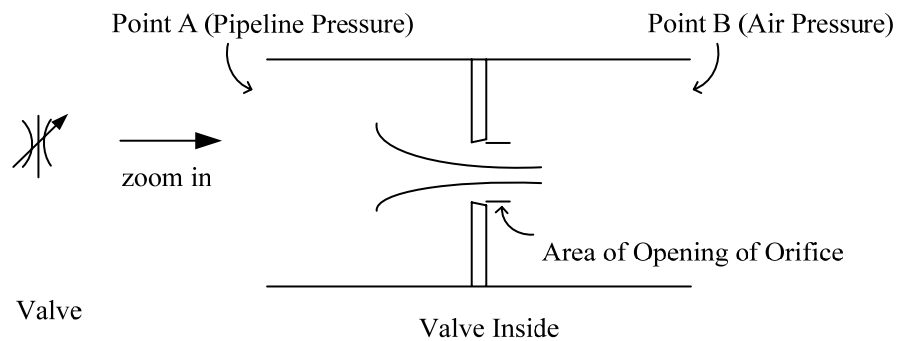
P_u is the upstream pressure of orifice (the pressure at Point A in Figure 4.2 (1)).

P_d is the downstream pressure of orifice (the pressure at Point B in Figure 4.2 (1)).

Since velocity of the fluid is simply the flow divided by the orifice area, that is $V = \frac{Q}{A} = C_d \sqrt{\frac{2}{\rho}(P_u - P_d)}$ then the user can also vary the outlet fluid velocity which for many sprinkler systems is a requirement. However, it is clear that if the pressure losses upstream to the discharge orifice are high, then the pressure at the outlet can be low resulting in low velocities even if the flow rate is acceptable.



(1) Valve Installed on Pipeline



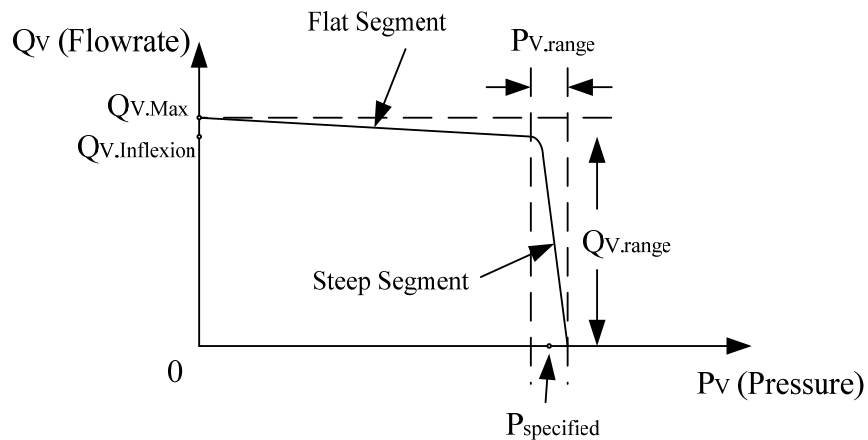
(2) Valve Inside Look

Figure 4.2 Schematic to illustrate the orifice equation

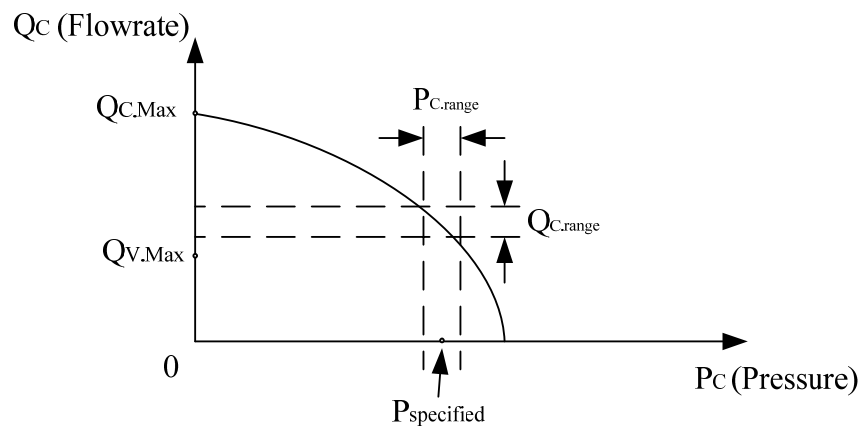
4.4 The pump characteristic curve

The pump characteristic curve is an important performance measure from which users design pipeline or hydraulic circuits. The curve provides information on how the pump discharge pressure changes with the variation in the pump discharge flowrate, and vice versa.

In most pump characteristic curves, the flowrate Q is plotted as the ordinate and the pressure P as the abscissa. Typical pump characteristic curves for Pumps #3 and #4 in the CBS are shown in Figure 4.3.



(1) VFD Controlled Pump #3



(2) Constant Speed Pump #4

Figure 4.3 Pump #3 and Pump #4 characteristic curves

Pump #3 pressure flow curve is typical of a VFD Controlled Pump (Figure 4.3 (1)). The pressure at the pump outlet is monitored and compared to a desired value. The error between the two is fed back to a controller which varies the frequency of the input signal to the pump's electric drive which in turn varies the shaft speed between the motor and pump until the error is minimized. With respect to Figure 4.3 (1), the dotted line would be the "ideal" characteristics whereas the solid line represents the practical operation. When the pump is at near maximum flow rating, (between Q_{vmax} and $Q_{vinflexion}$) the pressure can change as dictated by the load (line and user) resistances. Pressure is not controlled and thus user functions may not be satisfied at locations where fluid velocity at the outlets are important (sprinkler systems, fire suppression systems etc.). In the region where the pressure is approximately constant (P_{vrange}) the flow rate will vary with users' demands. In this region both the flow and pressure functions can be satisfied from the users' point of view.

With the VFD control, Pump #3 can achieve a better performance in comparison with the conventional constant speed pump. As long as the users' water demand is less than $Q_{vinflexion}$, Pump #3 can provide a nearly constant discharge pressure no matter how the water demand fluctuates.

Pump #4 (see Figure 4.3 (2)) is a constant speed unit. Pump #4 demonstrates a curve in which the pressure gradually increases with the decrease of flowrate. In order to satisfy the pressure function of the CBS, Pump #4 can only work in a small region ($Q_{C.range}$ and $P_{C.range}$). Outside of this region, the pump discharge pressure and flowrate cannot be maintained at the desired value. Thus, pump #4 is not a constant pressure system as pump #3 is (can be). It should be emphasized that because of the relationship between flow, pressure and outlet orifice area, the relationship between the flow and pressure functions becomes very complex.

For the CBS, the maximum $Q_{C.Max}$ of Pump #4 is bigger than the maximum $Q_{v.Max}$ of Pump #3. Consequently, if the uses' water demand exceeds what Pump #3 can deliver, (apparent when the pressure at the pump outlet drops significantly) the CBS controller will automatically switch to Pump #4 from Pump #3.

4.5 The operation of the pump system

The pump system is the core system in the CBS. As mentioned above, the water pressure and flowrate functions mainly depend on the appropriate operation of the pump system and the interrelationship between the functions can be very complex. In this section, an analysis of the pump system operation is presented. Figure 4.4 gives a schematic of the CBS which is used as a basis for discussion.

With reference to Figure 2.15, the CBS receives water from the City Water Treatment Plant (water intake), and then delivers water to the users (water discharge). It should be noticed that the water from the City is manageable; that is, it is assumed that the city can provide as much water as CBS requires.

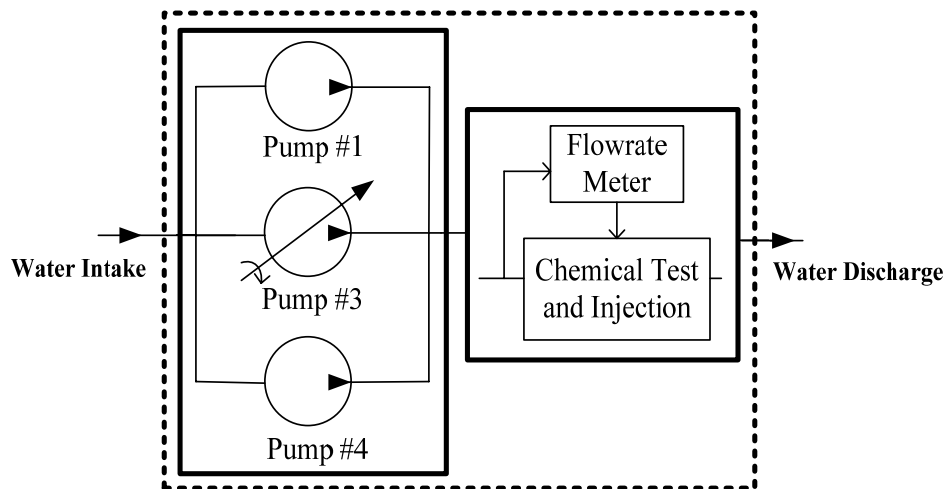


Figure 4.4 Schematic picture of the CBS

The pump operation sequence:

For most loading conditions, operation of pump #3 can satisfy user water demand. However,

- If the users' water flowrate increases and the desired discharge pressure of the CBS cannot be maintained above 0.62 MPa (90 PSI) for 300 seconds by Pump #3, then Pump #3 will shut off and Pump #4 will start.

- If a low flowrate is required below than $0.022 \text{ m}^3/\text{s}$ (or 350 GPM) for 300 seconds while Pump #4 runs then Pump #4 will shut off and the Pump #3 will start.

Figure 4.5 shows the control scheme of the CBS. Table 4.1 defines the operation of the signals. Switching between Pump #3 and Pump #4 is controlled automatically on site and is based on water pressure and flowrate. The pressure is measured by two pressure transducers at the CBS intake and discharge. The flowrate is measured by the flowrate meter at the CBS intake.

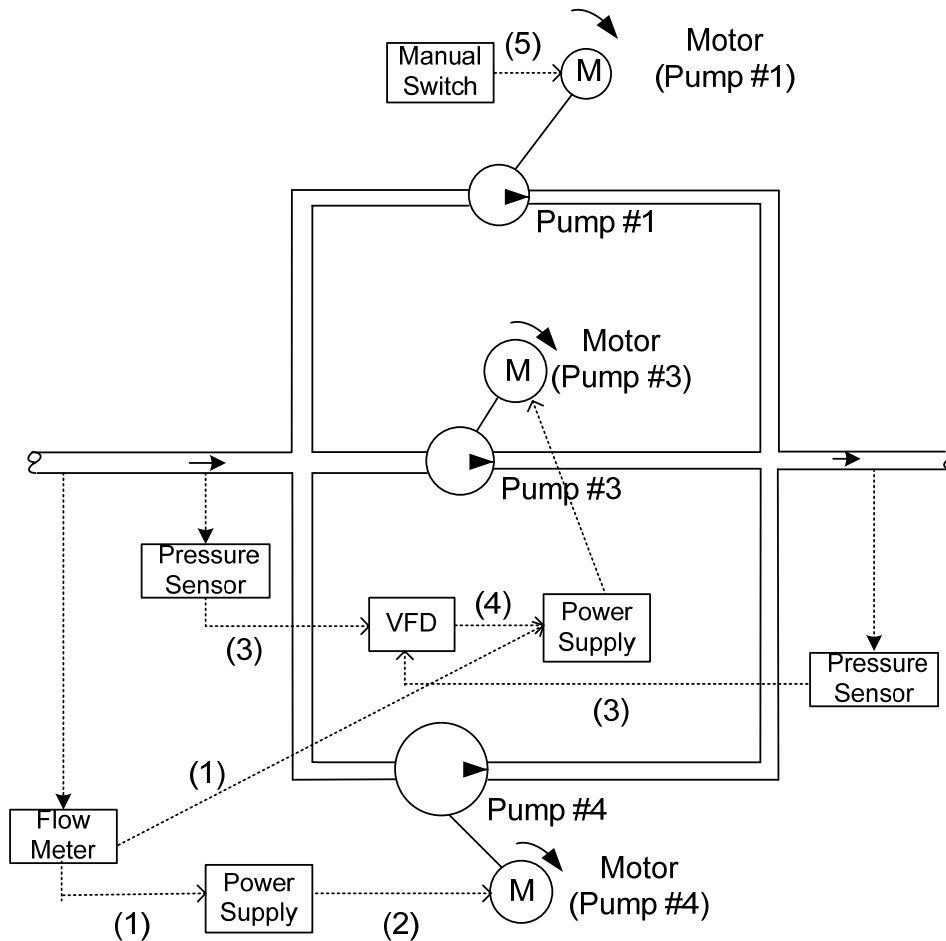


Figure 4.5 Control of the pump system

Pump #1 is normally not used but if required, can be activated remotely. Pump #2 has been removed from the CBS. Both of these units are constant speed pumps with operating characteristics similar to those shown in Figure 4.3 (2). Pump #3 is normally active and its speed is regulated by the AC power frequency to the motor. For the Pump #4 system, it operates

mainly following the pump characteristic curve. There is no other control unit, such as a VFD, or soft-starter in the Pump #4 system.

Table 4.1 Signals description

Signal No.	Description
Signal (1)	represents the signal of flowrate from the flow meter
Signal (2)	represents the electrical power to Pump #4.
Signal (3)	represents the pressure signals at the CBS intake and the CBS discharge.
Signal (4)	represents the VFD signal which is controlling the electrical power to Pump #3.
Signal (5)	represents the manual switch signal to the Pump #1.

4.6 Physical model of the chemical test and control system (CTCS)

The CTCS includes a set of components to accomplish the chemical test and injection task. With reference to Figure 4.6 the components of the CTCS are: a System Control and Data Acquisition (SCADA), an electrical panel, a junction box, a test unit, two vessels, a water level sensor, a tested water tank, a tested water pump, two chemical pumps, and two chemical-filled tanks.

Untested water first is sent to the Vessel B and Vessel A where the water is tested by the Test Unit. The tested water is sent to the tank and pumped back to pipe. The test result signal from the Test Unit is sent to the SCADA system and two chemical pumps. For example, if the chemical concentration is low, the chemical pump will increase its rotational speed and more chemicals will be injected into water. In the CBS, only Ammonia and Chlorine are injected to water. The other water quality factors, like NTU (nephelometric turbidity unit) and odor, are not tested.

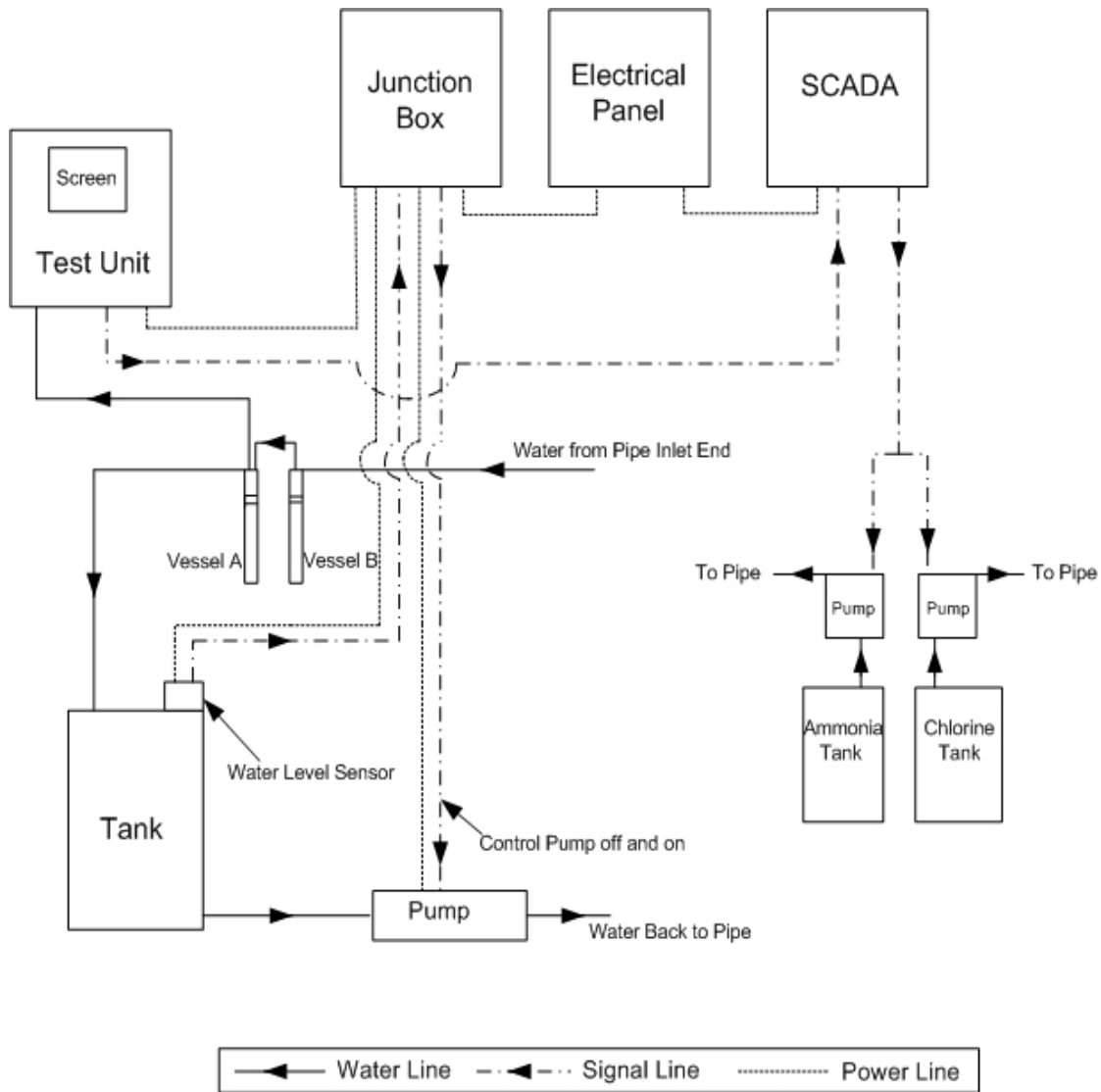


Figure 4.6 Schematic of the chemical test and control system (CTCS) in the CBS

Figure 4.7 reveals that the CTCS is a closed loop system. There are three important units: flow meter, chemical pumps and test unit. The actual flowrate of the CBS and the chemical concentration at the CBS discharge are measured. These two pieces of information via the test unit are sent to the SCADA system and then after processing, to the two chemical pumps. The two chemical pumps can automatically be switched on/off and the pump speeds can also be adjusted. The SCADA will alarm if the chemical concentration is out of safety range.

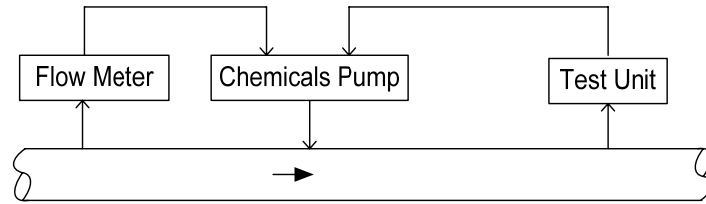


Figure 4.7 Closed loop system

4.7 Summary

In this chapter, a physical model of the CBS has been described. The model is important because it explains how the CBS operates and why the CBS operates in this way; for example, why a water demand increase will lead to the decrease of the CBS discharge pressure, and how the chemical test system operates under different conditions. The model also explains the principles that govern the CBS's behavior. The principles define how the CBS behaves and how it depends on the fundamental flow pressure relationships.

CHAPTER 5

RESILIENCE ANALYSIS METHODOLOGY

5.1 Introduction

Two overall objectives of this study were to develop an understanding of resilience and to introduce a means of system resilience “measure”. The first objective was presented in Chapter 3 in which the questions “what resilience is” and “why resilience is different from other similar concepts” were considered. The second objective is considered in this chapter where a new method for measuring system resilience is proposed. The concept underlying this method attempts to analyze from a quantitative point of view. As a result, a number will be obtained to represent the resilience index. It should be stressed that this number is not absolute in that only similar systems can be compared to determine relative resilience.

5.2 Resilience revisit and further background information

5.2.1 Recoverability is a key to resilience

As previously discussed in Chapter 3, resilience is a property of a system which measures how the system can still function by means of its own to a desired level after the system has been partially damage [Zhang, 2008]. According to this definition, it implies that recoverability is one step further in the measurement of resilience. The nature of resilience can be interpreted as system recoverability after damage. In a quantitative viewpoint, resilience can be measured by the number of ways of recovery. Generally speaking, the more ways of recovery, the more resilient a system is. It is also important to emphasize that resilience is focused on the ability of a system to recover from failure using its own internal sources.

Recoverability is categorized into two classes. The first class is “system reconfiguration” and the second is “replacement of components”. The two classes of recoverability are discussed below.

Reconfiguration: System reconfiguration is a major method for a resilient system to recover. For some resilient systems, the system structure contains flexibility. It is possible to recover the system function by changing the system's physical structure (for example, by-passing a leaking line by using an alternative route around the leak). As discussed in earlier chapters, one method of reconfiguration is function redundancy. Certain components can have more than one function: primary and secondary. The primary function is used in the normal operation whereas the secondary function can be utilized during emergency situations.

Replacement of Components: strictly speaking, resilience is about using system's own resource to recover. This implies that, with the understanding of resilience, no new component will be added into the "system" for recovery, whereas repairing puts emphasis on the use of external components. For example, if one pump in CBS is down and there is a spare (unused) pump in CBS by chance, the damaged pump can be replaced with the spare one, which will be considered as replacement of components.

5.2.2 Recovery process

The objective of this section is to clarify the understanding of how the recovery process contributes to system resilience. This section discusses recovery process from two aspects which are: defining what the dynamics of the recovery process are, and evaluating the indicators of resilience. The "dynamics" of the recovery process needs to be discussed in order to explain why the recovery process is considered as a "discrete event dynamic process" and why it is appropriate to analyze this process with certain project management tools.

The recovery process study mainly explains how the system resilience can be evaluated with different indicators (recovery time and cost). For example, in the CBS, suppose a certain component, say a pump, is damaged. If two or more recovery methods are found (which translates to a resilience index larger than one), which recovery method is better? A possible approach to this problem is to evaluate both the time for, and cost of, each recovery method. It is logical that the process which takes the smallest amount of time and the least cost could be the preferred choice.

1. Dynamics of the recovery process

In this thesis, the recovery process is considered as a “discrete event dynamic process” instead of a “continuous time dynamic process”. The recovery process is operated through a series of tasks. For example, after a pressure gauge failure has been identified at CBS, a group of workers will be “tasked” to fix the damage. According to the information provided by SaskWater, three normal tasks are followed:

1. Check the problem and decide what method is to be followed.
2. Repair or rebuild the component.
3. Adjust and check operation after repair.

The three tasks are usually managed in a step by step (sequential) manner. In other words, the beginning of one task should follow the completion of the previous task. The evolution of such recovery processes mainly depends on the occurrence of discrete events instead of by time. This kind of process is considered as a “discrete event dynamic process”, in which both the states of humans and the states of components change over certain “events”. For example, when damage happens in CBS, the states of pumps may change from operating to broken, and the states of SaskWater staff may change from standby to working. In addition, the occurrence of damage can be assumed to be discrete. Therefore, it is reasonable to view the recovery process as a discrete event dynamic process (which can be called a “macro process”).

In contrast to the “discrete even dynamic process”, there is another dynamic process called “continuous time dynamic process” (which can be called as a “micro process”). In the latter process, the states of system change continuously over time. For example, client water demand (flowrate) changes continuously over time. In residential areas, morning and evening water demands are normally higher than the demand at midnight. As another example, if Pump #3 of CBS starts running from zero to full speed (1750 RPM), the discharge flowrate of the Pump #3 will rise from 0 to 0.032 m³/s (or 510 GPM) without considering the client water demand. Based on SaskWater’s information, duration of such flowrate transition could take about 6 seconds. For

both examples, the dynamics associated with the flowrate change is continuous and hence the states of the substance (water) change over time.

It is found that the CBS system is a mixture of discrete event dynamic processes (e.g. the occurrence of damage) and continuous time dynamic processes (e.g. the flowrate transition of water). In a discrete event dynamic process (or a macro process), the time between the events could be substantial compared to a continuous time dynamic process (or a micro process). (For example, the pump discharge flowrate may change from 0 to 0.032 m³/s within 6 seconds (micro) but a pump breakdown may happen once per year (macro)). Therefore, the recovery process is mainly characterized as a discrete event dynamic process in the context of studying system resilience in this thesis.

2. Cost and time of the recovery process

If a system fails, there may be several recovery methods. For each recovery method, there is a recovery time and a recovery cost. The decision of choosing a recovery method can be determined (or evaluated) by comparing the cost and the time of each method. Two project management tools can be applied to study the recovery process in order to determine the time and cost. The details about the project management tools are introduced in Section 5.3.

It should be stressed that, in the author's opinion, there should be three indicators to evaluate the system resilience which are recovery cost, recovery time and recovery quality. The third, recovery quality is about whether the desired system function can be satisfied (fully or partially). The first two are discussed in this thesis. In the current stage of research, the third indicator, recovery quality, is not considered because of the added complexity it would add in this initial feasibility stage.

In summary, the dynamics of such a system are blended with discrete event and continuous time dynamic processes (or a mixture of macro and micro processes). In this study, the micro processes are not considered due to their short duration compared with the macro processes.

Since the events (e.g. component damage) in this study are macro, project management tools are suitable to analyze the recovery process. In the next section, these tools will be introduced.

5.3 Project management tools

In this section, a very brief discussion is presented to introduce the project management tools and the relevance between resilience and project management tools. Detailed information about project management tools is provided in Appendix A “Project Management Tools” where the applications of the project management tools are given.

Most projects can be divided into several tasks, some of which must be coordinated sequentially and some of which may be performed in parallel. To analyze and complete such projects, certain management tools have been widely used. The PERT (Project Evaluation and Review Technique) and the Gantt Chart are considered to have the good capability of assisting managers to reduce budget expenditures and to increase work efficiency.

The system resilience property is often reflected after damage. The recovery time and cost are important. The first factor pertains to recovery time of the process and the second factor is about the cost of the process. If this recovery process can be well managed, the total time and cost will be minimized. So the system will be more resilient. In project management studies PERT and Gantt Charts are two popular techniques to manage these tasks and as such can be used to examine the time sequencing and the cost of a recovery process.

5.4 Resilience analysis method

In this Section 5.4, the resilience analysis method will be proposed. This method is divided into two parts: Part 1: “Failure Analysis” in which the function loss and possible causes with respect to the function are investigated; Part 2: “Quantitative Resilience Measure” in which the possible recovery methods are considered. The two parts are combined together to be a complete methodology.

5.4.1 Failure analysis

The essence of resilience engineering is an emphasis on the function failure of a system. For example, in most water distribution systems, maintaining water pressure is a function. Control systems are designed to maintain pressure, and the field operator observes pressure variation through a pressure gauge or some other monitoring system e.g. SCADA. If pressure cannot be maintained, a function failure has occurred. A list of possible causes could be found to explain the function failure. In this thesis, the failure analysis is presented in the form of “If-Then Statements”. If the function is lost, then what are the causes? This is slightly different use of the If-Then approach in rule based expert systems for example where the “then” statement is a consequence of the if statement. Here the “then” statements are the causes. The failure analysis is very similar to the existing technique “Fault Tree” used in risk assessment. A simple example of the failure analysis is shown in Figure 5.1.

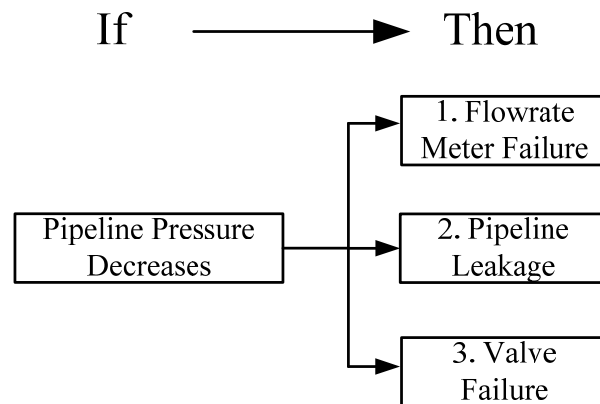


Figure 5.1 Failure analysis example

In this example, the function failure is a loss associated with a reduction of pressure. There are several possible causes for it, such as a “Flowrate Meter Failure”, “Piping Leakage” and “Gate Valve Failure”. The failure analysis usually is developed by experienced engineers who are working in the system. The purpose of failure analysis is to help system operators diagnose problem and schedule a recovery plan quickly.

In the entire resilience analysis methodology, the failure analysis (If-Then Statements) is the first step. It is then followed with the resilience measure as shown in section 5.4.2.

5.4.2 Quantitative resilience measure

As discussed in Chapter 3, existing studies involving resilience tend to focus on case studies and qualitative resilience analysis. From the aforementioned discussion, it can be seen that the resilience is strongly related to system recoverability after damage and perhaps can be measured using this event. In the following section, a novel resilience measure is proposed, which originates from a quantitative standpoint.

As introduced in section 5.2, a system can recover in a number of ways due to reconfiguration, and/or replacement of components. There are a number of ways a system can be reconfigured and/or replaced and thus it appears to be logical that a sum of the ways could be a reasonable method of quantitatively specifying a system's resilience. Mathematically this can be expressed as:

$$I_{RC} = I_C + I_R \quad \text{Eq (5.1)}$$

where I_{RC} is the total resilience index, I_R is the number of ways of reconfiguration, and I_C is the number of ways of replacing a component.

It must be emphasized that although the magnitude of the resilience number is a good indicator of a single system's ability to recover, the number has more impact in a relative sense when comparing two or more systems with similar function. For example, it is not reasonable to compare the resilience index between a pump and a pipe.

The definition of resilience index has been made quite simple in order to build upon its usage in application. As mentioned in the beginning of this Chapter, both time and cost influence resilience. The effect of the resilience number on total cost (or time) can be shown graphically in a form called the "resilience chart". The figure does not plot the cost as a function of the

resilience number but as a function of the particular “way” a system recovers. For example, suppose a system has a resilience index of four, $I_{RC} = 4$. The system can be expressed with the “resilience chart” as shown in Figure 5.2. The (1) beside the x-axis in Figure 5.2 represents the first way of recovery instead of one way of recovery. The (2) represents the second way of recovery instead of two ways of recovery. The y-axis expresses the time (cost) as a function of a specific way of recovery. The A represents that the first way of recovery has the time (cost) of A. The B represents that the second way of recovery has the time (cost) of B.

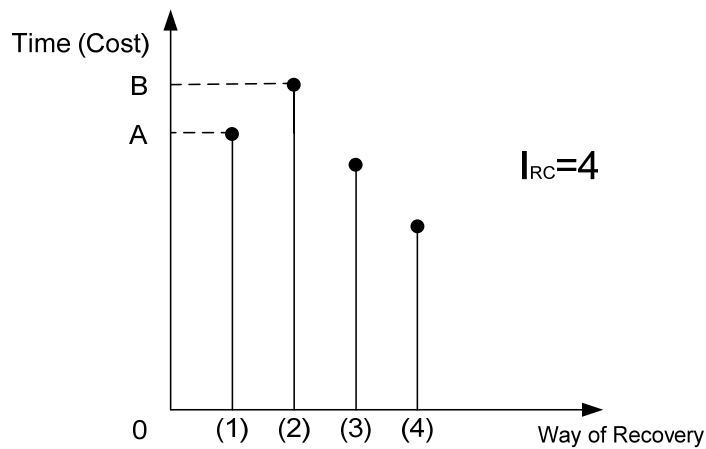


Figure 5.2 Resilience chart example (note that the numbers in brackets reflect the particular way of recover, not the total number of ways)

It should be mentioned that the recovery process will be modeled with the management tools (PERT and Gantt Chart) as discussed in the preceding section. The two factors (time and cost) will be analyzed by the two management tools.

5.5 An example for explaining the proposed resilience measure method

The resilience measure method is explained using a small water distribution system example as illustrated in Figure 5.3. The water distribution system example has nine pieces of pipe (A-B, C-D, D-E etc.). Water is normally delivered from location A to location F by route A-B-C-F (the blue line). This route contains three pieces of pipe (A-B, B-C, and C-F). If there is damage in one of A-B, B-C or C-F, the undamaged pipes in A-B-C-F combined with the remaining six pieces of

pipe (B-D, D-E etc.) can be reconfigured to recover water delivery. The system now will be examined for its resilience index.

It should be recalled that resilience is evaluated only as a consequence of damage at various levels and locations in the piping system. In the water distribution example, damage is assumed to occur in the pipes of A-B, B-C, and C-F. As a first step, assume that only one piece of pipe is broken; the consequence is a disruption of the water delivery function. The resilience index is calculated for each case (damage to A-B, damage to B-C, and damage to C-F). In the second step, the resilience index is calculated assuming two lines are damaged (damage to A-B&B-C, damage to A-B&C-F, or damage to B-C&C-F). As a last step, the resilience index is evaluated assuming three lines are broken (damage to A-B&B-C&C-F). For each step, calculation of the resilience index and establishment of the resilience chart are now considered.

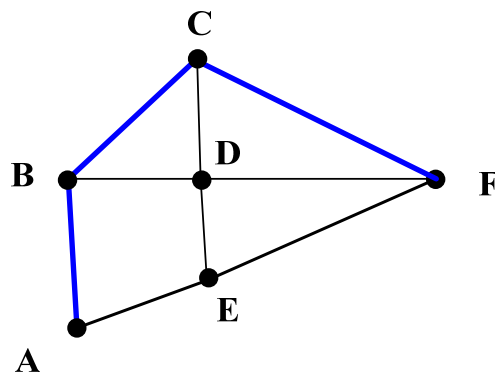


Figure 5.3 Water distribution system example

5.5.1 Failure analysis of the example system

The operating pipe system includes three pieces of pipes (pipes A-B, B-C, and C-F). If the pipe system function fails, the possible causes may be the failures of any combinations of the pipes A-B, B-C, and C-F. The If-Then Statement of the water distribution system example is given below in Figure 5.4.

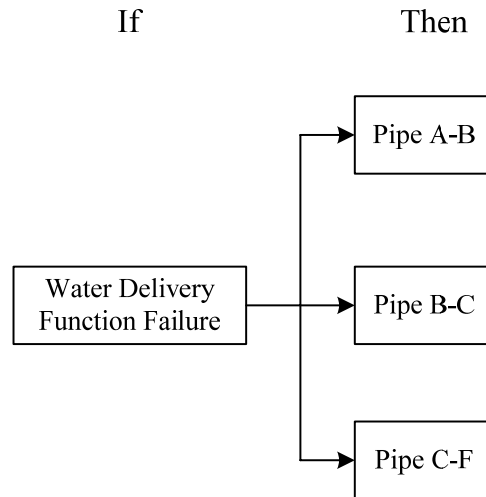


Figure 5.4 Failure analysis of water distribution system example

5.5.2 Resilience measure of the example system

5.5.2.1 One component damage resilience measure

(1) Resilience measure in the case of damage to pipe A-B

Consider the first step. As shown in Table 5.1, there are 4 ways to reconfigure the system. Obviously there is only one way for replacement. For illustration purposes only, some artificial cost and time estimates are assumed and are listed in Tables 5.1 and 5.2 for reconfiguration and replacement of pipe A-B damage.

For the reconfiguration method in Table 5.1, after failure, operators must open and close appropriate valves at the pipe connection nodes (such as nodes B and D in Figure 5.3) to make a new route for water delivery. It is assumed that travel time and physical labor for opening/closing one piece of pipe needs five working hours and costs \$250. For replacement of one failed pipe, it is assumed that the time for ordering and physically moving a single pipe into place is 48 hours at a cost of \$2000 (Note that moving two pipes would cost \$4000 but the time would still be two days). These numbers are now used to evaluate the total cost and time for each way of recovery.

With respect to Tables 5.1 and 5.2, there are four ways of system reconfiguration and one way of replacement of component in the case of damage to pipe A-B. Consider the third reconfiguration method in Table 5.1 as an example. Three pipes in the network (A-E, E-D, and D-B) can be used to recover the desired water deliver function. This means that pipes A-E, E-D, and D-B must be combined with the previous un-broken pipes B-C and C-F. Using the assumed costs in the previous paragraph, the time of reconfiguration is 15 hours and the cost is \$750 (opening/closing three valves to the pipes). If one now considers the fourth reconfiguration method as an example, two pipes (A-E and E-F) can be used. So the time of reconfiguration is 10 hours and the cost is \$500.

For this case, there are four ways of system reconfiguration (I_R is 4), and there is one way of replacement of component (I_C is 1). Therefore, the I_{RC} is 5 (from Eq. (5.1)).

Table 5.1 Reconfiguration of example system (damage: A-B)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-E-D-C-F	15	750
(2)	A-E-D-F	15	750
(3)	A-E-D-B-C-F	15	750
(4)	A-E-F	10	500

Table 5.2 Replacement of component of example system (damage: A-B)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	A-B	48 hours	2000 CAD

It may take the “Reconfiguration No. (1) A-E-D-C-F” in Table 5.1 as an example to explain the application of project management tools (PRER and Gantt Chart).

It is noted that, after damage of pipe A-B, the example water distribution system can be recovered with reconfiguration by opening pipe A-E, pipe E-D, and pipe D-C. Water is delivered through A-E-D-C-F. Three pieces of pipes are used to form a new water delivery line. Opening each pipe is assumed to cost \$250 and take 5 hours. Therefore the total cost is \$750 and 15 hours. The recovery process can be analyzed with PERT and Gantt Chart as shown in Figures 5.5 and 5.6.

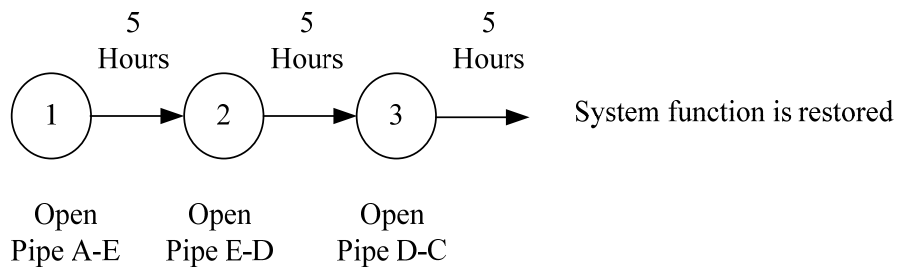


Figure 5.5 PERT of the example water distribution system

No	Task	Time							
		9:00	12:00	14:00	16:00	18:00	19:00	22:00	0:00
1	Open Pipe A-E	█							
2	Open Pipe E-D				█				
3	Open Pipe D-C						█		

Figure 5.6 Gantt Chart of the example water distribution system

Due to the simplicity of the example, it is not easy to reduce time and cost of the recovery significantly with PERT and Gantt Chart. However, it can be noted that the three tasks are managed in series. If operators can open the three pipes at the same time (or do the three tasks in parallel), the total time can be reduced from 15 hours to 5 hours.

Figures 5.7 and 5.8 show the resilience charts of the above example system with respect to time and cost as a function of ways of recovery.

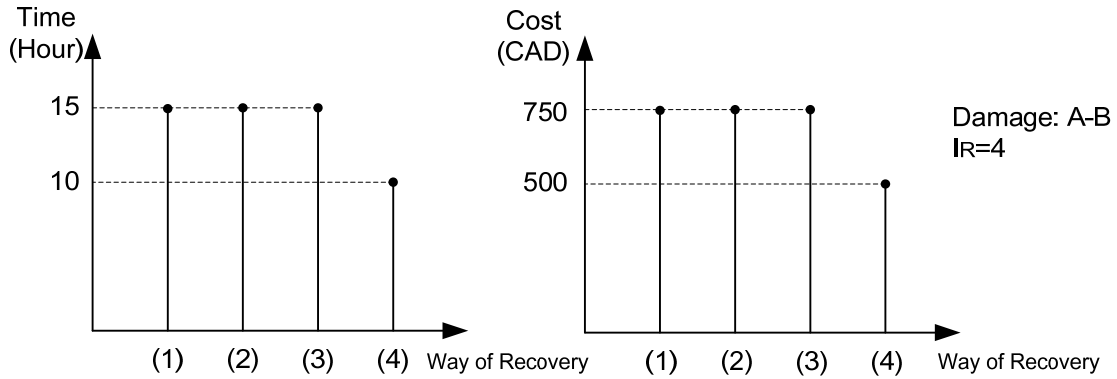


Figure 5.7 Resilience chart of reconfiguration (damage: A-B)

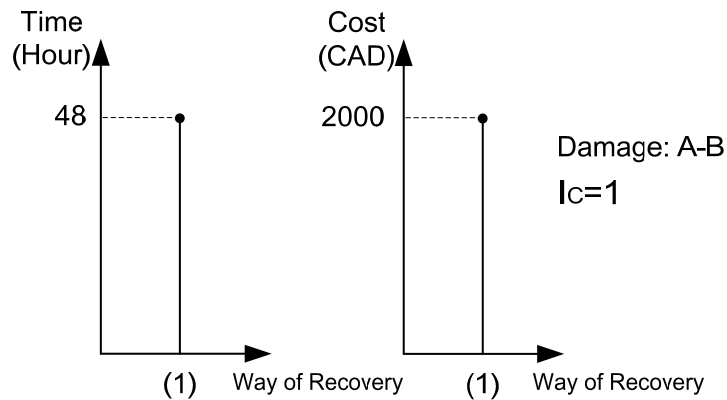


Figure 5.8 Resilience chart of replacement of component (damage: A-B)

(2) Resilience measure in the case of damage to pipe B-C

Using the same cost and time as was used in the previous example, Tables 5.3 and 5.4 list the cost and time results for the reconfiguration and replacement of components for the case of damage to pipe B-C. It can be shown that I_R is 6, and I_C is 1. Subsequently, the resilience index I_{RC} is 7.

Table 5.3 Reconfiguration of example system (damage: B-C)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-B-D-C-F	10	500
(2)	A-B-D-E-F	15	750
(3)	A-B-D-F	10	500
(4)	A-E-D-C-F	15	750
(5)	A-E-D-F	15	750
(6)	A-E-F	10	500

Table 5.4 Replacement of component of example system (damage: B-C)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	B-C	48 hours	2000 CAD

Figures 5.9 and 5.10 show the resilience charts for reconfiguration and replacement of components.

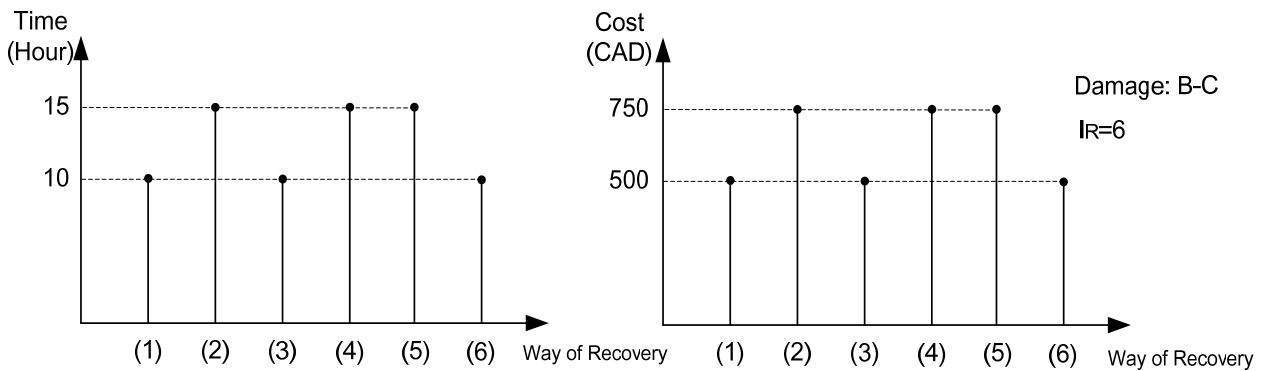


Figure 5.9 Resilience chart of reconfiguration (damage: B-C)

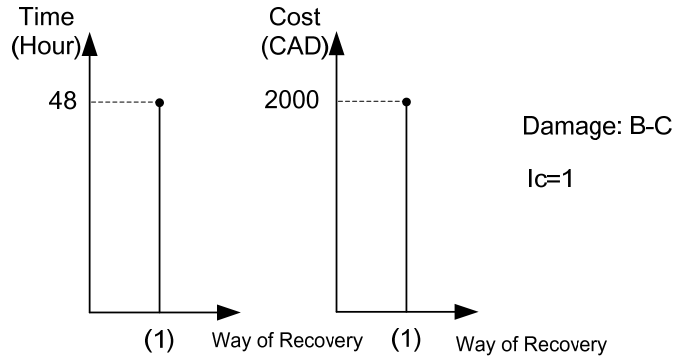


Figure 5.10 Resilience chart of replacement of component (damage: B-C)

(3) Resilience Measure in the Case of Damage to Pipe C-F

Using the same cost and time as was used in the previous example, Tables 5.5 and 5.6 list the cost and time results for the reconfiguration and replacement of components for the case of damage to pipe C-F. It can be shown that I_R is 6, and I_C is 1. Subsequently, the resilience index I_{RC} is 7.

Table 5.5 Reconfiguration of example system (damage: C-F)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-B-C-D-F	10	500
(2)	A-B-C-D-E-F	15	750
(3)	A-B-D-F	10	500
(4)	A-B-D-E-F	15	750
(5)	A-E-D-F	15	750
(6)	A-E-F	10	500

Table 5.6 Replacement of component of example system (damage: C-F)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	C-F	48 hours	2000 CAD

Figures 5.11 and 5.12 show the resilience charts for reconfiguration and replacement of components.

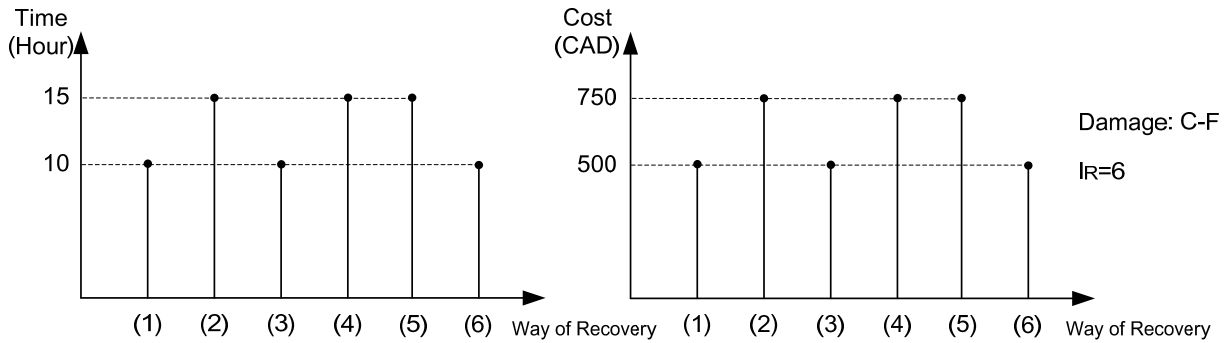


Figure 5.11 Resilience chart of reconfiguration (damage: C-F)

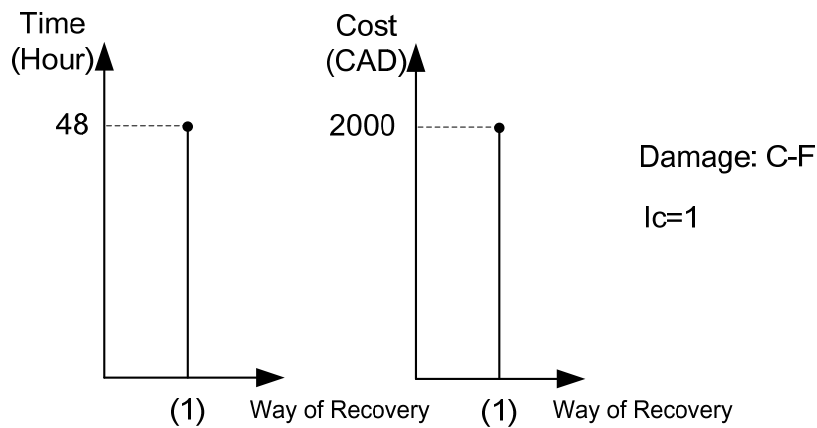


Figure 5.12 Resilience chart of replacement of component (damage: C-F)

5.5.2.2 Two component damage resilience measure

(1) Resilience measure in the case of damage to pipe A-B, B-C

Using the same cost and time as was used in the previous example, Tables 5.7 and 5.8 list the cost and time results for the reconfiguration and replacement of components for the case of damage to pipes A-B, B-C. It can be shown that I_R is 3 and I_C is 1. Subsequently, the resilience index I_{RC} is 4.

Table 5.7 Reconfiguration of example system (damages: A-B, B-C)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-E-D-C-F	15	750
(2)	A-E-D-F	15	750
(3)	A-E-F	10	500

Table 5.8 Replacement of components of example system (damages: A-B, B-C)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	A-B, B-C	48	4000

Figures 5.13 and 5.14 show the resilience charts for reconfiguration and replacement of components.

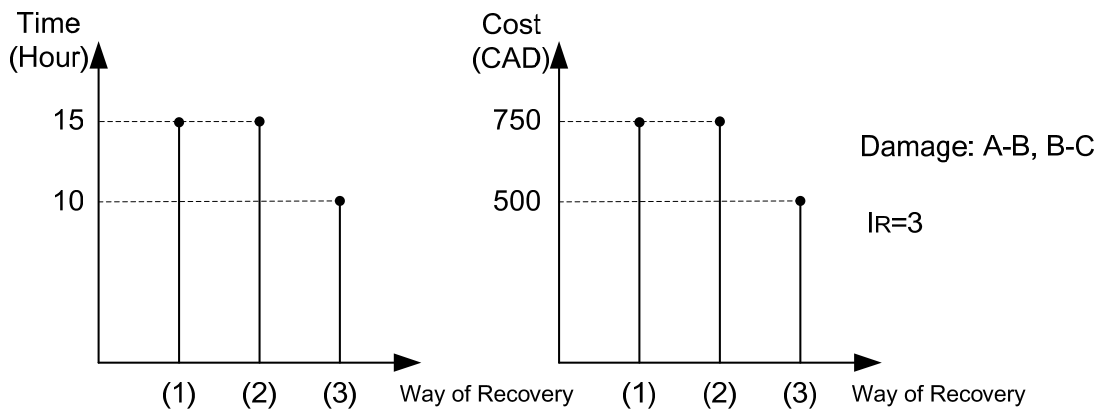


Figure 5.13 Resilience chart of reconfiguration (damages: A-B, B-C)

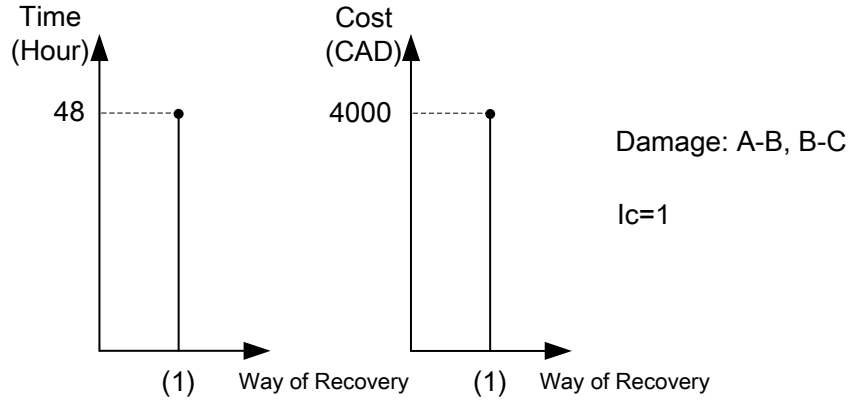


Figure 5.14 Resilience chart of replacement of components (damages: A-B, B-C)

(2) Resilience measure in the case of damage to pipe A-B, C-F

Using the same cost and time as was used in the previous example, Tables 5.9 and 5.10 list the cost and time results for the reconfiguration and replacement of components for the case of damage to pipes A-B, C-F. It can be shown that I_R is 2, and I_C is 1. Subsequently, the resilience index I_{RC} is 3.

Table 5.9 Reconfiguration of example System (damages: Pipe A-B, C-F)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-E-D-F	15	750
(2)	A-E-F	10	500

Table 5.10 Replacement of components of example system (damages: pipe A-B, C-F)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	A-B, C-F	48	4000

Figures 5.15 and 5.16 show the resilience charts for reconfiguration and replacement of components.

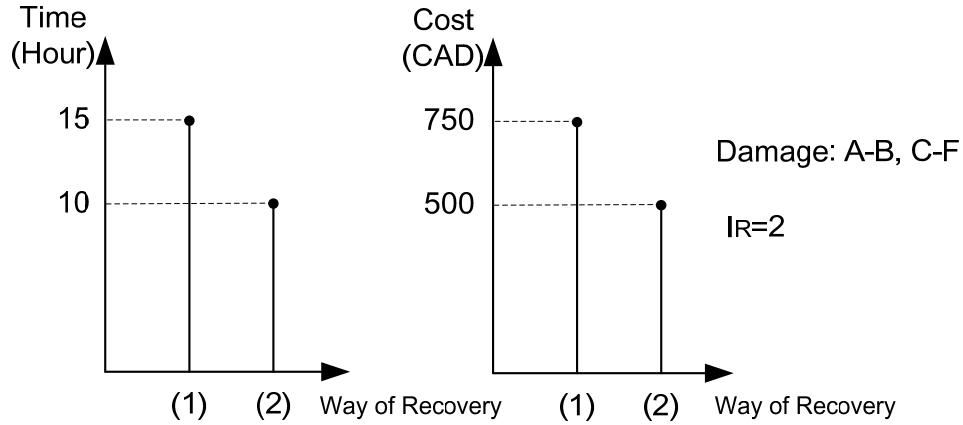


Figure 5.15 Resilience chart of reconfiguration (damages: A-B, C-F)

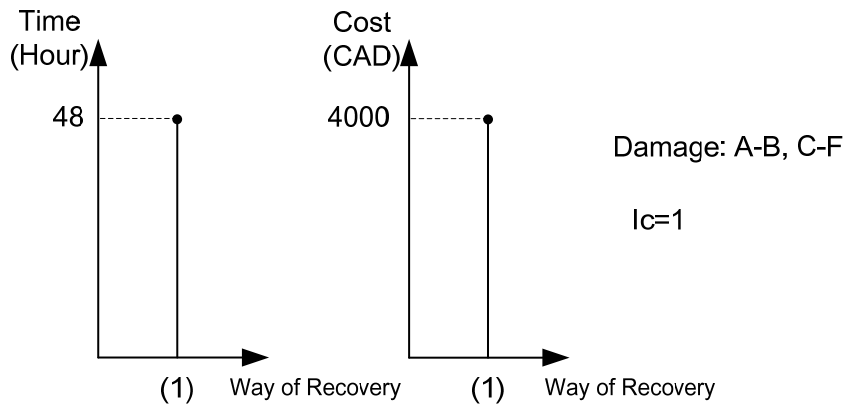


Figure 5.16 Resilience chart of replacement of component (damages: A-B, C-F)

(3) Resilience Measure in the Case of Damage to Pipes B-C, C-F

Using the same cost and time as was used in the previous example, Tables 5.11 and 5.12 list the cost and time results for the reconfiguration and replacement of components for the case of damage to pipes B-C, C-F. It can be shown that I_R is 4, and I_C is 1. Subsequently, the resilience index I_{RC} is 5.

Table 5.11 Reconfiguration of water distribution system example (damages: B-C, C-F)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-B-D-F	10	500
(2)	A-B-D-E-F	15	750
(3)	A-E-D-F	15	750
(4)	A-E-F	10	500

Table 5.12 Replacement of component of water distribution system example (damages: B-C, C-F)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	B-C, C-F	48	4000

Figures 5.17 and 5.18 show the resilience charts for reconfiguration and replacement of component.

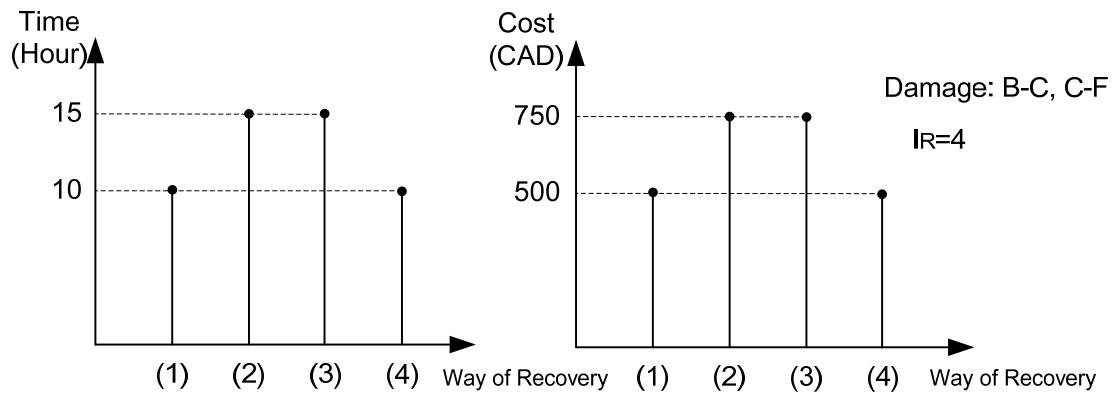


Figure 5.17 Resilience chart of reconfiguration (damages: B-C, C-F)

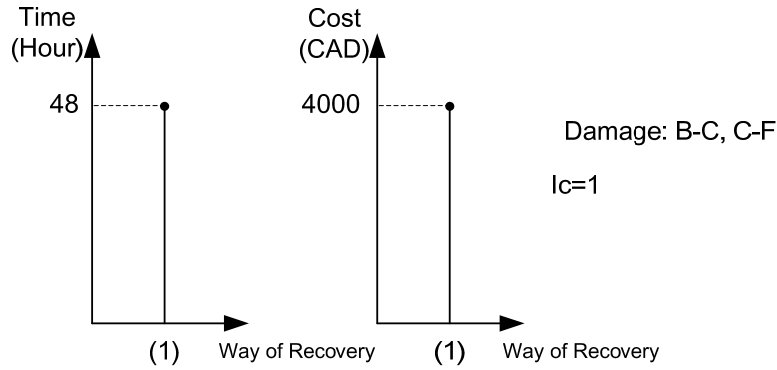


Figure 5.18 Resilience chart of replacement of component (damages: B-C, C-F)

5.5.2.3 Three component damage resilience measure

(1) Resilience measure in the case of damage top pipes A-B, B-C and C-F

Using the same cost and time as was used in the previous example, Tables 5.13 and 5.14 list the cost and time results for the reconfiguration and replacement of components for the case of damage to pipes A-B, B-C, and C-F. It can be shown that I_R is 2, and I_C is 1. Subsequently, the resilience index I_{RC} is 3. Figures 5.19 and 5.20 show the Resilience Chart.

Table 5.13 Reconfiguration of example system (damage: A-B, B-C, C-F)

Reconfiguration No.	Reconfiguration Method	Time (Hour)	Cost (CAD)
(1)	A-E-D-F	15	750
(2)	A-E-F	10	500

Table 5.14 Replacement of components of example system (damage: A-B, B-C, C-F)

Replacement of Component No.	Replacement of Component	Time (Hour)	Cost (CAD)
(1)	A-B ,B-C, C-F	48	6000

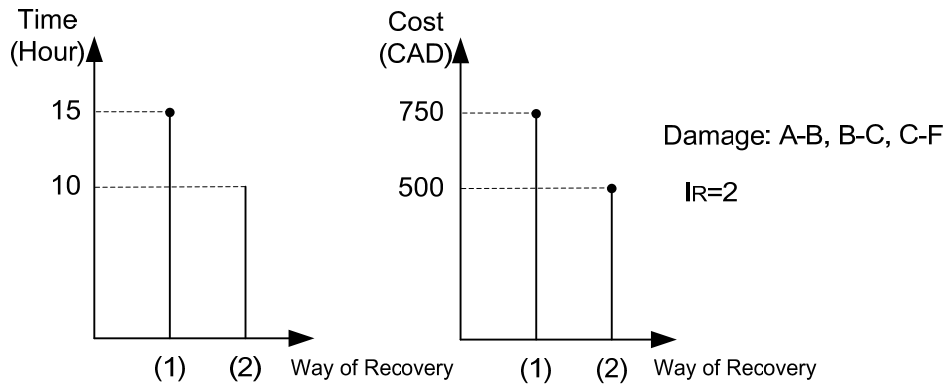


Figure 5.19 Resilience chart of reconfiguration (damage: A-B, B-C, C-F)

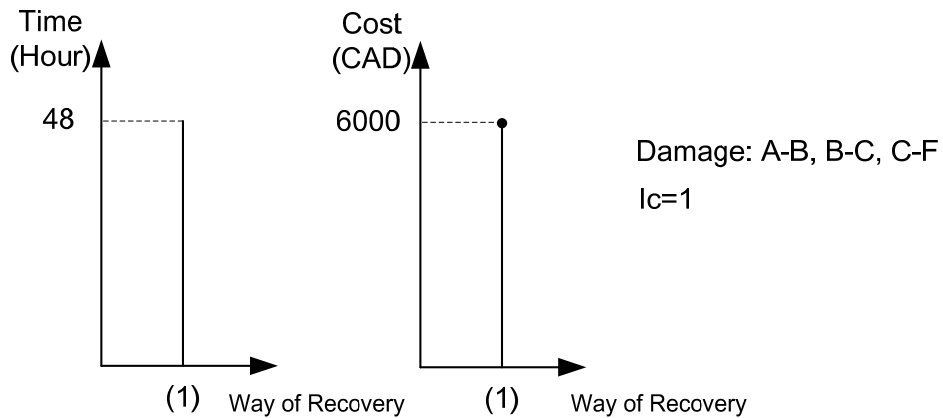


Figure 5.20 Resilience chart of replacement of component (damage: A-B, B-C, C-F)

5.5.3 Example discussion

In the above analysis, resilience is measured for six different cases of damage. The number of damaged component varies from one to three. The resilience chart provides useful information about system resilience with respect to two factors (time and cost) which are greatly concerned in practice.

Several things can be found in the above discussion. First, if more components are damaged, relatively few ways are available to recover the system function; system resilience drops off. Second, reconfiguration is a better way from a budget point of view because less money is spent

than for replacement. Third, if a system has more components with the redundancy feature, the system has a high possibility to recover.

Although this is not considered in this thesis, it is believed that overall resilience should include some weighting between all cases (from one component damage to multiple component damage). This will be discussed in greater detail in the recommendations for future research.

5.6 Summary

The chapter has introduced a new resilience analysis methodology. The novel part is that this method can measure a system's resilience quantitatively by the number of recovery ways. The methodology consists of two steps: (1) failure analysis which is used to relate the function loss with the possible causes, and (2) the resilience measure which quantitatively measures resilience. A simple example was considered in which the resilience index were quite high.

The next chapter applies the techniques discussed herein and preceding chapters to a particular example, the Clarence Booster Station.

CHAPTER 6

THE APPLICATION OF RESILIENCE ANALYSIS METHODOLOGY TO SASKWATER CLARENCE BOOSTER STATION

6.1 Introduction

As presented in Chapter 3, system resilience has been considered in a qualitative sense by many researchers. It still remains a challenge to develop new methods to analyze resilience from a quantitative standpoint. In Chapter 5, a new quantitative resilience analysis methodology was described. In this Chapter, this new methodology is applied to a practical example –SaskWater Clarence Booster Station (CBS).

It must be noted that the example so chosen was made in parallel to the development of the definition of resilience and the resilience index. As such, there was no preconceived notion of how resilient the CBS was and what form the final analysis would take. Hence the process of developing the definitions and gathering data on the CBS were done in an independent fashion.

6.2 Review of the proposed resilience analysis methodology

The proposed resilience analysis methodology includes two steps. The first step is “failure analysis”. It clarifies the relationship between system function failure and the possible causes of the function failure, in the form of “If-Then Statements”.

The second step is “resilience measure” which quantitatively measures resilience with respect to the possible causes identified in the “failure analysis” step. In this stage of research, the possible causes are assumed to be component damage. The components in the “resilience measure” were selected based on information provided by SaskWater (most components have been damaged at one time or the other). For each case of component damage, the resilience index is obtained by defining the possible ways of recovery. The project management tools are applied to analyze the

recovery process in order to estimate the recovery time and recovery cost. The two steps (failure analysis and resilience measure) can be illustrated in Figure 6.1.

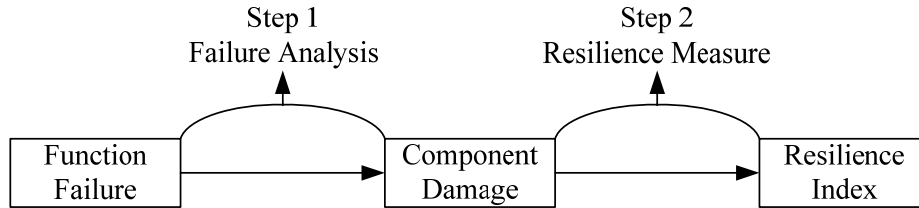


Figure 6.1 Two steps of resilience analysis methodology

6.3 Relevant information review

Project management tools (PERT and Gantt Chart) are used to estimate the time and cost of recovery process. In this thesis, time and cost are chosen as two indicators to evaluate the system resilience. The recovery process consists of several small tasks. Properly managing these tasks has an influence on the final system recovery time and recovery cost. For details of project management tools, please refer to Section 5.3 and Appendix A “Project Management Tools”.

If-Then Statements are used to relate the function failure and the possible causes. “If-Then Statements” have a slightly different use compared with the rule based expert system. The “If” statement defines the function failure, and the “Then” statement defines the causes of function failure. For details, please refer to Section 5.4.1.

Resilience charts are used to graphically summarize the ways of recovery (reconfiguration and replacement of components). At the same time, resilience charts express the time and cost for each possible recovery method. For details of the resilience chart, please refer to Section 5.4.2.

6.4 Assumptions

In order to simplify the proposed resilience analysis methodology, four assumptions are made:

Assumption No.1: Component damage is considered in a “discrete fashion”. That is, the component is considered to be completely damaged or not damage. Partial damage is not studied.

Assumption No.2: Component damage is considered to have an “immediate effect” on the overall system. From the occurrence of component damage to the system function failure, the time duration is very short. Therefore, it is ignored in this thesis.

Assumption No.3: Cost estimates have been provided by SaskWater. However, time for system recovery process is not well known and as such, values have been “artificially assigned” in order to illustrate the application. The time estimates have been vetted with SaskWater personnel who agree that these estimates are in the “ballpart”.

Assumption No.4: Only two states of recovery are considered, namely “full recovery” and “no recovery at all”. Further, the criterion to assess these two states is not explicitly considered but left for its definition associated with a particular application.

6.5 Application to SaskWater Clarence Booster Station (CBS)

6.5.1 Failure analysis

The first step, “failure analysis”, is presented in this section. First, with reference to the content in Section 2.3, CBS has two major functions which are maintaining water pressure and treating water. The two functions are accomplished by related subsystems or components. Second, it is possible to establish the “If-Then Statements” in order to express the two function failures and the possible causes (component damages). Third, though there are many components in CBS, only a selected number of components are used for “resilience analysis” to prevent this initial investigation from becoming too complicated.

The subsystems and components of two CBS functions are listed in Table 6.1. The first row is for the Pump System (PS) which supports the “maintaining water pressure” function. The second

row is for the Chemical Test and Control System (CTCS) which supports the “treating water” function.

Table 6.1 Three CBS functions and their subsystem/components

No.	Function	Subsystem	Major Components				
1	Maintain Pressure	Pump System (PS)	Pump& Motor #1	Pump& Motor #3	Pump& Motor #4	SCADA	Pressure Gauge
2	Treat water	Chemical Test and Control System (CTCS)	Test Unit	Chemical Pump	SCADA	N/A	N/A

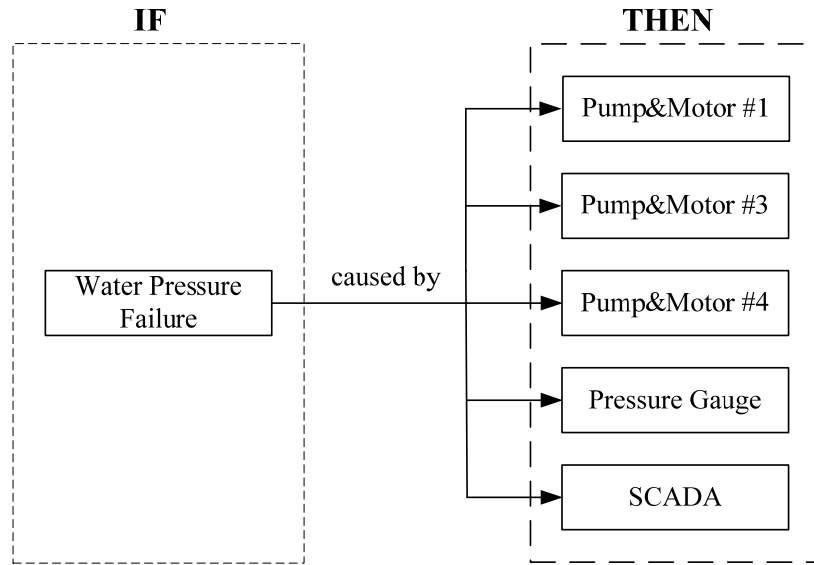
The failure analysis relates the function failure with the possible causes using the form “If -Then Statements”. The “If-Then Statements” of two functions of CBS are given in Figure 6.2. The left dotted box refers to “IF”. The right dotted box refers to “THEN”.

In Figure 6.2, there are two “If-Then statements”. If water pressure function failure occurs, the causes of failure may be damage of Pump & Motor #1, damage of Pump & Motor #3, damage of Pump & Motor #4, damage of Pressure Gauge, or damage of SCADA. In Figure 6.2 (2), if water quality function failure occurs, the causes of failure may be due to damage of the Test Unit, damage of SCADA, or damage of Chemical Pump.

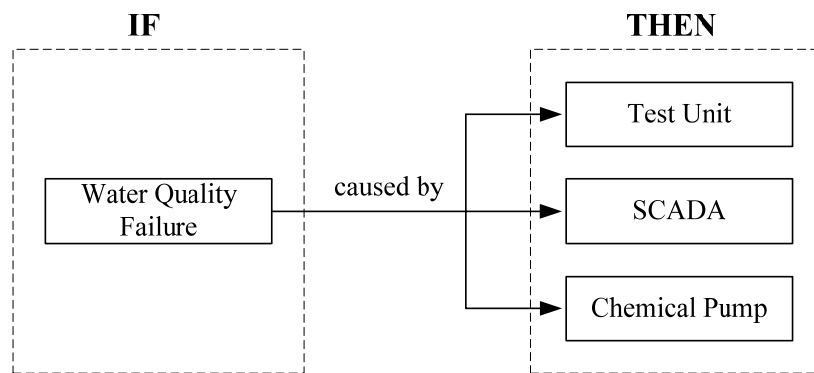
Once a system function fails, the causes are considered to be component damage and for each of these conditions, the resilience is obtained.

6.5.2 Quantitative resilience measure

In this section, the resilience of two subsystems is measured from “one component damage” condition to the case where all components in that category are in the “all component damage” condition. The procedure is to consider resilience of each subsystem for one component damage, two component damage, three component damage, etc. For each damage condition, the number of ways of recovery is obtained and presented as the resilience index.



(1) If-Then Statement of Maintaining Water Pressure



(2) If-Then Statement of Treating Water

Figure 6.2 If-Then statement regarding CBS

For the pump system (PS), there are 63 combinations of damage conditions (based on six components). For the CTCS, there are 7 combinations of damage conditions (based on three components). Table 6.2 shows the details of all possible damage conditions. The number in Table 6.2 is calculated by finding all possible combinations from all components.

Mathematically, this calculation is from the formula $\sum_{i=1}^N {}_N C_i$ where “N” equals to the total number of components in a subsystem and “i” equals to the number of damaged components. For instance, there are 7 ways of total damage conditions for CTCS. The number “7” is calculated in this way:

$$\sum_{i=1}^3 {}_3C_i = {}_3C_1 + {}_3C_2 + {}_3C_3 = \frac{3!}{1!(3-1)!} + \frac{3!}{2!(3-2)!} + \frac{3!}{3!(3-3)!} = 3 + 3 + 1 = 7.$$

Table 6.2 Damage conditions for two subsystems (PS and CTCS)

Subsystem	Total Damage conditions	Damage of one component	Damage of two components	Damage of three components	Damage of four components	Damage of five components	Damage of six components
PS	63	6	15	20	15	6	1
CTCS	7	3	3	1	N/A	N/A	N/A

6.5.2.1 Resilience measure for PS

6.5.2.1.1 Damage to Pump & Motor #1 only

Pump & Motor #1 is a backup pump. The failure of Pump & Motor #1 will not affect the normal operation of CBS.

6.5.2.1.2 Damage to Pump & Motor #3 only

In this example, the recovery method is by “Reconfiguration”.

When Pump & Motor #3 is damaged, a possible reconfiguration method is to retrofit Pump & Motor #4 with the VFD from Pump & Motor #3 and to bring pump #4 on line. Therefore, water pressure can be maintained regardless of the variation of water flowrate (or water demand). As noted in the assumptions, replacement of pump #3 with #4 without the VFD constitutes a quality-reduced (or partial) recovery because flow to consumer can be maintained but the pressure function cannot be achieved. This is an example of partial recovery and is not covered by this resilient definition at this time. This will be commented upon in Chapter 7. As noted in the assumptions, replacement of pumps #3 with #4 without the VFD constitutes a quality recovery issue because flow to the consumer can be maintained but the pressure function cannot be achieved. As stated in Assumption #4, this is not covered by this resilient definition at this time. This will be commented upon in Chapter 7.

According to SaskWater information, the possible reconfiguration process will include five steps. In the bracket of each step, the required time, the types of cost, and the required staff are given. The labor cost is determined at the rate of \$60 per hour. The material cost in step 4 is \$100. For instance, step 4 needs 48 hours. So the labor cost is \$2880 (48 times 60). The total cost includes labor cost (\$2880) and material cost (\$100) for step 4.

- 1) Evaluate the problem (2 hours/labor cost/operation staff).
- 2) Decide the reconfiguration solution details (24 hours/labor cost/operation staff and management staff).
- 3) Contact SaskWater electrical/instrumentation staff in headquarter and wait for the specialist (24 hour/labor cost/operation staff).
- 4) Do the reconfiguration task (48 hours/labor cost and operation material cost/ operation staff and electrical/instrumentation staff).
- 5) Check operation (4 hours/labor cost/operation staff).

As introduced in Section 5.2, the recovery time and recovery costs are two indicators of the system resilience. For each reconfiguration step, the time and cost are given in Table 6.3. To estimate the time and cost, the PERT and Gantt Chart were applied to each reconfiguration and this is now expanded upon.

Table 6.3 Time and cost information for damage of Pump & Motor #3

Reconfiguration Step	Task	Time (Hour)	Cost (\$)
(1)	Evaluate the problem	2	120
(2)	Decide the reconfiguration solution	24	1440
(3)	Contact SaskWater electrical/instrumentation staff and wait the required specialist	24	1440
(4)	Do the reconfiguration task	48	2980
(5)	Check operation	4	240

Consider the PERT of the reconfiguration method for Pump & Motor #3 damage without re-organization. The normal reconfiguration process is shown in Figure 6.3 for each step (task) defined in Table 6.3. Recovery is finished and system is back on line.

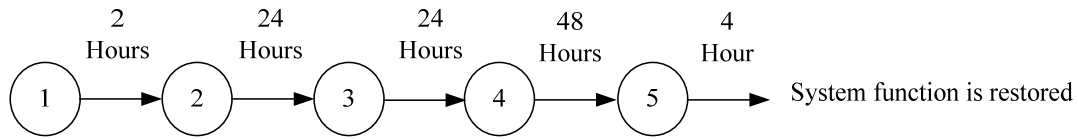


Figure 6.3 PERT of the reconfiguration method for Pump & Motor #3 damage without re-organization

These five tasks can be re-organized as shown in Figure 6.4 and as a result, the total time could be reduced from 102 hours to 78 hours. The cost could be reduced from \$6220 to \$4780. The saving of labor cost for 24 hours (102 minus 78) is \$1440 (6220 minus 4780).

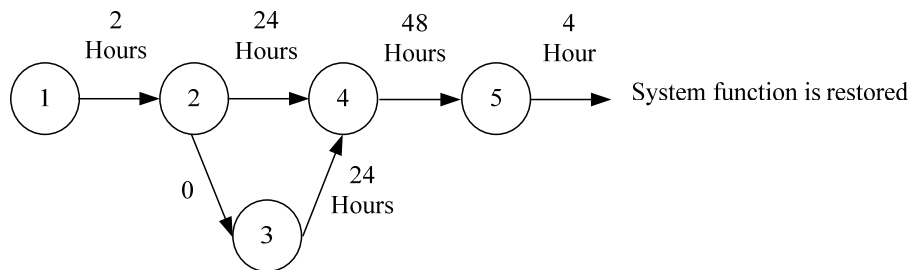


Figure 6.4 PERT of the reconfiguration method for Pump & Motor #3 damage after re-organization

Consider the Gantt Chart of the reconfiguration method for Pump & Motor #3 damage without re-organization. The normal reconfiguration process is shown in Figure 6.5.



Figure 6.5 Gantt Chart of the reconfiguration method for Pump & Motor #3 damage without re-organization

These five tasks can be re-organized via “project management” as shown in Figure 6.6 and as a result, the total time could be reduced from 102 hours to 78 hours. In addition, the cost could be reduced from \$6220 to \$4780. As would be expected, the results are the same as for PERT and hence the tool which can be chosen depends on the preference of the user.

As illustrated, the time of reconfiguration is considered to be 78 hours and the cost of reconfiguration is \$4780. There is no spare pump at CBS which can replace the Pump & Motor #3. Therefore, I_C is 0. I_R is 1. I_{RC} is 1. Figure 6.7 shows the resilience charts of reconfiguration with respect to time and cost without re-organization. It should be noted that a new pump could be ordered if replacement was not feasible but this would mean that the output function would be disturbed for considerable time and hence is not an indicator or resilience in this case. If a new pump could be replaced in a matter of hours from a local manufacturer, then it would be argued that this as part of the resilience index. However, since the definition of resilience focuses on internal sources for replacement, then this would not be the case.

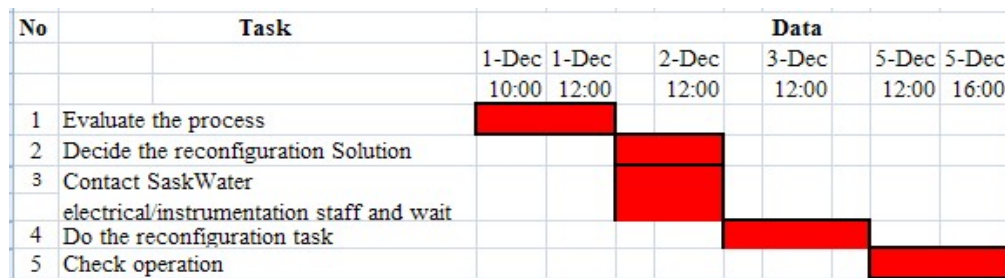


Figure 6.6 Gantt Chart of the reconfiguration method for Pump & Motor #3 damage after re-organization

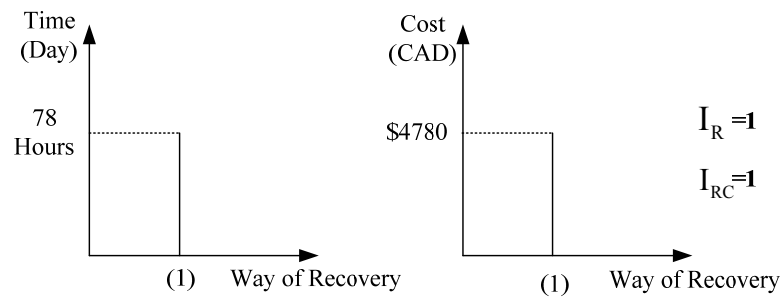


Figure 6.7 Resilience Chart of Reconfiguration without re-organization (Damage: Pump & Motor #3)

6.5.2.1.3 Damage to Pump & Motor #4 Only

Pump & Motor #4 has a bigger capacity and would be started when client water demand (or flowrate) increases. There is no reconfiguration method if Pump & Motor #4 is damaged. According to the SaskWater’s information, there is no redundant pump which can replace Pump & Motor #4 in CBS. In the case of Pump & Motor #4 damage, the “maintaining water pressure” function will fail. Therefore, I_R is 0. I_C is 0. I_{RC} is 0. Note that in this case, pump #3 can still be used but it cannot meet the demand flow and hence the desired pressure cannot be sustained. It would be considered as the quality of the failure which is not considered in this analysis.

6.5.2.1.4 Damage to Pressure Gauge

In this example, the recovery method is by “Replacement of components”.

The pressure gauge is used to measure the discharge water pressure. The pressure information is sent to SCADA which in turn controls the VFD (which varies the pump shaft speed). There is a spare pressure gauge in CBS. Once the working pressure gauge is damaged, it can be replaced with the spare one within the “source”. According to SaskWater information, the “replacement of components” process will be as follows. In the bracket, the required time, type of cost, and type of staff are given.

- 1) Check problem (1hour/labor cost/operation staff).
- 2) Discuss solution (2 hours/labor cost/operation staff and management staff).
- 3) Replace the damaged pressure gauge (4 hours/labor cost/operation staff).
- 4) Check operation and adjustment (1 hour/labor cost/operation staff).

As was done in the first example, PERT and the Gantt chart are applied to the steps (tasks). Figure 6.8 show the recovery process using PERT.

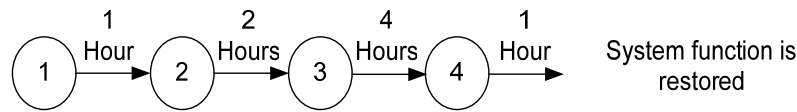


Figure 6.8 PERT of the “replacement of components” method for Pressure Gauge damage

From Figure 6.8, the total time for this “replacement of components” is eight hours and the cost \$480. It is found that the sequence of the four tasks is scheduled in a successive fashion. The Gantt Chart also is applied to this recovery process as shown in Figure 6.9.

No	Task	Date									
		9-10 AM	10-11 AM	11-12 AM	0-1 PM	1-2 PM	2-3 PM	3-4 PM	4-5 PM	5-6 PM	
1	Check problem										
2	Discuss solution										
3	Replace the damaged one										
4	Check operation and adjustment										

Figure 6.9 Gantt Chart of the “replacement of components” method for Pressure Gauge damage

Re-organization is not easy for this example. So, the suggested method of reducing time and cost is to focus on the two longer-time tasks (Steps 2, and 3). Any time reduction in either of these steps will greatly decrease the total time (or cost) of whole recovery process.

In Figure 6.10, the resilience chart is shown for this case. I_R is 0. I_C is 1. I_{RC} is 1.

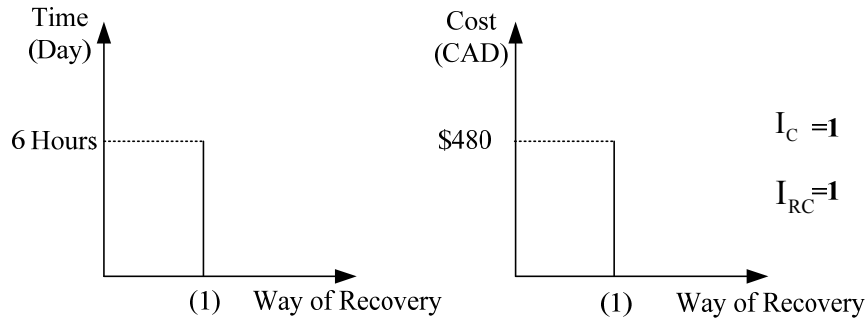


Figure 6.10 Resilience chart of reconfiguration (damage: Pump & Motor #3)

6.5.2.1.5 Damage to SCADA only

Within the PS (pump system), SCADA is responsible for gathering data from the pressure gauge and sending control signal to the VFD in order to control the pump speed. There is no spare SCADA at CBS. There is no possible reconfiguration method if SCADA is damaged. In the case of SCADA damage, the “maintaining water pressure” function will fail. Therefore, I_R is 0. I_C is 0. I_{RC} is 0. As before, the SCADA system could be replaced from outside sources but this is not part of this definition.

6.5.2.1.6 Damage to Variable Frequency Drive (VFD) only

The VFD is used to vary the pump speed according to the fluctuation of water demand (flowrate). During high water demand, the VFD increases pump speed. During low water demand, the VFD decreases pump speed. Therefore, water pressure can be maintained.

There is no spare VFD at CBS and there is no possible reconfiguration method if the VFD is damaged. In the case of VFD damage, the “maintaining water pressure” function will fail. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

6.5.2.1.7 Damage to Pump & Motor #3 and Pressure Gauge

If the Pump & Motor #3 and Pressure Gauge are both damaged, the recovery can be taken with both “reconfiguration” method and “replacement of component” method. The “maintaining water pressure” function can be recovered by retrofitting Pump & Motor #4 with the VFD from Pump & Motor #3 and to bring pump #4 on line, and by replacing the damaged pressure gauge with the redundant one. In this situation, the whole recovery is contributed by two different methods instead of a single one. Therefore, I_R is considered as 0.5, I_C is 0.5, and I_{RC} is 1.

6.5.2.1.8 Damage to other situations

For this specific research example (Clarence Booster Station), the resilience analysis for the many other cases of damage of two or more components is very similar and indeed, results in I_R being 0, I_C being 0, and I_{RC} being 0. Each of these cases is considered in Appendix B “Resilience analysis of the pump system”. All cases are summarized Table 6.4.

Table 6.4 Resilience index of PS under various damage conditions

No.	Damage	Ways of Reconfiguration I_R	Ways of Replacement of Components I_C	Resilience Index I_{RC}
1	Pump #1	N/A	N/A	N/A
2	Pump #3	1	0	1
3	Pump #4	0	0	0
4	SCADA	0	0	0
5	VFD	0	0	0
6	Pressure Gauge (PG)	0	1	1

7	Pump #1,#3	0	0	0
8	Pump #1,#4	0	0	0
9	Pump #1, SCADA	0	0	0
10	Pump #1, VFD	0	0	0
11	Pump #1, PG	0	0	0
12	Pump #3,#4	0	0	0
13	Pump #3, SCADA	0	0	0
14	Pump #3, VFD	0	0	0
15	Pump #3, PG	0.5	0.5	1
16	Pump #4, SCADA	0	0	0
17	Pump #4, VFD	0	0	0
18	Pump #4, PG	0	0	0
19	SCADA, VFD	0	0	0
20	SCADA, PG	0	0	0
21	VFD, PG	0	0	0
22	Pump #1, #3, #4	0	0	0
23	Pump #1, #3, SCADA	0	0	0
24	Pump #1, #3, VFD	0	0	0
25	Pump #1, #3, PG	0	0	0
26	Pump #1, #4, SCADA	0	0	0
27	Pump #1, #4, VFD	0	0	0
28	Pump #1, #4, PG	0	0	0

29	Pump #1, SCADA, VFD	0	0	0
30	Pump #1, SCADA, PG	0	0	0
31	Pump #1, VFD, PG	0	0	0
32	Pump #3, #4, SCADA	0	0	0
33	Pump #3, #4, VFD	0	0	0
34	Pump #3, #4, PG	0	0	0
35	Pump #3, SCADA, VFD	0	0	0
36	Pump #3, SCADA, PG	0	0	0
37	Pump #3, VFD, PG	0	0	0
38	Pump #4, SCADA, VFD	0	0	0
39	Pump #4, SCADA, PG	0	0	0
40	Pump #4, VFD, PG	0	0	0
41	SCADA, VFD, PG	0	0	0
42	Pump #1, #3, #4, SCADA	0	0	0
43	Pump #1, #3, #4, VFD	0	0	0
44	Pump #1, #3, #4, PG	0	0	0
45	Pump #1, #3, SCADA, VFD	0	0	0
46	Pump #1, #3, SCADA, PG	0	0	0
47	Pump #1, #3, VFD, PG	0	0	0
48	Pump #1, #4, SCADA, VFD	0	0	0
49	Pump #1, #4, SCADA, PG	0	0	0
50	Pump #1, #4, VFD, PG	0	0	0

51	Pump #1, SCADA, VFD,PG	0	0	0
52	Pump #3, #4, SCADA, VFD	0	0	0
53	Pump #3, #4, SCADA, PG	0	0	0
54	Pump #3, #4, VFD, PG	0	0	0
55	Pump #3, SCADA, VFD, PG	0	0	0
56	Pump #4, SCADA, VFD, PG	0	0	0
57	Pump #1, #4, SCADA, VFD, PG	0	0	0
58	Pump #3, #4, SCADA, VFD, PG	0	0	0
59	Pump #1, #3, SCADA, VFD, PG	0	0	0
60	Pump #1, #3, #4, SCADA, PG	0	0	0
61	Pump #1, #3, #4, SCADA, VFD	0	0	0
62	Pump #1, #3, #4, VFD, PG	0	0	0
63	Pump #1, #3, #4, SCADA, VFD, PG	0	0	0

6.5.2.2 Resilience Measure for CTCS

In a similar manner to Section 6.5.2.1, the resilience index was calculated for the CTCS and the results are summarized in Table 6.5 in next page. Details of all cases are considered in Appendix C “Resilience analysis of the Chemical Test and Control System”.

6.6 Interaction among two subsystems' resilience

The above analysis only focuses on the resilience of subsystems. It is necessary to discuss the interrelationship between them. It is found that PS and CTCS are not greatly coupled except they are controlled by the same component – SCADA. SCADA contributes greatly to the resilience of PS and CTCS. If SCADA fails, two subsystems will fail immediately.

6.7 Summary

In Chapter 6, the resilience of research example (SaskWater Clarence Booster Station) is analyzed quantitatively following the proposed methodology given in Chapter 5. The resilience index of each subsystem (PS and CTCS) is obtained (I_R , I_C , and I_{RC}) for various damage conditions.

Table 6.5 Resilience index of CTCS under various damage conditions

No.	Damage	Ways of Reconfiguration I_C	Ways of Replacement of Component I_R	Resilience Index I_{RC}
1	Test Unit	0	0	0
2	Chemical Pump	0	0	0
3	SCADA	0	0	0
4	Test Unit, Chemical Pump	0	0	0
5	Test Unit, SCADA	0	0	0
6	SCADA, Chemical Pump	0	0	0
7	Test Unit, Chemical Pump, SCADA	0	0	0

The time and cost of the recovery process are also examined with two project management tools. The tools are helpful to reschedule the recovery process for these conditions in which I_R , I_C , and I_{RC} are non zero. Both time and cost can be reduced.

It is noted that CBS should not be considered a resilient system because CBS has few redundant components and reconfiguration methods are few. However, it must be emphasized that the resilience is a comparative process and hence for valid resilience evaluation, the CBS should be compared to other pumping stations.

CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

7.1 Overview of the thesis

This thesis has introduced a preliminary study on the characteristics of resilience and an analysis methodology for the system resilience. The particular application that was used throughout the thesis was a pumping station (the SaskWater Clarence Booster Station (CBS)). A literature review of research that has been oriented towards resilience was conducted and summarized. This review was important in establishing the major goals of the thesis – i.e. to develop a new working definition for resilience, to distinguish resilience from other similar concepts, and to develop a method to measure system resilience in a quantitative manner. The CBS was used to illustrate the proposed methodology. To accomplish this goal, three specific objectives were proposed.

Objective 1: study the characteristics of resilience and develop a new working definition for resilience.

Objective 2: differentiate resilience from other similar concepts such as reliability, robustness, redundancy, repairing and sustainability and enhance the feature of resilience.

Objective 3: develop a new methodology for measuring a system's resilience from a quantitative standpoint and apply this methodology to a specific application – the SaskWater Clarence Booster Station (CBS) in Saskatoon.

In Chapter 2, the operation of and components in the SaskWater Clarence Booster Station were described. In Chapter 3, the current studies and various existing definitions regarding resilience were reviewed. A new working definition of resilience was proposed with the focus of system recoverability with a system's own resource. The characteristics of resilience were identified by differentiating resilience from five similar concepts which are reliability, robustness,

redundancy, repairing and sustainability. In Chapter 4, a “physical” model of CBS was presented by answering two questions “how does CBS operate?” and “why does CBS operate in such way?” In Chapter 5, a new quantitative resilience measure methodology was developed. This methodology consists of two steps, “failure analysis” which related the function failure with the possible causes and “resilience measure” which analyzed the number of ways of recovery. In the resilience analysis process, two project management tools (Gantt Chart and PERT) were used to evaluate recovery methods in order to determine the recovery time and cost. In Chapter 6, the proposed methodology was applied to the SaskWater Clarence Booster Station. In this application, two subsystems of CBS (PS: Pump system, CTCS: Chemical Test and Control System) were analyzed with respect to resilience. The resilience index for each subsystem was measured by finding out the number of possible ways of recovery quantitatively.

7.2 Conclusions:

This thesis study can lead to the following conclusions:

1. The representation of resilience in the form of an index based on ways of recovery is an important step in quantifying resilience, and development of such a representation is feasible.
2. Resilience is a system’s property that is based on both static characteristics (e.g. the components of CBS and the relationships among these components) and dynamic characteristics (how the recovery process changes with respect to time or event). Therefore, a resilience index must include both of the characteristics.
3. Resilience has its own identity which is distinct from robustness, reliability, sustainability, and repairing.
4. Redundancy is a necessary and sufficient condition. Redundancy is a means while resilience is an end. Design for resilience means to design redundancies into systems.

5. The CBS as a single entity has a very low resilience index which could make its function very vulnerable if failure occurs.

7.3 Major contributions

The main contributions of this thesis are presented as follows:

1. A new working definition of resilience is developed based on the comprehensive analysis of several existing definitions and of similar concepts such as robustness, reliability, sustainability, repairing, and redundancy. The effectiveness of this new definition is verified by the successful formulation of a quantitative measure for resilience. The new definition has cleared off much confusion about resilience in the current literature.
2. A quantitative measure for a system's resilience, which embodies both the static and dynamic characteristics of a system, is proposed. The measure has paved a way for both analysis and synthesis of a resilient system. This measure is, perhaps, the first one in the current literature.
3. A comprehensive analysis of the resilience property of a real system (i.e., CBS) is provided. The result of the analysis can be useful to the CBS management body for adjusting its strategy in design and operation management of the CBS for enhanced resilience.

7.4 Limitations and future works

7.4.1 Limitations

The first main limitation with this research is that the proposed resilience methodology is more meaningful when applied to two or more similar systems. However, in this study, because of the limited time and resources, only one specific plant (CBS) was considered and as such no comparison between different systems was possible.

In this thesis, only two indicators were considered, and this is the second limitation. In the author's opinion, there should be three indicators for the resilience evaluation which are recovery time, recovery cost and recovery quality. Recovery quality is important because sometimes the damaged system can only partially function instead of fully.

The third limitation is that human factor (human resource and energy) has not been considered in the analysis of the recovery process in order to furnish the resilience index, though the recovery activity is considered. In fact, in the current study, the human resource and energy is implicitly assumed to be no limit. This assumption can hinder application of the proposed measure, as there may be a situation where human resource and energy are not sufficient to carry on the recovery activity.

7.4.2 Future works

To address the first limitation, it is recommended that future studies apply the proposed methodology to another pumping station similar to CBS. The resilience indexes of the two pumping stations can be compared. Such a comparison can serve as a further validation of the effectiveness of the proposed resilience measure. To address the second limitation, the proposed measure needs to be extended to incorporate the concept of the quality of recovery or partial recovery. A closely related issue is about demand; a specific question is whether demand dynamics should be taken into account in resilience assessment. This issue makes sense for a situation where the quality of recovery decreases (e.g., water pressure cannot be maintained after a recovery process with an amount of pressure loss) while the demand may also reduce (e.g., demand on water pressure reduces). To address the third limitation, further studies should be directed to including human resource and energy in the formulation of the recovery process.

It is further recommended that a method to integrate the separate resilience indices of various damage conditions together into a single number. This could be done using various mean methods (e.g. arithmetic mean, weighted mean, and geometric mean which are discussed in Appendix D "Supplementary discussion about MEAN"). Consider the weighted mean as an example: based on the occurrence possibilities of various damage conditions, a weight can be

assigned to separate resilience index. A single resilience index could be established by summing up the individual indices.

Last, it is recommended that other computer modeling tools (such as Petri Nets) be used to model the research example (CBS). The properties of CBS could be graphically observed in a visual manner on a computer. The computer modeling tools may also facilitate the study of the third resilience evaluation indicator – recovery quality. The change between the normal (undamaged) function and the recovered function (after recovery) can be analyzed and compared.

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Appendix A Project Management Tools

A.1 Using Management Tools

The objective of this Appendix is to expand on the two management tools that were used in the thesis: PERT and the Gantt Chart.

A.1.1 Using PERT

In order to use PERT, the user should be familiar with several things, such as the project objective, the dependencies amongst tasks, and resource limitation. In most PERT application cases, seven steps are followed.

1. Identify all tasks.
2. Identify the first task that must be completed.
3. Identify any tasks that can be coordinated simultaneously.
4. Repeat the above process until all tasks are sequenced.
5. Identify each task's duration.
6. Determine the critical path. Make necessary modifications while the project is in progress.

A.1.2 An Example Using PERT

In order to better understand how to use the PERT, a typical project is analyzed following the procedure given in Section A.1.1. In this project, five events are identified.

Event A: Writing Project Plan.

Event B: Preparing Instrumentation and Machines.

Event C: Construction.

Event D: Negotiation with Clients.

Event E: Project Finished.

The general structure of the project is initialized with event A, “Writing Project Plan”. After the plan is given out, necessary construction tools such as instrumentation and machines are prepared. When the preparation is completed, the construction work is formally commenced. During the ongoing construction, engineers need discuss with clients regarding the project details until “Project Finished”. The dependencies among the five events are clearly shown in Figure A.1.

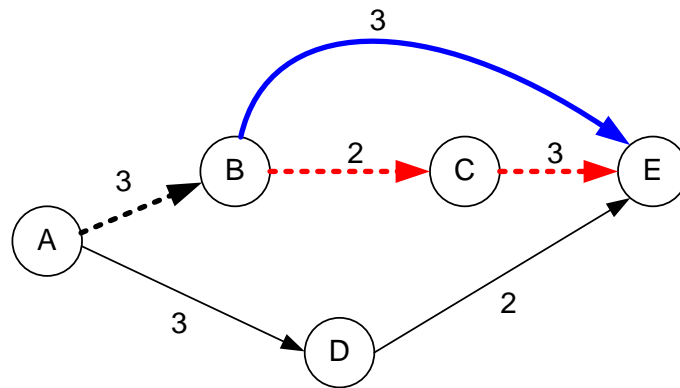


Figure A.1 An example of the PERT (dotted thick lines represent the critical path)

The numbers which are attached to lines represent the time required from one event to the following one. For example, three days are allotted from Event A “Writing Project Proposal” to Event B “Preparing Instrumentation and Machines”. The allotted time of the remaining tasks are:

- From Event A to Event B (Task No.1): 3 days,
- From Event A to Event D (Task No.2): 3 days,
- From Event B to Event C (Task No.3): 2 days,
- From Event B to Event E (Task No.4): 3 days,
- From Event C to Event E (Task No.5): 3 days,
- From Event D to Event E (Task No.6): 2 days.

In the PERT analysis, the critical path is often studied. The critical path is considered as the longest path time wise taken from the initial task to the terminal task and is shown as the “dotted thick line” illustrated in Figure A.1. The critical path in the example consists of Event A, B, C

and E. The project time is equal to the critical path time which is eight days. If more manpower could be put into tasks belonging to the critical path, the overall time is likely to be shortened.

Besides the critical path, the slack time is other important factor in interpreting the PERT diagram. It will also be very helpful when system resilience is discussed. The slack time is the amount of time that a task can be delayed than the scheduled project finish date.

To calculate the slack time, first determine the earliest and latest completion times for each task. To find the earliest completion time, take the task scheduled time. To find the latest completion time, take the latest time of finishing the task without delaying the entire project. The slack time is calculated by subtracting the earliest completion time from the latest completion time. Again taking the PERT in Figure A.1 as an example, the slack time of Task No.4 is the total time of Task No.3 and Task No.5 (red line, 5 days) minus the scheduled time of the Task No.4 (blue line, 3 days). So, the slack time is 2 days. In other words, the Task No.4 can be given another 2 days extra time to finish without delaying the entire project.

If resources and manpower can be borrowed from the task with slack time to the task belonging to the critical path, the project may be finished with fewer days.

A.1.3 Using the Gantt Chart

For each task, a user draws a horizontal bar. The bar's start point represents the date when the task is scheduled to begin, and the bar's end point represents the date when the task is expected to finish. Once a horizontal bar is drawn, the user repeats the procedure and finds any tasks that can be operated in parallel or sequentially.

When the project starts, the Gantt Chart user just fills the hollow horizontal bar with the length which is proportional with the workload that has been finished. If a task is fully completed, the hollow bar of this task should be fully filled with color. In order to judge how the current process goes, sometimes an imaginary vertical line through the chart at the current date is drawn. The vertical bar indicates the current date. It helps the Gantt Chart user to find out how much work has been finished and how much future work should be done. A task crossing the imaginary

vertical line represents an ongoing task in hand. If a bar is partially filled with color and the filled bar's end point is on the left of the imaginary line it indicates the task is behind schedule. If a bar is drawn at the right of the imaginary line, it indicates that the task is ahead of schedule.

No	Task	Date							
		1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul
1	Event A to Event B	█	█	█					
2	Event A to Event D	█	█	█					
3	Event B to Event C				█	█			
4	Event B to Event E				█	█	█		
5	Event C to Event E						█	█	█
6	Event D to Event E				█	█			

Figure A.2 Gantt Chart example

The Figure A.2 shows an ongoing project which is the same one in Section A.1. The two left columns list out six tasks involved in the project. The horizontal bar indicates the duration of each task. The interrelationships between these tasks are clearly shown. For instance, the tasks of No.3, No.4, and No.6 greatly rely on the completion of the tasks of No.1 and No.2. And the task of No.5 depends on the finish of Task No.3. If more resource and manpower can be given to tasks No.1 and No. 3, the entire project time will be reduced.

A.2 The Advantages and Limitations of the Management Tools

A.2.1 PERT

The PERT is used with all forms of projects, including civil construction, software development, and research projects. The PERT is highly prized by its users for several reasons:

- Estimating the project end time.
- Identifying the critical tasks that directly influence the project completion time.
- Identifying the tasks that have slack times.

The PERT also has some limitations. First, the total time of a project is estimated based on the limited data and the project manager's subjective judgment. The actual duration of a project may differ from the initial estimation. If the project is very large, there may be numerous tasks and dependencies. These will make the PERT very complex and difficult to construct.

A.2.2 Gantt Chart

When the Gantt Chart is implemented, the users usually intend to schedule and track the progress of projects. The Gantt Chart allows users to understand project process readily without requiring to complete lessons in project management. The schedule information is easily demonstrated in a graphical format as indeed the PERT.

Although the Gantt Chart is useful and valuable for projects, its horizontal bar does not exactly represent the workload of the task. Therefore, the potential of a "behind-schedule" condition is easily neglected. For example, if two tasks have the same required time to finish and but are quite different in the complexity of their tasks, one is likely to take more time to finish and become a "behind-schedule" one.

A.3 Application Example of the Management Tools

The pump is a key component in the water supply system. It is used to take water from natural sources such as rivers and lakes. It is also used to pressurize the water for long distance delivery. During the visits to the SaskWater local stations, the author found that most of the SaskWater pumping stations face an aging pump problem. Because there are many solid particles in the water, the impellers of pumps are readily damaged. Therefore, SaskWater spends a lot of time and manpower to repair/replace the damaged impeller. In order to quickly repair the impeller and recover the service of the pumping station, it is necessary to introduce some management strategies. In the following paragraphs, the two management tools, PERT and Gantt Charts, are used to analyze the impeller repairing process.

The normal impeller repairing process can be divided into several typical tasks which are listed as the following six ones. It is noted that the duration associated with each task is not based on “real” data.

- 1: Detect and confirm impeller problem (1 day).
- 2: Make preparation works.
 - 2.1: Scheduling the workforce (1 day).
 - 2.2: Ordering a new impeller (3 days).
- 3: Inform water clients of the outage of pump operation (1 day).
- 4: Appoint worker to pumping station to repair the damaged impeller (2 days).
- 5: Adjust the pump system (1 day).
- 6: Back to work.

In Figure A.3, the impeller repairing process is firstly analyzed with the PERT. Several things can be found. The first one is that the total time for recovering pump operation is eight days. Secondly, the critical path is 1-2.2-3-4-5-6. The “Ordering a new impeller” in the critical path takes the longest time which is 3 days. The total repairing time is mainly influenced by the new impeller ordering. Third, concerning the slack time, only the “2.1 Scheduling the workforce” has 2 days slack time.

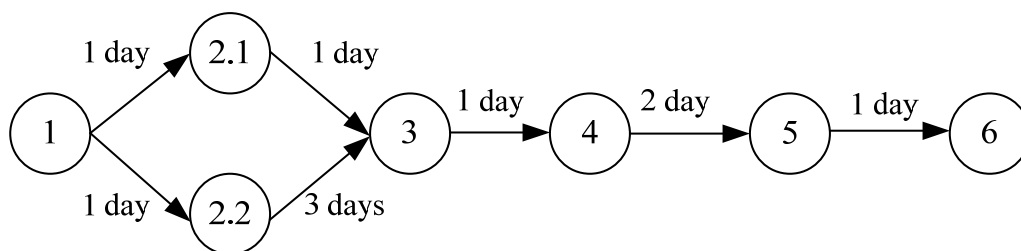


Figure A.3 Analysis of impeller repairing with PERT

In Figure A.4, the Gantt Chart is applied to model the impeller repairing process. The tasks are shown in the Figure A.4. It is found that the tasks are generally managed in a sequenced fashion. So the dependencies among them are notable. If one task is delayed, the entire repairing will be delayed.

No	Task	Date						
		1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul
	After Detect wearing problem of the impeller							
1	Make preparation works - Scheduling workforce	█						
2	Make preparation works - Ordering a new impeller	█	█	█				
3	Inform water clients of the outage of pump operation				█			
4	appoint worker to pumping station to repair the failed impeller					█	█	
5	adjust the pump and make it back to normal work							█

Figure A.4 Analysis of impeller repairing with the Gantt Chart

Appendix B Resilience Analysis of the CBS Pumping System

The following section in Appendix continues the discussion of the resilience analysis of the Pumping System (PS) of CBS. The resilience analysis considers the condition of two damages, three damages, four damages, five damages, and six damages.

B.1 Damage to Pump & Motor #1 and Pump & Motor #3

If Pump & Motor #1 and Pump & Motor #3 are both damaged, a possible reconfiguration method is to retrofit Pump and Motor #4 with the VFD from Pump & Motor #3 as discussed in Section 6.5.2.1.2. The time of reconfiguration is 78 hours and the cost of reconfiguration is \$4780 (project management). The function loss of “maintaining water pressure” can be recovered. Therefore, I_R is 1. I_C is 0. I_{RC} is 1. Figures B.1 shows resilience chart for reconfiguration with respect to time and cost.

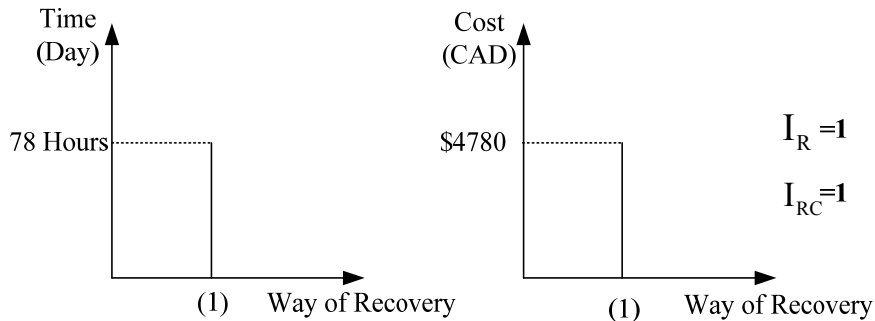


Figure B.1 Resilience Chart of reconfiguration (Damage: Pump & Motor #1 and #3)

B.2 Damage to Pump & Motor #1 and Pump & Motor #4

If Pump & Motor #1 and Pump & Motor #4 are both damaged, there is no method to recover the PS. The water pressure cannot be maintained with the fluctuation of the water demand (flowrate). The “maintaining water pressure” function will lose. So, I_R is 0. I_C is 0. I_{RC} is 0.

B.3 Damage to Pump & Motor #1 and SCADA

If Pump & Motor #1 and SCADA are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the lost function. In the case of Pump & Motor #1 damage and SCADA damage, the “maintaining water pressure” function will lose. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.4 Damage to Pump & Motor #1 and VFD

If Pump & Motor #1 and VFD are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. The pump speed cannot be varied in light of water demand. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.5 Damage to Pump & Motor #1 and Pressure Gauge

If Pump & Motor #1 and Pressure Gauge are both damaged, there is a spare pressure gauge in CBS which can be used to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 1. I_{RC} is 1.

B.6 Damage to Pump & Motor #3 and Pump & Motor #4

If Pump & Motor #3 and Pump & Motor #4 are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the lost function “maintaining water pressure”. The reason is, during high water demand period, enough water cannot be supplied. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.7 Damage to Pump & Motor #3 and SCADA

If Pump & Motor #3 and SCADA are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.8 Damage to Pump & Motor #3 and VFD

If Pump & Motor #3 and VFD are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.9 Damage to Pump & Motor #3 and Pressure Gauge

If Pump & Motor #3 and Pressure Gauge are both damaged, there is a spare pressure gauge in CBS which can be used to replace the damaged one. There is a possible reconfiguration method is to retrofit Pump and Motor #4 with the VFD from Pump & Motor #3. With above damage conditions and recovery methods, the “maintaining water pressure” function can be recovered. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.10 Damage to SCADA and VFD

If SCADA and VFD are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function and “treating water” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.11 Damage to Pump & Motor #4 and SCADA

If Pump & Motor #4 and SCADA are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.12 Damage to Pump & Motor #4 and VFD

If Pump & Motor #4 and VFD are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.13 Damage to Pump & Motor #4 and Pressure Gauge

If Pump & Motor #4 and Pressure Gauge are both damaged, there is a spare pressure gauge in CBS which can be used to replace the damaged one. Therefore, I_R is 0. I_C is 1. I_{RC} is 1.

B.14 Damage to SCADA and Pressure Gauge

If SCADA and Pressure Gauge are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.15 Damage to VFD and Pressure Gauge

If VFD and Pressure Gauge are both damaged, there is no “reconfiguration” method or “replacement of components” method to recover the “maintaining water pressure” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

Note: for the conciseness purpose, the rest resilience analysis of the PS is put in the appendix. However, a summery is given in Table 6.x for readers' review.

B.16 Damage to Pump & Motor #1, Pump & Motor #3, and Pump & Motor #4

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.17 Damage to Pump & Motor #1, Pump & Motor #3, and SCADA

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.18 Damage to Pump & Motor #1, Pump & Motor #3, and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.19 Damage to Pump & Motor #1, Pump & Motor #3, and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.20 Damage to Pump & Motor #1, Pump & Motor #4, and SCADA

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

A.21 Damage to Pump & Motor #1, Pump & Motor #4, and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.22 Damage to Pump & Motor #1, Pump & Motor #4, and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.23 Damage to Pump & Motor #1, SCADA and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.24 Damage to Pump & Motor #1, SCADA and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.24 Damage to Pump & Motor #1, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.25 Damage to Pump & Motor #3, Pump & Motor #4 and SCADA

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.26 Damage to Pump & Motor #3, Pump & Motor #4 and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.27 Damage to Pump & Motor #3, Pump & Motor #4 and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.28 Damage to Pump & Motor #3, SCADA and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.29 Damage to Pump & Motor #3, SCADA and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.30 Damage to Pump & Motor #3, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” methods to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.31 Damage to Pump & Motor #4, SCADA and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.32 Damage to Pump & Motor #4, SCADA and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.33 Damage to Pump & Motor #4, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.34 Damage to SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.35 Damage to Pump & Motor #1, Pump & Motor #3, Pump & Motor #4 and SCADA

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.36 Damage to Pump & Motor #1, Pump & Motor #3, Pump & Motor #4 and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.37 Damage to Pump & Motor #1, Pump & Motor #3, Pump & Motor #4 and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.38 Damage to Pump & Motor #1, Pump & Motor #3, SCADA and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” methods to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.39 Damage to Pump & Motor #1, Pump & Motor #3, SCADA and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.40 Damage to Pump & Motor #1, Pump & Motor #3, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.41 Damage to Pump & Motor #1, Pump & Motor #4, SCADA and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.42 Damage to Pump & Motor #1, Pump & Motor #4, SCADA and PG

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.43 Damage to Pump & Motor #1, Pump & Motor #4, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.44 Damage to Pump & Motor #1, SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.45 Damage to Pump & Motor #3, Pump & Motor #4, SCADA and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.46 Damage to Pump & Motor #3, Pump & Motor #4, SCADA and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.47 Damage to Pump & Motor #3, Pump & Motor #4, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.48 Damage to Pump & Motor #3, SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.49 Damage to Pump & Motor #4, SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.50 Damage to Pump & Motor #1, Pump & Motor #3 Pump & Motor #4, SCADA, and VFD

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.51 Damage to Pump & Motor #1, Pump & Motor #3 Pump & Motor #4, SCADA, and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.52 Damage to Pump & Motor #1, Pump & Motor #4, SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.53 Damage to Pump & Motor #3, Pump & Motor #4, SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.54 Damage to Pump & Motor #1, Pump & Motor #4, SCADA, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” method to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.55 Damage to Pump & Motor #1, Pump & Motor #3, Pump & Motor #, VFD and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” methods to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

B.56 Damage to Pump & Motor #1, Pump & Motor #3 Pump & Motor #4, VFD, and Pressure Gauge

“Maintaining water pressure” function will lose. There is no “reconfiguration” or “replacement of components” methods to recover the lost function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

Appendix C Resilience analysis of the Chemical Test and Control System

The following section in Appendix continues the discussion of the resilience analysis of the Chemical Test and Control System (CTCS) of CBS. The resilience analysis considers the condition of two damages, and three damages.

C.1 Damage to Test Unit Only

After the Test Unit is damaged, the Chlorine concentration cannot be measured. The Chemical Pump cannot be controlled to properly add chemical (Chlorine) to water. There is no method to recover the “treating water” function. Therefore, I_R is 0. I_C is 0. I_{RC} is 0.

C.2 Damage to Chemical Pump Only

If the chemical pump is damaged, the chemical (Chlorine) cannot be added to water. Water quality cannot be maintained. There is no method to recover the “treating water” function. I_R is 0. I_C is 0. I_{RC} is 0.

C.3 Damage to SCADA Only

If the SCADA is damaged, the signal from Test Unit cannot be transmitted to Chemical Pump. The Chemical pump cannot be controlled for adding chemical to water. There is no method to recover the “treating water” function. I_R is 0. I_C is 0. I_{RC} is 0.

C.4 Damage to Test Unit and SCADA

If the Test Unit and SCADA are damaged, there is no method to recover the CTCS. The “treating water” function will lose. I_R is 0. I_C is 0. I_{RC} is 0.

C.5 Damage to Chemical Pump and SCADA

If the Chemical Pump and SCADA are damaged, there is no method to recover the CTCS. The “treating water” function will lose. I_R is 0. I_C is 0. I_{RC} is 0.

C.6 Damage to Test Unit and Chemical Pump

If the Chemical Pump and SCADA are damaged, there is no method to recover the CTCS. The “treating water” function will lose. I_R is 0. I_C is 0. I_{RC} is 0.

C.7 Damage to SCADA, Test Unit and Chemical Pump

If the SCADA, Test Unit and Chemical Pump are damaged, there is no method to recover the CTCS. The “treating water” function will lose. I_R is 0. I_C is 0. I_{RC} is 0.

Appendix D Supplementary discussion about MEAN

For each subsystem, total resilience index can be considered from a statistical standpoint. It is possible to use arithmetic mean, weighted mean and geometric mean as the overall resilience index for CBS.

(1) Arithmetic mean can be expressed as

$$\bar{X} = \frac{\sum_{i=1}^N X_i}{N} \quad \text{Eq. (1)}$$

\bar{X} is the arithmetic mean, X_i is each resilience index under one specific damage condition, N is the total number of possible damage conditions.

Applying the information of Table 6.3 to the Eq. (1), it is found: PS has resilience index of 1.14, CTCS has resilience index of 1, and VTCS has resilience index of 1.

(2) Weighted mean recognizes that different damage condition may have a disproportionate influence on the mean. The weighted mean is computed with the following equation.

$$\bar{X} = \sum_{i=1}^N w_i X_i = (w_1 X_1 + w_2 X_2 + \dots + w_N X_N) \quad \text{Eq. (2)}$$

\bar{X} is the weighted mean, X_i is each resilience index under one specific damage condition, W_i is the weight factor for each damage condition (the weight factor can be considered as the occurrence possibility of certain damage), N is the total number of possible damage conditions.

Due to the lack of information about the weight factors in the CBS example, there is no exact result for the weighted mean method.

(3) Geometric mean is often calculated as follows

$$\bar{X} = \sqrt[N]{X_1 \times X_2 \times \dots \times X_N} \quad \text{Eq. (3)}$$

\bar{X} is the geometric mean, X_i is each resilience index under one specific damage condition, N is the total number of possible damage conditions.

Applying the information of Table 6.3 to Eq. (3), it is found that PS has resilience index of 1.26, CTCS has resilience index of 1, and VTCS has resilience index of 1.

It is also easy to find out the overall resilience index for the CBS. The CBS resilience index using arithmetic mean is 1.25. The CBS resilience index using weighted mean is based on different weights. The CBS resilience using geometric mean is 1.12.