Integrated Asset Management Framework and Model for Water Distribution Networks

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The Canadian Infrastructure Report Card (2012) estimates the replacement value of water assets to be $362 billion. Water distribution and wastewater collection networks have been in service for more than a century in the majority of the cities in Canada. Although “out of sight” infrastructure might often be “out of mind”, the functionality of these city arteries greatly influences public health. Lack of effective maintenance and proactive renewal plans increase the incurred costs of water infrastructure systems drastically until affordable water fees cannot cover them. The Sustainable Water and Sewage System Act (MEO, 2002) followed by the Water Opportunities and Water Conservation Act (MEO, 2010), both encourage public utilities to develop financially sustainable plans for water and wastewater systems. In addition, both Ontario Regulation 453/07 (MEO, 2007) and Public Sector Accounting Board (PSAB) Statement 3150 (CICA, 2007) require all public water utilities to prepare annual reports on the current and the future condition of their in-service assets. Managing aging water infrastructure systems with limited financial resources requires comprehensive asset management plans that help decision-makers minimize the total life-cycle cost of their assets while enhancing levels of service. A viable asset management plan should incorporate a Strategic plan (10+year), to set the policies and strategies; Tactical plan (2-10 years), to develop capital programs; and Operational plan (1-2 years), to establish capital projects. Effective dynamic communication among planning levels is critical to share and exchange information and, thus, promote alignment of their respective objectives.

This research develops an Integrated Water Infrastructure Asset Management (IWIAM) model comprised of strategic, tactical and operational plans to (1) align corresponding objectives; (2) share and exchange their information; and (3) optimize the allocation of financial resources.

A novel hybrid Agent-Based and System Dynamics (AB-SD) modelling approach is employed to develop an IWIAM for water distribution networks. The SD and AB models are used to understand the complex dynamic behaviour of water infrastructure systems for network-level (i.e., strategic) and component-level (i.e., tactical-operational), respectively. A four-step Plan-Do-Check-Adjust (PDCA) iterative management process, along with an integrated Water Infrastructure Database (WIDB) is utilized to provide effective interaction and communication among all three planning levels. The research applies a bi-level heuristic optimization algorithm to find optimal solutions to group renewal activities in the development of capital programs.

The proposed research makes several noteworthy contributions to the body of knowledge for water distribution networks:

(1) The development of an integrated decision-support system using Agent-Based and System Dynamics methods to aid water decision-makers in asset management planning;

(2) The development of a platform for interactions between the network- and component-levels to align network-centric with component-centric decisions;

(3) The development of an optimization model to select, group, and schedule optimal R&R activities;

(4) the development of a bi-level heuristic optimization algorithm to find optimal solutions for group scheduling of capital works.

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"In the Name of Allah, the Most Beneficent, the Most Merciful"

I would like to express my sincere gratitude and deepest appreciation to my supervisors Dr. Mark Knight and Dr. Andre Unger, for their kind advice and exceptional mentorship throughout my Ph.D. program. This research truly benefited from their constant encouragement and support of my ideas. I am also thankful to Dr. Carl Haas, Dr. Mahesh Pandey and Dr. Mohammad Kohandel, my internal committee members, for their review of my research proposal, offering insightful comments, and reviewing this thesis. It is a privilege to have Dr. Steven Conrad as my External Examiner and review my thesis for which I am highly grateful.

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Dedication

To my beloved wife

Zahra

for her love, support, and encouragement in my life.

,

My parents and siblings

for their love and continuous support

&

My little son

Amirali

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Chapter 1.

Introduction

1.1. Background

The history of water distribution systems goes back to ancient civilizations such as the Indus, Mesopotamians, Persian, and the Roman Empire, who advanced them by applying engineering techniques in the construction of aqueducts, cisterns, wells, fountains, bathrooms and other sanitary facilities (Mays et al. 2007). After the commencement of using water distribution networks for fire protection purposes in the 1880s, the delivery of potable water demand via pipes has thrived. Although "out of sight" infrastructures, such as water distribution and wastewater collection networks, might often be "out of mind", it is broadly accepted that promoting the overall health of a city and increasing inhabitants' longevity heavily depends on having access to a safe drinking water supply and waste disposal networks (IIMM 2011).

After the Second World War, major industrial cities needed massive investment for the construction of new infrastructure, in general, and water supply systems, in particular, due to the "baby boom" and urbanization in the 1940s and 50s (Mirza and Haider 2003; Sanford Bernhardt and McNeil 2008). In the next decades, the infrastructure management paradigm gradually shifted from new construction to ongoing preservation. However, under-investment, limited financial resources, and ineffective decision support systems have led to significant infrastructure backlogs in recent years (Mirza 2007).

The continuously deteriorating nature of pipes and renewal actions, including replacement, rehabilitation, and repair, accentuates the dynamic behaviour of water infrastructure systems over their life-cycles. Water distribution networks cannot be replaced entirely but piece by piece. Therefore, their lifespans should be assumed infinite (Cardoso et al. 2012). Municipal decision-makers need to adopt a systematic approach to deliver services of such a complex, dynamic, and endless system in an efficient and rational manner.

In the 1980s, Infrastructure Asset Management was introduced to aid decision-makers in systematically coordinate activities and practices in an infrastructure system to sustain desired levels of service throughout its life cycle, optimally allocate limited resources, and balance between its associated performance, cost, and risk.

Many definitions have been introduced for Infrastructure Asset Management, such as ISO 55000s (2011), PAS 55 (2008), Uddin et al. (2013), Grigg (2002), USEPA (2008), FHWA (1999), Falls et al. (2001), and Brown & Humphrey (2005). The International infrastructure management manual (IIMM, 2011) defines the goal of infrastructure asset management as "*to meet a required level of service, in the most cost-effective manner, through the management of assets for present and future customers.*"

Asset managers also believe that a systematic and comprehensive approach should be employed to gain a robust asset management model across an organization. Grigg (2002) and PAS 55 (2008) have highlighted this attribute. PAS 55 describes an asset management practice as "*Systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their life cycles for the purposes of achieving its organizational strategic plan.*"

In addition to a systematic perspective, a successful asset management plan should take into account the performance of assets in both short- and long-term planning horizons. The United States Federal Highways Administration (FHWA 1999) supporting the above attributes mentioned that "*...asset management provides a framework for handling both short- and long-range planning*"

The Sustainable Water and Sewage System Act (Ministry of the Environment Ontario 2002) followed by the Water Opportunities and Water Conservation Act (Ministry of the Environment Ontario 2010), both state the requirements of infrastructure asset management plans for water, wastewater, and stormwater systems to comply with financial sustainability. In addition, both Ontario Regulation 453/07 (Ministry of the Environment Ontario 2007) and Public Sector Accounting Board (PSAB) Statement 3150 (CICA 2007) require all municipalities and public utilities to prepare annual reports on the current and the future condition of their in-service assets.

A viable asset management plan should align the objectives of all planning levels: strategic, tactical, and operational. This alignment needs strong co-ordination vertically between all managerial levels with the capability to readily share all types of information mutually (IIMM 2011). Furthermore, a comprehensive asset management plan includes not only strategic plans to set long-term policy levers but also program management plans (tactical plans), as well as, project management plans (operational plans).

1.2. Problem Statement and Motivation

Many efforts have been made to develop asset management models and Decision-Support Systems (DSSs) for water distribution networks (Dandy and Engelhardt 2001; Dridi et al. 2008; Hong et al. 2006; Kleiner et al. 2001; Loganathan et al. 2002; Luong and Nagarur 2001; Nafi and Kleiner 2010; Roshani and Filion 2014; Salman et al. 2013; Shamir and Howard 1979; Walski 1987). However, they are all relevant to the tactical or operational levels to address day-to-day decisions through a component-level perspective.

Grigg and Bryson (1975), Bagheri and Hjorth (2007), Qi and Chang (2011), Zarghami and Akbariyeh (2012), and Scholten et al. (2014) have attempted to model water distribution systems for the development of strategic plans through a network-level approach. However, they do not take into account the interaction between social, financial, and physical components in water infrastructure systems. Rehan et al. (2011) developed causal loops diagrams among the water system's component to capture their interactions and developed the first-known system dynamics model applied to water system management at the strategic level incorporating physical infrastructure, finance, and customer sectors. This system dynamics model was advanced later by Rehan et al. (2013, 2015) and Ganjidoost (2016) to extend the model applicability to explore more sophisticated management strategies.

Infrastructure asset management guidelines and documents (IIMM 2011; ISO 55000 2014; PAS-55-1 2008; PAS-55-2 2008) prescribe an integrated approach to effectively manage infrastructure systems, such as water distribution networks, taking into account the interactions between strategic, tactical and operational plans, as well as, the interactions between social, physical, and financial sectors. Nonetheless, the review of the literature reveals that there is no integrated DSS or simulation model has yet been developed for water distribution networks that is capable of integrating strategic, tactical, and operational planning processes.

Another gap of most current models and DSSs for water distribution systems (Burn et al. 2003; Dandy and Engelhardt 2001; Dridi et al. 2008; Kleiner et al. 1998a; b; Moglia et al. 2006; Saegrov

2005; Xu et al. 2013) is that they try to find the optimal schedule of individual pipe for renewal action rather than pipes in a renewal group. Some researchers attempted to quantify and study the advantages of bundling the renewal actions in water distribution networks (Nafi and Kleiner 2010; Rokstad and Ugarelli 2015; Roshani and Filion 2014; Salman et al. 2013). However, they are limited to either cost reduction or performance improvement. Li et al. (2015) developed a heuristic optimization method with multiple group-scheduling criteria to investigate the best solutions for grouping replacement actions to reduce costs and service interruptions. However, it is restricted to component-level with reactive renewal strategy. Reviewing the current group-scheduling model for renewal planning in water distribution networks reveals that there is no optimization model developed to find optimal work-packages for capital works that enhance the system’s cost, risk, and levels of service, simultaneously.

1.3. Research Goal and Objectives

The overall goal of this research is to propose a novel framework to integrate strategic, tactical, and operational levels of planning and develop an integrated Decision Support System (DSS) for water distribution networks. This goal is achieved by pursuing the following specific research objectives:

1) Review the available decision-support systems including developed simulation models and asset management planning tools and their implications for water distribution systems, to identify research gap in the development of an integrated asset management model incorporating all levels of planning;

2) Propose a simulation methodology that is capable of integrating strategic, tactical, and operational plans and align their objectives;

3) Compare and contrast a network-level planning perspective versus an integrated network- and component-levels planning perspective on the long-term performance of water distribution systems.

4) Develop an integrated asset management model to simulate the interactions between network-level and component-level in water distribution networks.

5) Verify and validate the model to ensure that it is capable of addressing both network- and component-centric planning requirements successfully.
6) Develop an effective optimization methodology to explore the impacts of a group-scheduling renewal strategy on a water distribution system’s cost, risk, and levels of service over its life-cycle.
7) Compare and contrast the impacts of optimal and risk-based renewal grouping strategies over the performance indicators of water distribution networks.

1.4. Thesis Organization

This thesis is organized in an integrated-article format – that is, each of Chapters 2 to 4 addresses one or several of the above-listed research objectives. Figure 1-1 presents a graphical summary of the remainder of the thesis chapters and the main research tasks performed in each of those chapters.

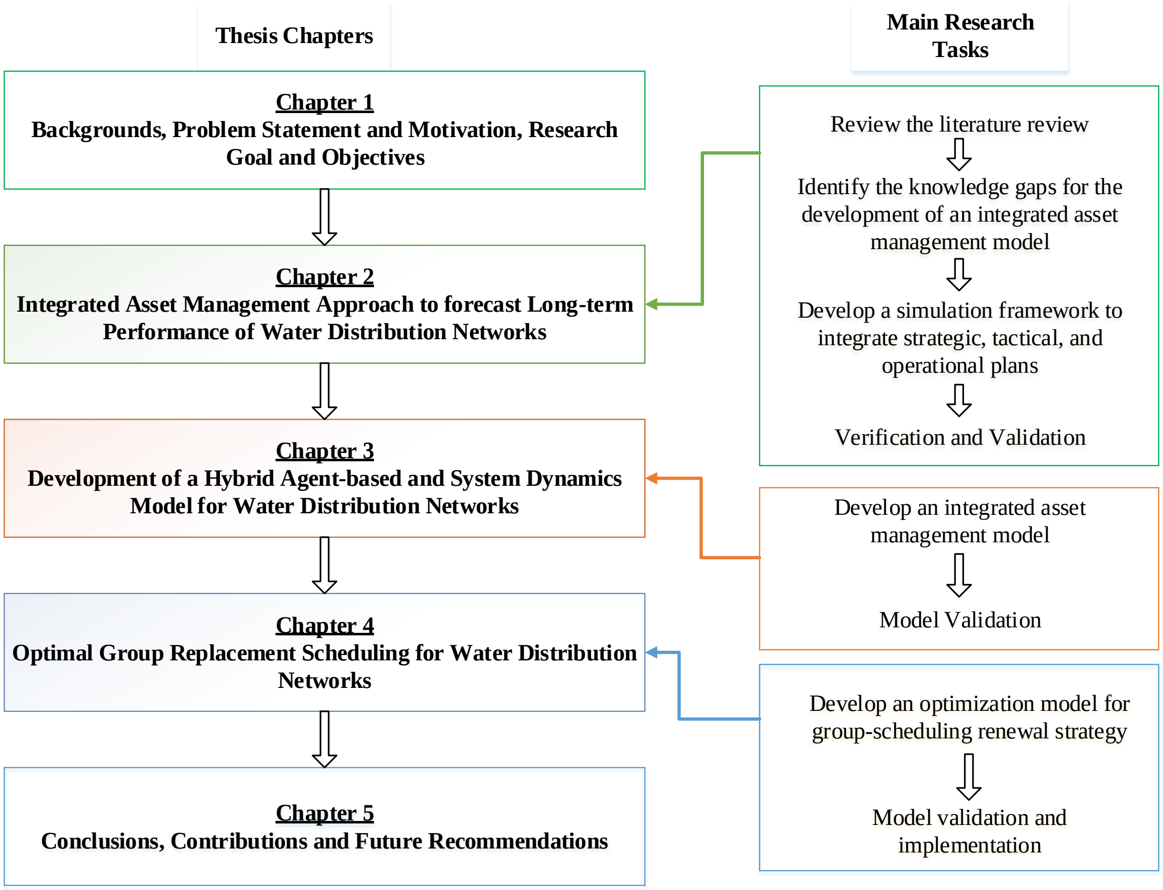


Figure 1-1- Thesis chapters, organization and objectives.

Chapter 2 develops an integrated asset management framework to incorporate strategic, tactical, and operational levels of planning for water distribution systems. A hybrid Agent-Based and System Dynamics (AB-SD) simulation model is utilized to couple top-down (i.e., network-level) and bottom-up (i.e., component-level) approaches to align different levels of planning. This study adopts the SD model developed by Rehan et al. (2011) for the network-level simulations. The proposed framework is implemented a hypothetical water distribution network to compare the integrated strategic-tactical planning model (i.e., the AB-SD model) versus the strategic planning model (i.e., the SD model) to forecast the long-term performance of the network.

In Chapter 3, the AB-SD model and its associated behavioural modules are presented. Three hypothetical networks are designed to demonstrate how the AB-SD model can be implemented in water distribution networks. This demonstration shows how the AB-SD model can address: component-centric decisions, such as pipe renewal schedule and optimal replacement/rehabilitation alternatives; and network-centric decisions, such as annual water fees and network rehabilitation rate.

Chapter 4 advances the AB-SD model (1) to develop optimal capital programs that benefited from grouping water mains for replacement actions, and (2) to investigate the impact of optimal group renewal strategy on the long-term performance of water distribution networks. The classical optimization methods are computationally exhaustive since the solution space to explore for the optimal groups of water mains is extremely large in a real-sized water distribution network. Therefore, a bi-level optimization methodology based on Genetic Algorithm (GA) is developed to enable the model to search the solution space efficiently.

A general summary of all the chapters' conclusions, the original contributions to the state of knowledge, and directions for future research are presented in Chapter 5.

Chapter 2.

Integrated Asset Management Approach to Forecast Long-term Performance of Water Distribution Networks

Abstract

Several decision support systems have been developed for the management of water distribution networks. However, they analyze water systems from only one perspective without incorporating interactions between different levels of planning. A network-wide perspective is essential to explore the interactions and feedback effects between interconnected sectors in a complex and dynamic water distribution system. Thus, global knowledge of the network, such as the aggregate information of pipe inventory, is sufficient to simulate the water distribution system at the strategic level of planning. However, consideration of individual distributed assets is necessary to address tactical and operational decisions. ISO 55000s (2014) and International Infrastructure Management Manual (IIMM 2011) highlight the necessity of coordination between strategic, tactical, and operational levels to develop a viable asset management plan. A review of current DSSs reveals that no integrated asset management planning tool exists for water supply systems. Rehan et al. (2011) successfully applied the System Dynamics approach to simulate the long-term behaviour of water distribution networks at the strategic level. This chapter introduces a framework by coupling an Agent-Based modelling approach with System Dynamics (AB-SD) to develop an integrated decision support system coordinating strategic, tactical, and operational plans for water distribution networks. Three hypothetical networks are simulated to validate the hybrid model. The results show that the AB-SD model outputs similar long-term trends to the SD model in terms of all financial, physical, and social performance indicators.

Keywords: asset management, water distribution network, integrated asset management, system dynamics, agent-based

2.1. Introduction

Water scarcity and inadequate access to safe drinking water are the leading causes of severe health problems in societies (Hunter et al. 2010). Drinking water delivery in cities mostly relies on water pipelines comprised of distribution and transmission lines. These assets account for around three-quarters of total water infrastructure value (Canadian Infrastructure Report Card 2016). To maintain current levels of service for the customers of ageing water networks, old pipes that are reaching or have exceeded the end of their service life need to be replaced or rehabilitated. Urbanization and population growth also necessitate expansion of water pipeline networks, which entails a multitude of new construction to meet ever-increasing water demands. Lack of sufficient investment to maintain water infrastructure, plus ineffective renewal programs, can progressively increase water infrastructure deficits and degrade its physical condition. Comparing the figures of recent successive Canadian Infrastructure Report Cards (2016; 2012) reveals that Canadian water infrastructure has struggled with underinvestment and increasing backlog in recent years. The percentage of water infrastructure rated in “fair” to “very poor” condition increased from 15.1% in 2012 to 29% in 2016. Mirza (2007) presented a similar rapidly deteriorating trend for Canadian water and wastewater systems. He noted that the deficits of water and wastewater systems increased from $21 billion in 1996 to $31 billion in 2007.

Water supply systems have not only a complex, dynamic inter-relationships between physical components but also with socio-economic entities, including water consumers and the financial sector of water utilities. Rehan et al. (2013) argued that the performance of water distribution networks directly affects water consumers, as they may incur more costs for lower quality services due to the poor condition of water distribution networks. Water utility managers should increase water fees to cover increasing operational and capital expenses of a deteriorating water infrastructure network. However, as fees rise people tend to conserve more water to reduce their water bills, causing a drop in annual revenue for the utility. Ultimately, the water fee is set in a multilateral challenge among water consumers, utility managers, and the physical condition of the water network. These feedback-loop interactions among the system components over time imply the dynamic complexity of water supply systems. Water distribution networks cannot be replaced entirely but instead piece by piece; therefore, their lifespans should be assumed to be infinite (Cardoso et al. 2012). Hence, a holistic approach incorporating interactive relationships between the water system's sectors should be adopted to efficiently manage dynamic, complex water infrastructure systems over their infinite lifetime.

Infrastructure Asset Management aids decision-makers "to meet a required level of service, in the most cost-effective manner, through the management of assets for present and future customers" (IIMM 2011). Decision-making processes in large organizations, such as urban water supply systems, occur at different planning levels: strategic, tactical, and operational. Strategic plans look at the whole infrastructure system through a broad time frame (often equal to or greater than the average service life of the individual assets) using a network-wide top-down approach to translate regulatory requirements and mandatory policies into long-term strategies, corporate goals, the system's vision and mission, and long-term financial policies. Technical action programs are developed based on tactical plans to comply with long-term system strategies. Tactical plans usually have a 5-10 year planning horizon to prioritize capital, operational and maintenance activities, and flag them for action. Operational plans act as guidelines for day-to-day practices, by allocating limited budgets to operational and maintenance activities and capital projects with a one-to-three year outlook. In agreement with ISO 55000s (2014), a viable integrated asset management plan should be able to incorporate and coordinate all three levels of planning to drive the infrastructure system in a consistent direction from all perspectives (Figure 2-1). International Infrastructure Management Manual (IIMM 2011) also points out that strong coordination vertically between all managerial levels, with the capability to readily share all types of information, is required to align their objectives.

The definition of "integration of infrastructure asset management" has been described using alternative meanings in the literature. Sometimes it refers to integrating various asset types in a cooperative asset management plan such as for roads, water supply systems, wastewater collection systems, and recreational buildings (Saidi et al. 2018; Uddin et al. 2013). In this research, integrated asset management refers to incorporating all three levels of planning into one decision support system to align their desired objectives.

Rehan et al. (2011) introduced the first known application of System Dynamics (SD) in the development of a decision support tool to forecast the long-term performance of water pipeline networks using a global understanding of water supply systems. They successfully applied the SD modelling method to develop interconnections and recognize feedback loops between different components in the physical, financial, and consumer sectors using a top-down approach. However, their SD model solely utilizes the strategic level and is incapable of addressing decisions associated with distributed water system components.

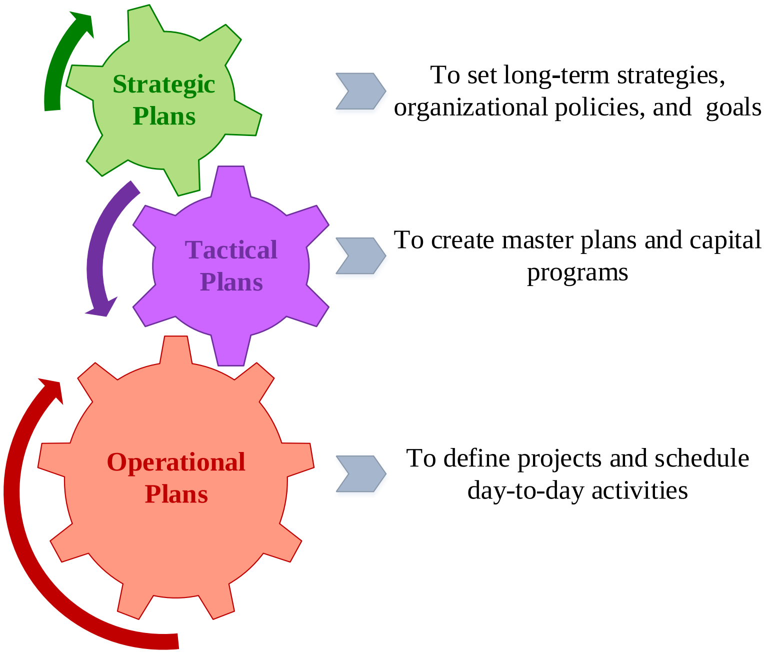


Figure 2-1- Strategic, tactical, and operational integrated asset management

This study aims to develop an integrated asset management framework to incorporate strategic, tactical, and operational levels of planning for dynamic, interactive water distribution systems. For this purpose, a novel hybrid Agent-Based and System Dynamics (AB-SD) simulation model is applied to combine top-down (i.e., network-level) and bottom-up (i.e., component-level) approaches to align different levels of planning. The objectives of this chapter are (1) to identify a knowledge gap in the development of an integrated Decision-Support-System (DSS) for water infrastructure asset management, (2) to present the framework of AB-SD model development, and (3) to demonstrate how the AB-SD model can overcome the drawback of the SD model, developed by Rehan et al. (2011), by integrating network-level and component-level views in planning approach for water distribution networks.

The following section reviews the current asset management models and decision support tools for water infrastructure systems to show the research gap in the development of integrated asset management models. This chapter then discusses the methodology to develop an integrated asset management model. Thereafter, model validation and verification exercises utilizing three basic pipe inventory profiles with two renewal scenarios are presented. The intent of this model demonstration is to show the impact of amalgamation of the network-level perspective, using aggregate information, with the component-level perspective, using the information of distributed assets, on the long-term performance of water distribution systems.

2.2. Decision Support Systems for Water pipeline Infrastructure

Infrastructure asset management models can be classified by their perspective on the water distribution networks: strategic, tactical, and operational. They may view the system from one or more than one planning perspective.

The focus of most studies has been on the operational level to schedule renewal activities (replacement or rehabilitation) so as to achieve a desired optimal performance, mostly defined as minimization of costs. These studies range from pipe-centric models, in which determining the optimal renewal time for a pipe is desired (Hong et al. 2006; Loganathan et al. 2002; Luong and Nagarur 2001; Shamir and Howard 1979; Walski 1987), to network-centric models, in which finding the optimal renewal plan for the components of whole network is targeted (Dandy and Engelhardt 2001; Dridi et al. 2008; Kleiner et al. 2001; Nafi and Kleiner 2010; Roshani and Filion 2014; Salman et al. 2013).

The key pillars of tactical plans for urban water infrastructure are as follows: risk management, consisting of reliability and criticality analysis; feasibility processes, assessing technical applicability of available renewal techniques to replace, rehabilitate or repair; and prioritization processes, ranking all capital, operational and maintenance activities (Uddin et al. 2013). Salman et al. (2013) and Scholten et al. (2014) are among many who have partially tackled tactical planning for water pipeline networks by proposing optimization models.

A network-wide, high-level perspective should be employed in strategic planning for water distribution networks to forecast their long-term condition and performance indicators. System Dynamics (SD) as a modelling technique is widely used to understand the nonlinear behaviour of complex dynamic systems such as a water pipeline network demanding global structural dependencies of the system's components (Borshchev and Filippov 2004; Uddin et al. 2013). Along with other research areas, SD is applied in urban water infrastructure asset management (Bagheri and Hjorth 2007; Grigg and Bryson 1975; Qi and Chang 2011; Zarghami and Akbariyeh 2012). These studies have analyzed water distribution networks from a water-supply-management perspective, considering pertinent financial and social factors without any concern about the physical attributes of water mains. Rehan et al. (2011) introduced the application of SD modelling in water distribution and wastewater collection networks comprised of linear infrastructure assets (i.e., pipes), finance, and consumer sectors. They later developed and implemented two separate SD models for water distribution networks (Rehan et al. 2013, 2015) and wastewater collection networks (Rehan et al. 2014a; b). Shadpour et al. (2015) then conducted a numerical analysis to verify those SD models by verifying against nonlinear algebraic differential equations. Ganjidoost et al. (Ganjidoost 2016; Ganjidoost et al. 2017a; b) advanced them by joining water and wastewater system and adding more components. The key knowledge gap of all developed SD models has been the lack of interaction of strategic model with lower levels of planning (tactical and operational), although they have great merit of simulating feed-back effects between water-system components in different sectors. Appendix A provides a detailed review of currently available infrastructure asset management models for water distribution networks.

Decision Support Tools (DSTs), as computer-aided tools, enable water utilities, municipalities, and organizations to render efficient decisions based on the infrastructure asset database and to analyze and display pertinent information (Uddin et al. 2013). In fact, DST is an integral part of infrastructure asset management. The DSTs offered for water infrastructure management can be categorized into two main streams as follows:

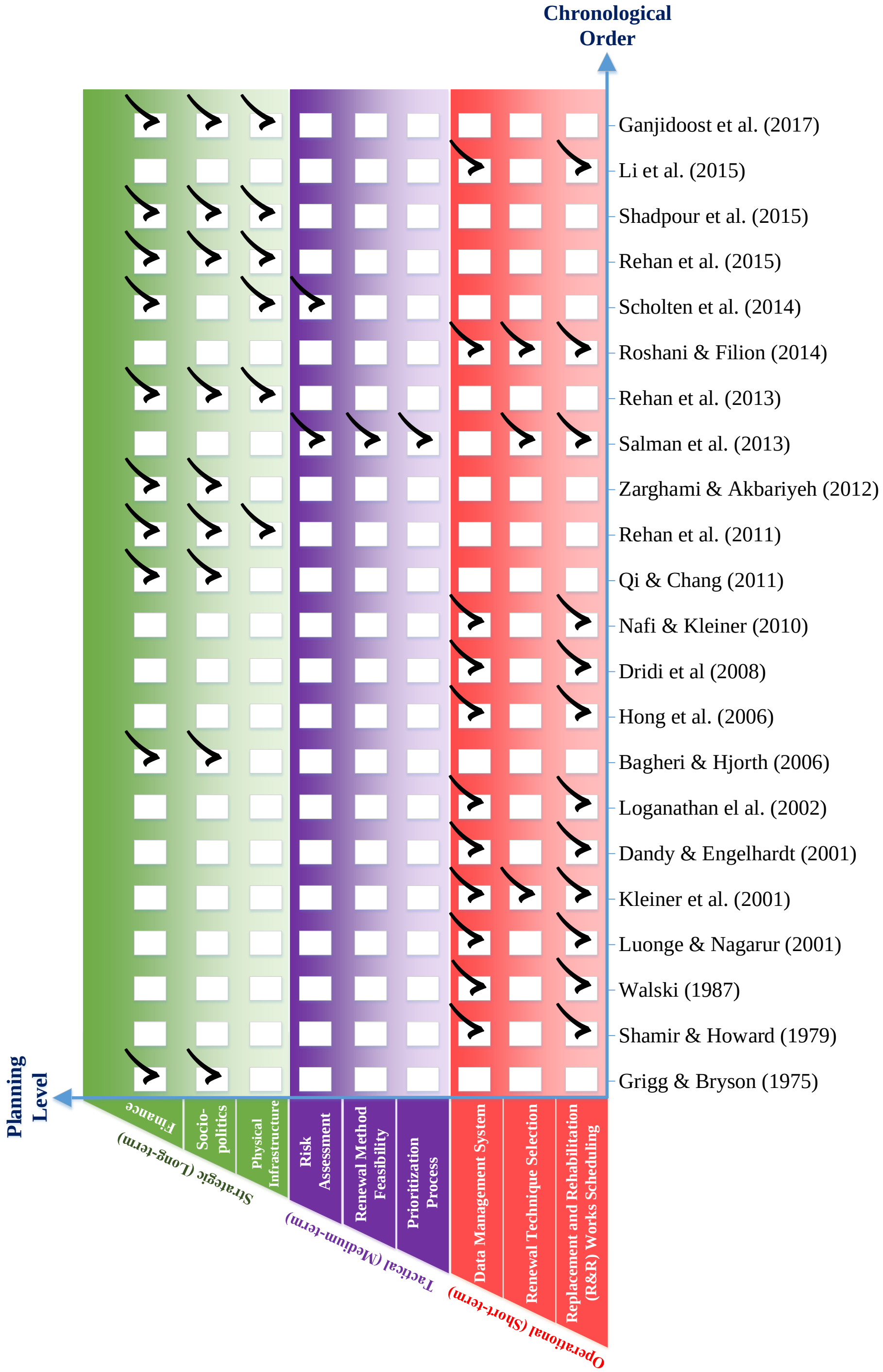
- Academic-based DSTs such as KANEW (Deb et al. 1998), UtilNets (Hadzilacos et al. 2000), PARMS-PLANNING (Burn et al. 2003), PARMS-PRIORITY (Moglia et al. 2006), CARE-W (Saegrov 2005), DSSWATER (Salman 2011), and AWARE-P (Leitão et al. 2016).

- Commercial software packages such as InfraModex, MIMS, IBM Maximo, Synergen, CityWorks, Hansen, RIVA- modelling, Infrastructure 2000, and Harfan (Halfawy et al. 2006).

Reviewing the academic-based DSTs reveals that apart from AWARE-P, which is a conceptual framework for IAM development, none of DSTs support an integrated planning approach. Furthermore, none of them support a renewal program that considers all levels of planning simultaneously. Halfawy et al. (2006) also showed that most available municipal asset management commercial software tools are limited to the operational level and have only little or no functionality to support long-term renewal planning decisions.

Alegre et al. (2013) proposed a framework (i.e., AWARE-P) to create an infrastructure asset management plan integrating all three planning levels. Although their framework incorporates a cyclic process allowing a feedback mechanism within each planning level and top-down information flow, it has neither a bottom-up feedback mechanism nor any feedback loops among a system's components. Ganjidoost et al. (2015) introduced a conceptual platform, borrowing from Industry Foundation Classes (IFC) developed in the building industry and EXPRESS-G data modelling language, enabling efficient planning data sharing and management among integrated multi-level (strategic, tactical, and operational) water and wastewater asset management. An integrated water infrastructure system neutral database and two interlayer neutral data files (strategic-tactical and tactical-operational) are embedded to store, exchange and feed common information. Although both studies attempted to push the envelope by proposing a framework to support interactions between planning levels, no integrated management model or tool has yet been developed for water distribution networks.

Figure 2-2 summarizes the reviewed studies and their respective target areas. This representation clearly highlights the lack of an Integrated Water Infrastructure Asset Management (IWIAM) tool comprising all strategic, tactical, and operational planning levels with both top-down and bottom-up interactions. Having such a tool would enable decision-makers in different managerial layers to readily share and exchange information in a complex dynamic water system; align the objectives of long-, medium-, and short-term plans; and efficiently allocate limited financial resources to meet the requirements of different planning levels.



	Strategic (Long-term)			Tactical (Medium-term)			Operational (Short-term)		
	Finance	Socio-politics	Physical Infrastructure	Risk Assessment	Renewal Method Feasibility	Prioritization Process	Data Management System	Renewal Technique Selection	Replacement and Rehabilitation (R&R) Works Scheduling
Ganjidoost et al. (2017)	✓	✓	✓	☐	☐	☐	☐	☐	☐
Li et al. (2015)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Shadpour et al. (2015)	✓	✓	✓	☐	☐	☐	☐	☐	☐
Rehan et al. (2015)	✓	✓	✓	☐	☐	☐	☐	☐	☐
Scholten et al. (2014)	✓	☐	✓	✓	☐	☐	☐	☐	☐
Roshani & Filion (2014)	☐	☐	☐	☐	☐	☐	✓	✓	✓
Rehan et al. (2013)	✓	✓	✓	☐	☐	☐	☐	☐	☐
Salman et al. (2013)	☐	☐	☐	✓	✓	✓	☐	✓	✓
Zarghami & Akbariyeh (2012)	✓	✓	☐	☐	☐	☐	☐	☐	☐
Rehan et al. (2011)	✓	✓	✓	☐	☐	☐	☐	☐	☐
Qi & Chang (2011)	✓	✓	☐	☐	☐	☐	☐	☐	☐
Nafi & Kleiner (2010)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Dridi et al (2008)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Hong et al. (2006)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Bagheri & Hjorth (2006)	✓	✓	☐	☐	☐	☐	☐	☐	☐
Loganathan el al. (2002)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Dandy & Engelhardt (2001)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Kleiner et al. (2001)	☐	☐	☐	☐	☐	☐	✓	✓	✓
Luonge & Nagarur (2001)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Walski (1987)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Shamir & Howard (1979)	☐	☐	☐	☐	☐	☐	✓	☐	✓
Grigg & Bryson (1975)	✓	✓	☐	☐	☐	☐	☐	☐	☐

Figure 2-2- Research scope of reviewed Infrastructure Asset Management Models for water distribution networks

2.3. Complex System Simulations and Water Supply Systems

Systems Dynamics (SD) and Agent-Based (AB) modelling are both widely applied in simulation modelling of complex systems. They are both able to capture the dynamic interactions among a system's components to understand the system behaviour and the underlying principles through capturing the mechanism of feedback loops in the system (Schieritz 2002). However, each of these simulation methods has its own merits based on modelling objectives.

System Dynamics (SD) is a feedback-based, object-oriented modelling method developed by Forrester (1958) to model and understand the non-linear behaviour of complex systems. The underlying concept of system dynamics involves simulating how a change in a variable causes a series of perturbations in the system, which is modified by other variables and itself. Researchers are utilizing SD simulation in a wide range of applications, from modelling social, ecological, and economic systems to management, planning, and engineering domains (Ford and Ford 1999; Sterman 2000).

Agent-Based (AB) modelling can be traced back to the 1940s and reveals the behaviour of a complex system by modelling the behaviour of all individual, autonomous, interactive agents who are interacting with and affecting each other, learning from their experiences, and adapting their behaviours so they fit their environments better (North and Macal 2007). The application of agent-based modelling embraces a broad range of disciplines, from biology, the social sciences, archeology, anthropology, and ecology to economy and system management. A detailed discussion of agent-based modelling applications can be found in Gilbert (2019), North and Macal (2007), and Taylor (2014).

The following briefly discusses some SD and AB modelling applications in water infrastructure systems.

2.3.1. Application of SD in water infrastructure systems

Many researchers have applied the SD modelling method to study the behaviour of water systems under various managerial scenarios. Qi and Chang (2011) developed an SD model incorporating socio-economics, population, and water demand variables to predict water demand in both long- and short-term horizons. Zarghami and Akbariyeh (2012) developed an SD model for urban water resource management and implemented it for the water system of Tabriz city, Iran. They studied the municipal water infrastructure system, taking into account water supply resources, potential sources of water demand, and management tools (wastewater reuse and recycling, inter-basin water transfer, water price, and conservation tools). Another SD model by Osman and Ali (2012) considered the interactions between physical infrastructure assets, system operators, users, and politicians. The model enables asset managers to investigate the impact of budget allocation on user fees, levels of service, and user satisfaction.

Rehan et al. (2011) developed the first known SD model in water and wastewater infrastructure asset management and investigated the impact of financial policy levers on the long-term performance of municipal water distribution and wastewater collection networks. The model integrates physical infrastructure, financial, and consumer sectors by structuring feedback-loop effects and interconnections between variables in different sectors. This SD model was also verified by a separate study using Differential Algebraic Equations (DAEs) (Shadpour et al. 2015). Later, they developed a separate SD model for water distribution networks to study financially sustainable management strategies in a long-term run (Rehan et al. 2013). This model was then implemented and validated for a mid-sized city located in southern Ontario, Canada (Rehan et al. 2015). They also developed and implemented another SD model for wastewater collection networks (Rehan et al. 2014a; b). The subsequent studies advanced these SD models to investigate scenarios that are more complicated in compliance with financial sustainability (Ganjidoost 2016; Ganjidoost et al. 2015, 2017a; b).

2.3.2. Application of AB in water infrastructure systems

The AB modelling method is often used when the individual behaviour of a system’s components (i.e., agents) matters. Davis (2000) has developed a Multiple Agent Decision-Support System (MADSS) for use in watermain rehabilitation decision making. He recognized the four main categories of relevant factors in decision processes: (1) engineering factors (customer complaints, geographic features, hydraulic characteristics, leakage parameters, reline/replace decisions, and water quality), (2) external factors (company consultants, contractors, customers, and regulatory factors), (3) organizational policies (asset management, budgetary constraints, demographic policies, operational costs, policy constraints, risk management), (4) technical factors (archive databases, case library, GIS databases, reference manuals, solution viability, technical reports).

Sanford Bernhardt and McNeil (2008) reviewed infrastructure management decision-making processes and agent-based modelling concepts to explore the application of AB in infrastructure management. They pointed out that AB approaches can transcend the limitations of traditional modelling used in infrastructure asset management. They established a pavement management framework as an example, based on the agent-based paradigm. Chu et al. (2009) studied the behaviour of domestic water consumption, which has a significant influence on urban water demand. Their AB model can predict consumer behaviours by considering the drivers of household water use, including water-saving technologies being available in water appliance market, regulatory policies, economic development, social consciousness, and preferences. The model was then implemented in a case study in Beijing to highlight the possible benefits. Galán et al. (2009) carried out a similar study on domestic water management for the metropolitan area of Valladolid, Spain. Osman (2012) presented a generic framework for urban infrastructure management by applying agent-based modelling with four agent types: assets, users, operators, and politicians. The model provides a facility to study the effects of users' social and psychological behaviour on their consumption of municipal infrastructure services. AB models are also used in water resource management, considering a group of active agents and their interactions based on behavioural rules. Berglund (2015) explores water resources systems as complex adaptive systems that can be studied using agent-based modelling. He demonstrates the difference between active and reactive agents with two illustrative case studies in water resources planning and management.

2.3.3. System modelling: System Dynamics (SD) vs. Agent-Based (AB)

SD modelling, founded on nonlinear differential equations, typically looks at a system while assuming a small number of aggregate states in which the system individuals are homogenized. By contrast, system heterogeneity can be readily captured by using AB (Rahmandad and Sterman 2008). Unlike SD, where the state of a complex system is determining by aggregated variables, called stocks, the global behaviour of the system emerges as a result of individual behaviours and interactions at the agent-level in AB models. The AB models are decentralized and constructed based on individual attributes and behaviours within interactive processes in the absence of knowledge about the system structure, including high-level interactions and interdependencies (Borshchev and Filippov 2004). Therefore, SD can be applicable to a high level of abstraction with less detail in modelling and hence is ideal for strategic level modelling.

In contrast, AB can be used across all abstraction levels but requires more detail about the system at the tactical and operational levels. For this reason, an SD model can be substituted with an agent-based model, but not vice versa. The greater complexity of AB models, the more computational efforts occur. More-complex systems need a deep understanding of the system with disaggregate details (Uddin et al. 2013). Figure 2-3 depicts the application domain of each type of modelling in water infrastructure system asset management.

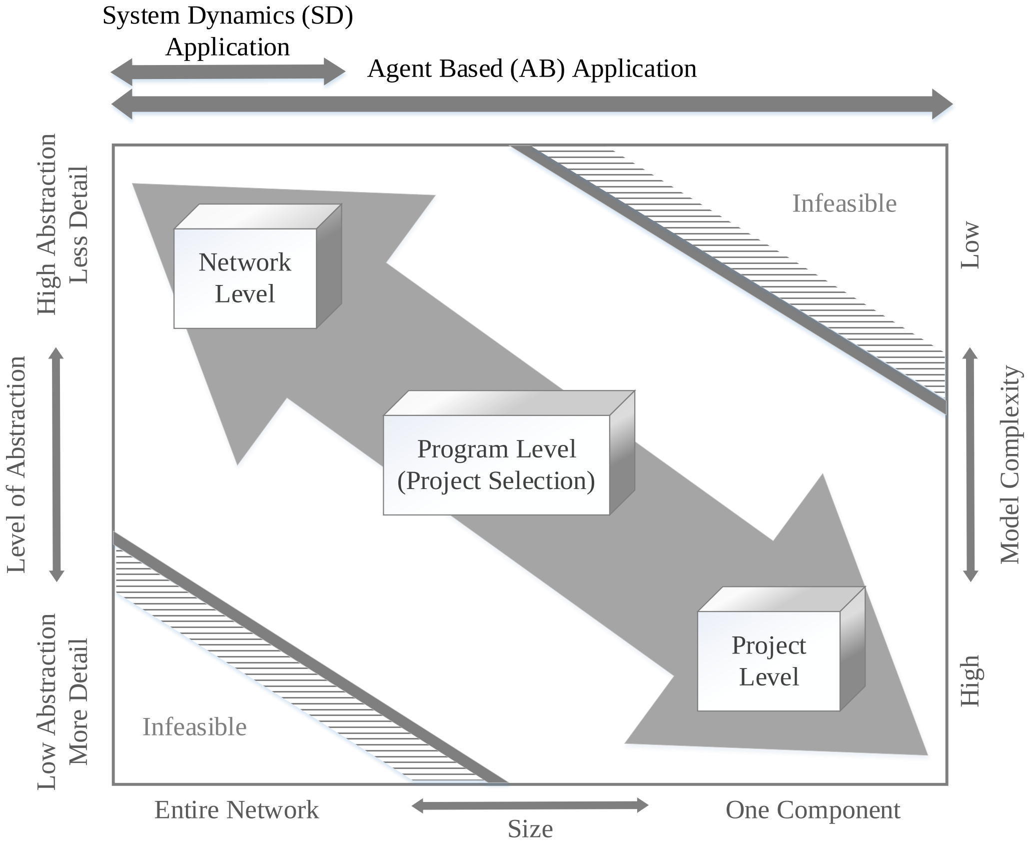


Figure 2-3- Application domains of system dynamics and agent-based modelling (adopted from Borshchev and Filippov 2004; Uddin et al. 2013)

In water distribution networks, a network-wide understanding of the system can be readily captured using a top-down SD modelling approach to predict the long-term performance of the entire system and to understand and capture the interactions between physical, financial, and consumer sectors (Rehan et al. 2011). Nevertheless, it has intrinsic limitations in recognizing the decisions made at component levels such as renewal technique selection, risk assessment, and rehabilitation schedule. A bottom-up AB modelling approach can simulate any decision-making processes running within each network's components (agents) and form the system's structure by congregating the component behaviours.

In summary, agent-based modelling method has merit when:

- the main actors in the system are discrete, identifiable and decentralized agents;
- the agents differ, or the environment is heterogeneous;
- there is a local interaction between agents;
- agents are adaptive;
- individual behaviours matter; and,
- agents have a spatial presence.

In this study, a hybrid AB-SD modelling approach is employed to develop an Integrated Water Infrastructure Asset Management (IWIAM) tool for water distribution networks that will generate long-term strategies taking advantage of SD modelling method, along with medium-term tactical programs and short-term projects using AB modelling method.

2.4. Hybrid AB-SD Model Framework

The AB-SD model consists of four main parts: Master agent, Segment agents, a Water Infrastructure Database, and a Plan-Do-Check-Adjust (PDCA) cyclic process. Figure 2-4 illustrates a conceptual framework of the AB-SD model. The following sections provide a brief description of each component of the model.

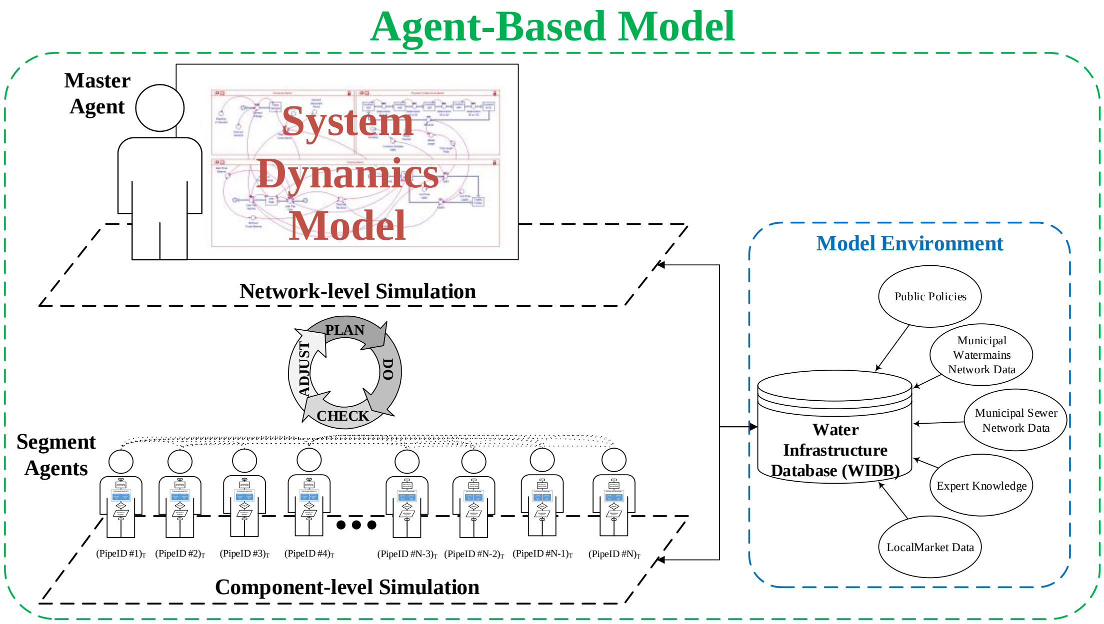


Figure 2-4- Hybrid AB-SD framework for IWIAM development

2.4.1. Master Agent

Master agent represents a high-level decision-maker who analyzes water distribution networks through a top-down approach. For this purpose, an SD model is embedded in the Master agent to analyze various scenarios for the long-term performance of the networks. This study adopts the SD model developed by Rehan et al. (2011), comprised of three interconnected sectors: physical infrastructure, finance, and consumer (Figure 2-5).

The state of the Maser agent is determined by the water network variables defined by SD elements, which are: stocks, flows, dynamic variables, parameters, and links. Stock is an accumulative or depletive variable, whose value changes only in response to connected flows. Condition-group pipe inventories, water user fees, and water demands can be mentioned as examples for stock variables, which are shown by square icons. Flow causes an increase (inflow) or decrease (outflow) in a connected stock at a rate defined by its value. For example, pipe deterioration rates, water fee hike rates, and water demand changes are defined as flow variables in the current SD model for water distribution networks and are demonstrated by a controlled-arrow symbol. The time-dependent calculations are performed in dynamic variables such as the network's average condition, while parameter elements represent constant values over simulation time such as capital unit costs. The relationships between the SD elements are defined by links, which are shown by arrows.

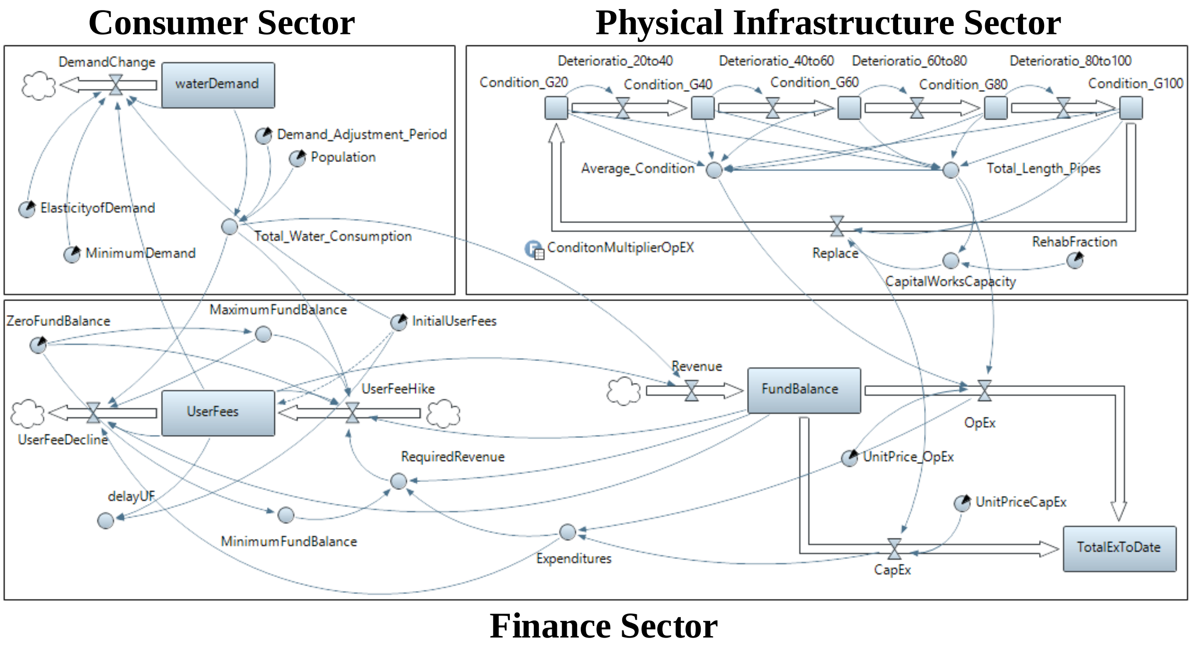


Figure 2-5- Replicated system dynamics model, adopted from Rehan et al. (2011), represented by Master agent

The output of the SD model is the performance of the water system over a 100-year period, which is used as inputs for the lower planning levels. This information defines policy levers for the lower planning levels, such as annual capital budget or total capital works, for developing capital programs and projects.

2.4.2. Segment Agents

A Segment agent represents a pipe or a group of connected pipes located between two isolation valves in a water distribution network. Each agent has two categories of attributes: static, which are descriptive and constant over the simulation period; and dynamic, which are calculated and may change during the simulation period. In this hybrid model, the static attributes of a Segment agent are the pipe ID, length, diameter, number of service connections, number of connected fire hydrants, and spatial characteristics such as geographical coordinates, land use, and natural or artificial barriers. The pipe installation date, material, age, liner, critical tier class, criticality index, reliability index, feasible renewal techniques, renewal unit cost, renewal action (replace, rehab, repair or do nothing), and selected renewal technique are considered to be the dynamic attributes of a Segment agent.

A decision-maker who is responsible for decisions made on each segment should provide answers to three main questions: (1) which segment? (2) when should it be replaced or rehabilitated? and (3) how?

There are two types of interactions in agent-based modelling: agent-agent interactions and agent-environment interactions. Most of the information required for internal processes taking place within each single agent is provided by the latter type of interactions. Renewal technique selection, criticality assessment, and reliability analysis are examples of internal processes. However, agent-agent interactions are essential in processes that require mutual sharing of information to establish a decision – such as the process for prioritizing pipe renewal, in which Segment agents are sharing their states and attributes to be compared and ranked. In more advanced models, agent-agent interactions will be used extensively. For example, candidate pipes for replacement need to be within reasonable proximity to be selected for a capital project. From a simulation point of view, any candidate Segment agent for replacement needs to be locally searching among its neighbors to find other appropriate candidates for grouping together to form a capital work-package.

Pipes in water distribution networks are scattered within particular geographical dimensions in a connected grid pattern. Therefore, their pertinent geographic information system (GIS) is chosen as the model environment to provide the required spatial information.

2.4.3. Plan-Do-Check-Adjust (PDCA) cyclic process

The core function of IWIAM model is to align strategic, tactical, and operational plans for water distribution networks. For this purpose, the management principles of PDCA are employed to coordinate network-level and component-level simulations to align high-level strategies with capital programs. PDCA is a four-step cyclic process to improve the alignment of a plan over time continually.

Figure 2-6 illustrates the mechanism of PDCA process in AB-SD model. Given a 100-year planning period at the network level and 5-year period for short-term planning horizon at the component-level, the following actions occur at each of the PDCA steps:

- Plan-step: Initially, the SD simulation model runs in the Master agent for 100 years at the network-level to forecast the long-term performance of the network. Network parameters like water fee, water demand, capital expenses (CapEx), and operational expenses (OpEx) are forecasted through a series of dynamic interactions between the network's variables (Figure 2-6a).
- Do-step: The first five-year results of CapEx established by Master agent flow down to the component-level, to constrain the annual budget allocation. These annual capital budgets are then used to develop a capital program for the first five years. In each year, deteriorated segments are selected for replacement by an Agent-Based (AB) simulation until the total capital expenditure is less than the capital budget for that year. The new annual capital expenditures will be the total capital expenses required to replace all selected individual segments in each year of the five-year program (Figure 2-6b). As the total capital expenses are set to be less than or equal to the total capital budgets, therefore, the new annual capital expenditure (new CapEx) may be different than what has been initially calculated by the Master agent using the SD simulation.
- Check-step: The new CapEx may alter other network performance indicators as they are determined over dynamic interactive operations in the SD simulation. Therefore, the SD model should be initialized to the starting point of the last SD simulation and re-run based on the results of the AB simulation for the same five-year period. This AB-SD simulation checks if any changes have occurred in other performance indicators due to the new CapEx in Do-step (Figure 2-6c).
- Adjust-step: The new results from the AB-SD simulation is compared with the SD simulation, and the long-term performance of the network is updated based on any results (Figure 2-6d). The state of the SD model at the end of fifth year will be set as the initial point for running another SD simulation for the next 100-year period.

The iterative PDCA process is repeated until the entire long-term planning period (i.e. 100 years) is checked and adjusted.

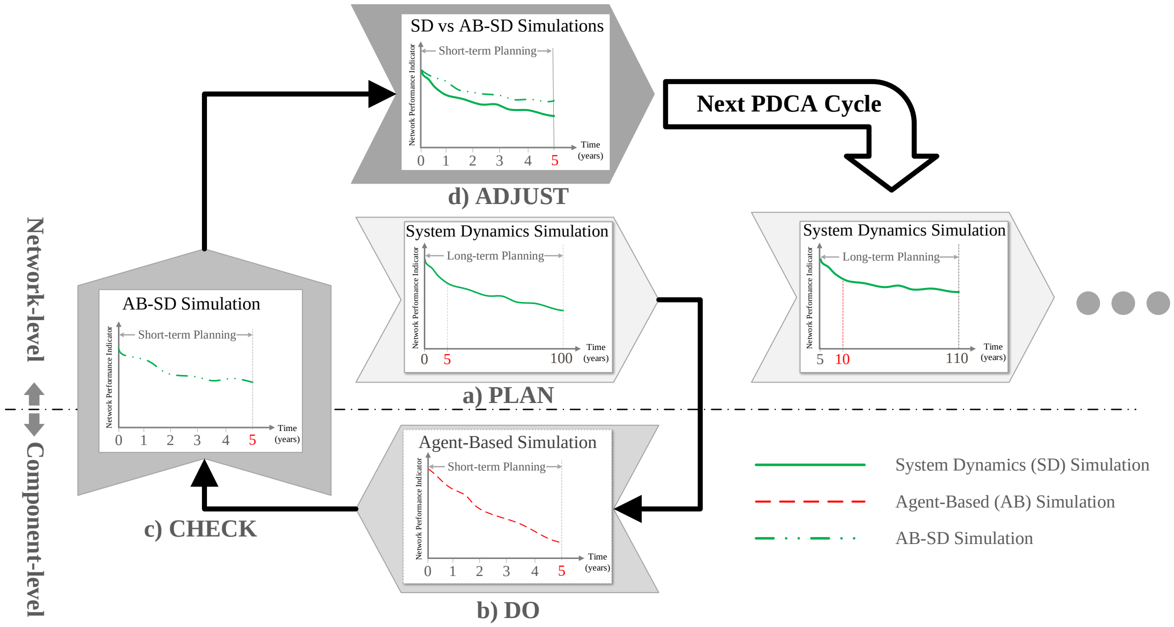


Figure 2-6- Iterative PDCA process for planning levels alignment

2.4.4. Water Infrastructure Database (WIDB)

The water infrastructure database is a centralized place to store, exchange and share data, typically used within various planning levels. Indeed, it facilitates data management and enables the integration and coordination of strategic, tactical, and operational plans in a comprehensive water infrastructure asset management. The data from both internal and external sources are fed into the water infrastructure database. The internal sources encompass the data generated during the simulation and are shared with the model components for their analyses. Model users collect and input information from external sources. The data associated with a municipal watermain network is an external data source that provides information such as pipe features, GIS maps, and demographic data. Public policies, legislations and rules, expert knowledge, and the water industry market are other external data sources.

2.5. Hybrid AB-SD Model Simulations

In the last few years, several software modelling tools have been developed for the application of agent-based simulation, such as NetLogo (Sklar 2007), Repast (North et al. 2006), Swarm (Blum and Merkle 2008), MASON (Luke et al. 2005), and AnyLogic (Borshchev and Filippov 2004). A multimethod simulation environment is required to couple agent-based and system dynamics modelling methods into a single simulation model. A review of currently available tools found that AnyLogic is a suitable simulation tool that supports both AB and SD simulation methods (Allan 2010). It also provides a platform to extract, exchange, and store the required data readily and visualize them in a spatial environment (i.e., GIS maps). Hence, this research uses research-version 7.3.7 of AnyLogic to develop the AB-SD model for integrated management of water distribution systems.

For verification and validation purposes, a hypothetical water distribution network with a 700 km pipe-length is assumed to serve 100,000 consumers. Aggregated pipe inventory distributions are used to run the SD model for network-level analyses. The water pipes are aggregated into five age-groups labelled as CG20, CG40, CG60, CG80, and CG100, representing the total length of pipes with 0-20, 21-40, 41-60, 61-80 and 80+ years old, respectively. However, a disaggregated inventory distribution is used at the component-level given that decisions are made on each single pipe segment. Therefore, pipe inventories are viewed from both aggregated- and disaggregated-viewpoints. In an integrated AB-SD model, the SD model is used to simulate the water distribution network at network-level (i.e., strategic) while the AB model supports the simulation of the network at the component-level (i.e., tactical/operational).

2.5.1. Network-level simulations

All network-level simulations are completed using the data reported in Rehan et al. (2011). A 100-year simulation period is set for long-term planning to align with the 100-year service life of pipes. The unit cost of capital works is assumed to be $1000 per meter of pipe segment. The operational unit cost for a brand-new pipe is $50, but it exponentially increases as the pipe condition deteriorates in accordance with the function presented in Rehan et al. (2011). Financial sustainability is set as a strategic goal, which requires a policy lever specifying zero fund balance over the planning period. To meet the goal, the network revenue generated by collecting water fees should cover the total capital and operational expenditures. The initial user fee is set as \$3.75 per m^3 to generate the required revenue equal to expenditures. Water demand is initialized to 300 liters per capita per day (lpcd) but changes according to the price elasticity of water demand equal to -0.35 in a 20-year adjustment period. This means that an increase in water fees causes a decrease in water demand as consumers will conserve more water to sustain their water bills in an affordable range. However, minimum water demand of 200 lpcd is assumed, to prevent further decreases in water demand regardless of water fees increases.

Although any user-defined deterioration function can be embedded in the model to simulate the pipe deterioration process, a simple age-based deterioration function is used in this study. The deterioration rates between age-groups are set as one-twentieth of total length pipe within an aggregated age-group moving into the next older one in each time-step.

2.5.2. Component-level simulations

Three primary processes are executed to allocate the available annual capital budgets among candidate pipe segments for replacement: (1) segment selection for replacement, (2) segment prioritization, including criticality and reliability analyses, (3) replacement technique selection. These processes respectively determine which, when and how a segment is replaced.

As stated before, the main objective of this study is to investigate the impact of integrating network-level and component-level simulations on the performance analysis of water distribution networks. To this end and for the sake of simplicity, all attributes of the segments in the hypothetical network are assumed to be the same except for their ages. Therefore, the prioritization process is solely a function of age. Open-cut replacement technique is chosen for all replacement activities. The unit cost of replacing a water main using open-cut method is assumed to be \$4 per meter length, per mm diameter (i.e., equivalent to \$1000 per pipe meter given pipe diameter of 250mm). A simple age-based ranking selection process is employed to reflect the prioritization process. The pipe deterioration process is performed by calculating the actual age of each pipe segment after each time-step.

For validation and verification exercises, the model simulates a mid-sized hypothetical network consists of 14,000 segments, each with a length of 50 m and a diameter of 250 mm. A 5-year period is set for running the hybrid AB-SD model at the component-level to develop capital programs.

2.6. Model Verification and Validation

The purpose of verification and validation exercises is to ensure a model performs as the intentional design specification and reproduces the behaviour of a real-world system (North and Macal 2007). Several verification techniques, such as dimensional consistency, structured code walk-throughs, debugging walk-throughs, and unit testing, are implemented to ensure that the AB-SD model is programmed correctly without any errors, oversights, or bugs (North and Macal 2007; Sterman 2000). The following presents a series of "what if" experiments to validate the AB-SD model. Initially, the SD module is validated against the SD model developed by Rehan et al. (2011). After that, a hypothetical network with three different initial conditions of pipe inventory is simulated under two capital investment scenarios to ensure the rational behaviour of the integrated AB-SD model.

2.6.1. SD model validation

Rehan et al. (2011) used STELLA 7.0.2 (isee systems), a visual programming software, to simulate an SD model for water distribution networks. This SD model is replicated in AnyLogic, and verification exercises are conducted for model credibility. Rehan et al. (2011) run the SD model for a hypothetical network with the initial aggregated age distribution of Figure 2-7 to explore three different cases under three rehabilitation scenarios (Scenario 1 to 3).

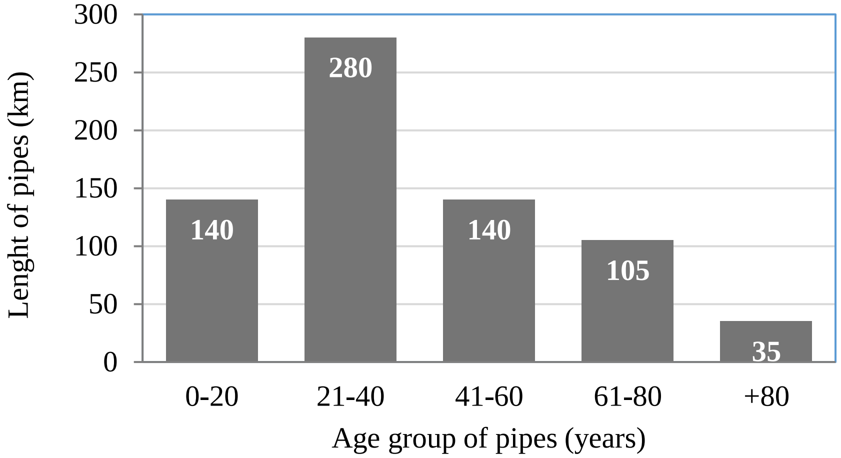
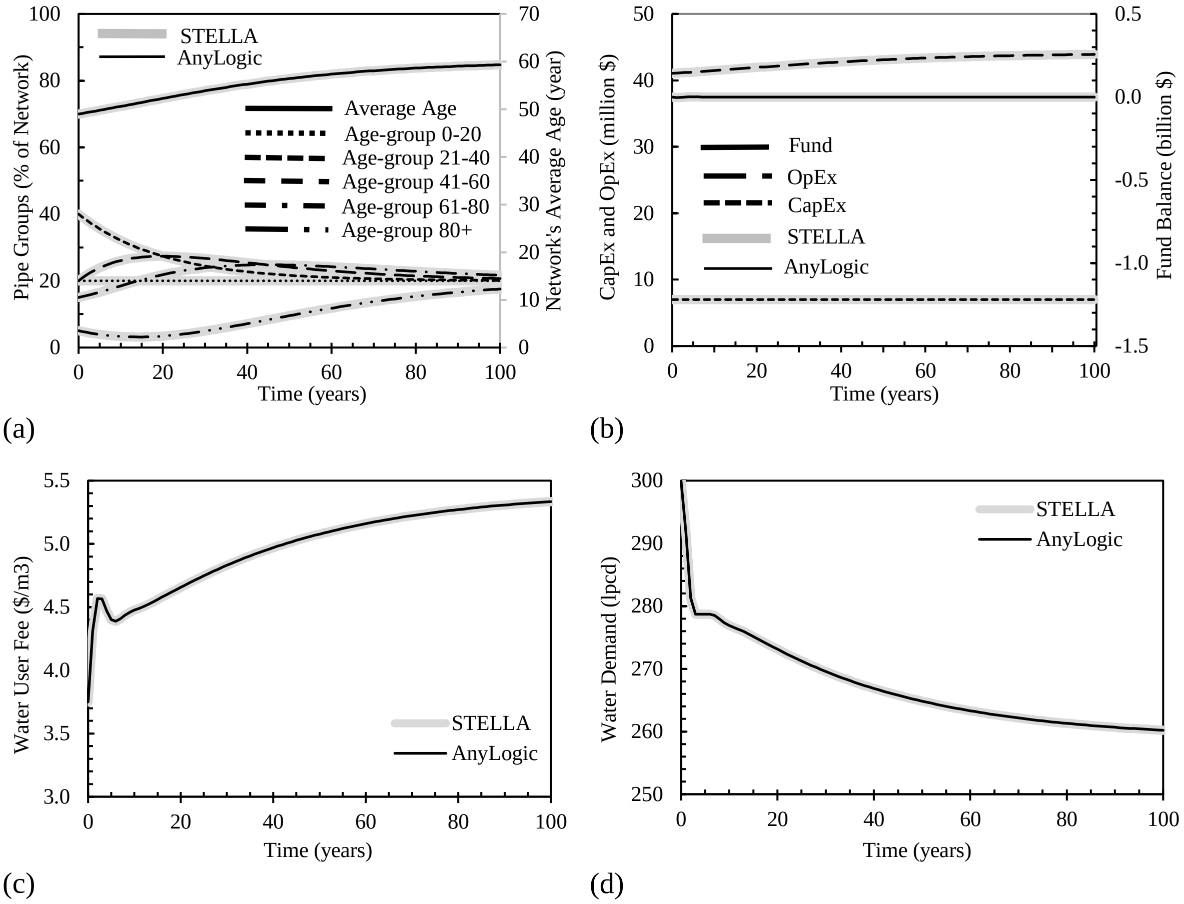


Figure 2-7- Initial aggregated age distribution of the network used by Rehan et al. (2011)

Scenario 2C in Rehan et al. (2011) is replicated by the SD model using AnyLogic and validated by comparing to Rehan's results developed in STELLA. This scenario includes a 1% annual replacement strategy with user fees adjusted to generate sufficient revenues to cover expenditures (i.e., zero fund balance) subject to a price elasticity of demand. Initial conditions and assumptions are considered identical in both simulation models. Both SD models are set to utilize fourth-order Runge-Kutta equations with time-step or 0.25 years.

Figure 2-8 presents the results of comparing the SD models using STELLA and AnyLogic. The percentage of pipe length in each age-group and network average age are shown in Figure 2-8a. Financial indicators, including capital expenditures (CapEx), operational expenditures (OpEx), and fund balance over the 100-year planning horizon, are illustrated in Figure 2-8b. Figure 2-8c and Figure 2-8d display water user fee and water demand variation, respectively, over a 100-year simulation period. The overlaid plots of all performance indicators confirm the consistency of SD model simulations using both simulation tools.



(a) (b)

(c) (d)

Figure 2-8- Comparison of SD simulation results for Scenario 2C using STELLA (Rehan et al. 2011) and AnyLogic

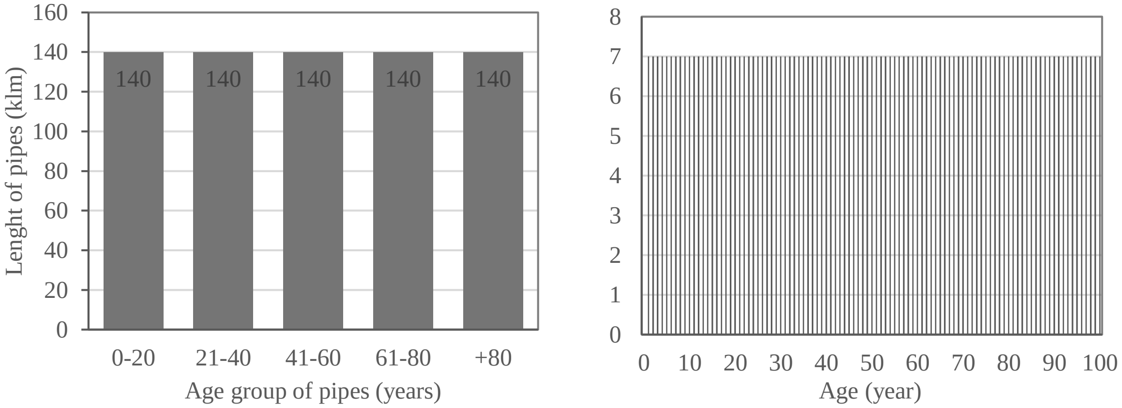
2.6.2. AB-SD model validation

A number of factors may differentiate the financial planning results at the network- and component-level. The goal of simulations at the network-level is to understand the structure and dynamic behaviour of water infrastructure systems. However, there are individual objects with local behaviour rules and interactions at the component-level. Therefore, the total length of pipe belonging to a specific age cohort is the concern of network-level planning, while pipes as individual entities are considered in component-level planning. Accordingly, an aggregate-continual deterioration process is assumed for the network-level analysis. At the same time, each individual pipe segment with its specified length has a certain age at any given time and ages, as an individual segment, as the simulation proceeds in time. These different viewpoints on pipe inventory profiles are the main source of discrepancy in the results of the two planning levels. Adding more complexity, such as considering different rehabilitation and replacement techniques, will impose more distinctive factors between network- and component-level planning. The following demonstrates how integrating network- and component-level perspectives impacts long-term performance indicators of water distribution networks.

2.6.2.1. Simulation scenarios

In this study, three water distribution networks with different pipe inventory age distributions are assumed for this model demonstration: Network A, Network B, and Network C.

In Network A (Figure 2-9), the total length of pipe is identical for all ages throughout the 100-year period. Therefore, Network A has a uniform inventory profile for both aggregated and disaggregated age distributions, which are used in the SD and AB models, respectively.

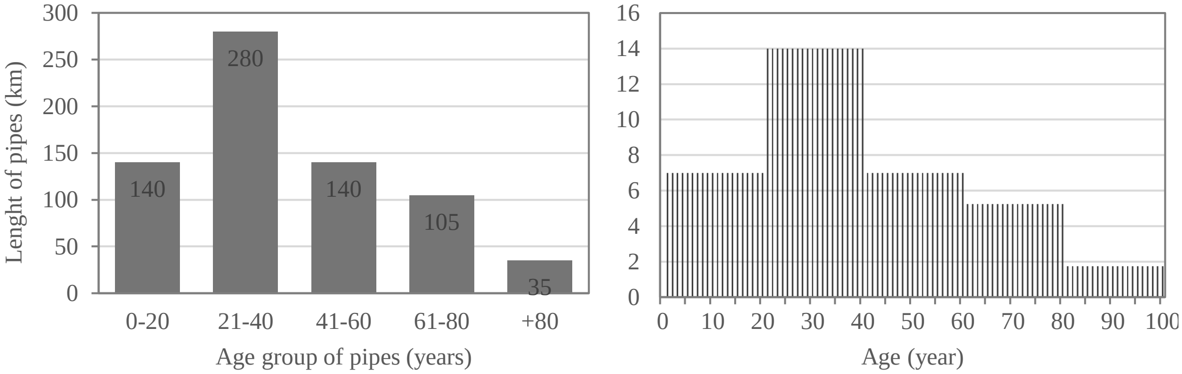


(a) Aggregated distribution

(b) Disaggregated distribution

Figure 2-9- Network A age distribution

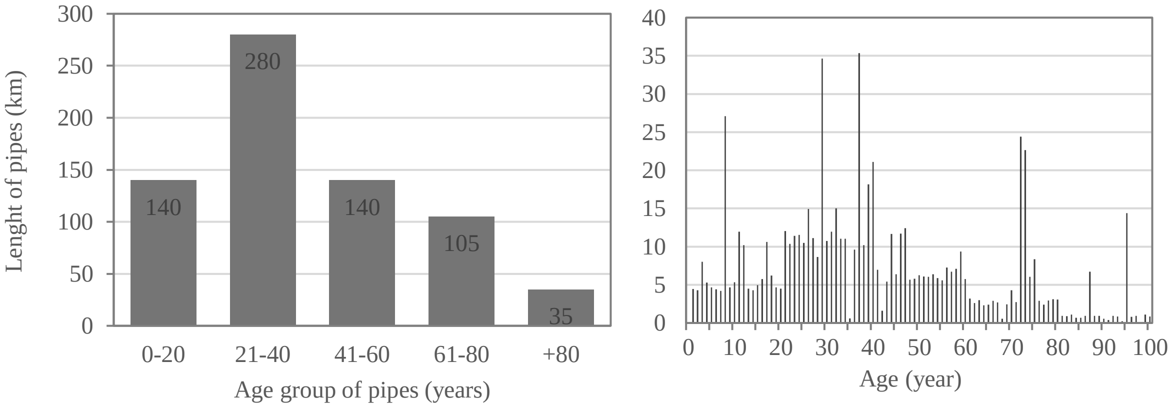
In Network B (Figure 2-10), the total length of pipes in each age-group are different, while the total length of pipes within an age-group is the same. Hence, Network B has an irregular age distribution from an aggregated perspective while it has a uniform age distribution within each age-group from a disaggregated perspective.



(a) Aggregated distribution (b) Disaggregated distribution

Figure 2-10- Network B age distribution

In Network C (Figure 2-11), the total length of pipes in each age-group and within it are different. Hence, Network C has an irregular distribution for both aggregated and disaggregated age distributions. Note that the aggregated age distributions of Networks B and C are identical to Rehan et al.'s (2011).



(a) Aggregated distribution (b) Disaggregated distribution

Figure 2-11- Network C age distribution

For this analysis, two renewal strategies are explored: (1) do-nothing scenario: no replacing activities within the network, (2) proactive renewal scenario: 1% of the network is replaced annually. The former is labeled A0, B0, C0, and the latter is labeled A1, B1, C1 for networks A, B, and C, respectively.

2.6.2.2. Simulation Results

The simulation results of networks A, B, and C, under both renewal scenarios, are provided in Figure 2-12, Figure 2-13, and Figure 2-14, respectively. In all figures, solid-lines illustrate the results of the hybrid AB-SD model, which simulates water distribution networks from an integrated perspective. The dashed lines show the results of the SD model, which represents the long-term performance of the water distribution network from only a network-level perspective without any interactions with the component-level simulations. From the physical point of view, the dashed-lines (i.e. the SD model's results) represent the system simulations considering only aggregate age-distribution at the network-level, while solid line (i.e. the AB-SD model's results) combine both aggregated and disaggregated age-distributions, coupling network- and component-level simulations.

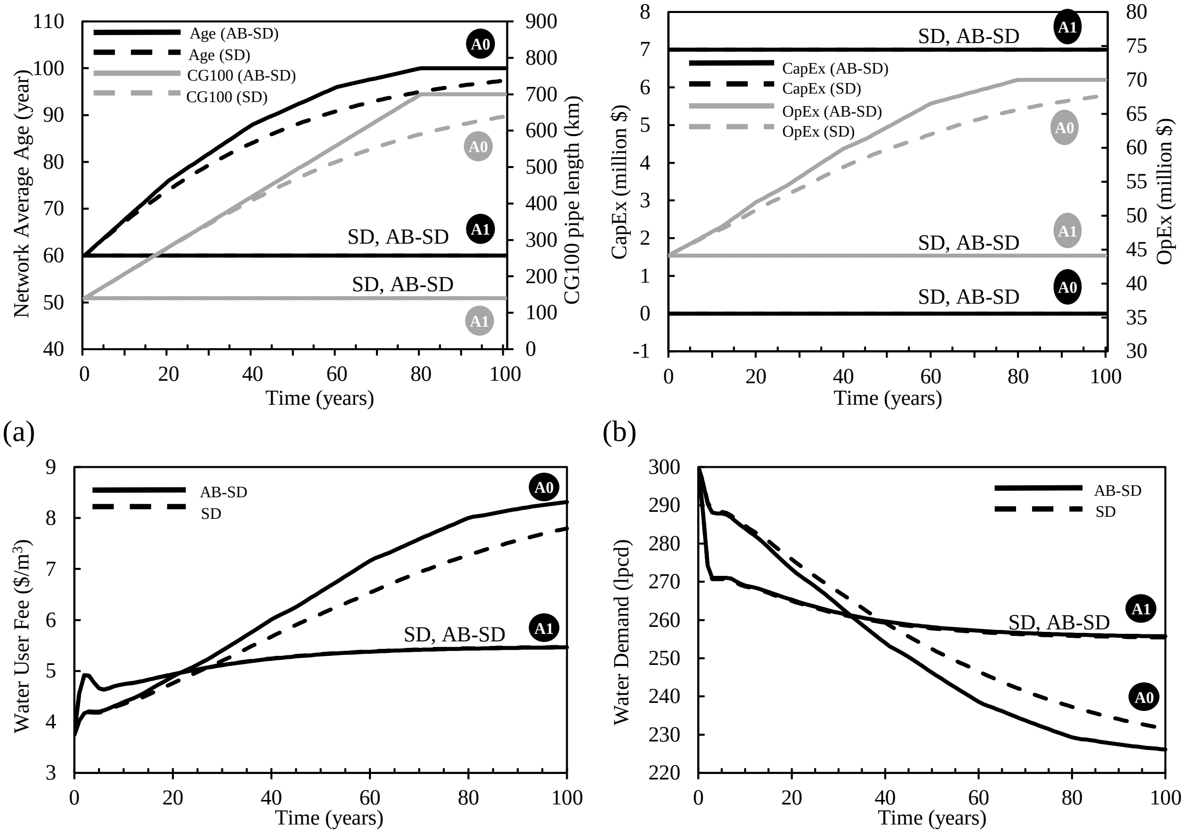
Figure 2-12a shows the average network age on the left y-axis and the total length of pipe in CG100 on the right y-axis. The AB-SD results show that if we do not replace any deteriorated pipes, the network average age, which is 60 years at the start-point, reaches 100 years at year 80 and remains constant for the following years. The total length of pipe in CG100 also verifies this result. In the do-nothing scenario, pipes accumulate in CG100 without any reduction over the 100-year simulation period. Consequently, the total length of pipes in CG100 reaches the maximum possible amount of 700 km, at year 80 and remains constant for the next years, a result highlighting that there is no pipe in younger age-groups after year 80 that can move into CG100. The SD results (dashed-lines) show the same increasing trends for both performance indicators but in smoother ways. The feedback effects between aggregated and disaggregated age distributions in the AB-SD model differentiate its results from the results of the SD model. To clarify, the calculation of total length pipe in CG100 is highlighted. In the AB-SD model, the actual total length of pipes more than or equal to 80 years old is calculated as the CG100 value in each time-step. Disaggregated age-distribution of Network A in Figure 2-9b indicates that 7 km of pipes per annum is accumulated in the age-group

80+ years (i.e., CG100). Hence, the aggregated pipes in CG100 linearly increase until all pipes in the network are added to it. With the flow mechanisms in the SD model, the values of condition groups are calculated by adding their inflow to and subtracting their outflow from their current values. In the do-nothing scenario, nothing is added to CG20, whereas CG20 is depleted through "Deterioration_20to40" flow with the rate of 5% of total length in CG20 at each time-step (Figure 2-5). Consequently, the value of "Deterioration_20to40" flow is exponentially decreasing, and it will successively happen to other flows ("Deterioration_40to60", "Deterioration_60to80", and "Deterioration_80to100"). Therefore, the rate of adding pipe into CG100, via "Deterioration_80to100" flow, is not fixed and decreases from 7 km per year at an initial time to almost-zero in infinity.

In the proactive scenario with a 1% renewal strategy for Network A, all flows, including deterioration flows and "replace" flow, will have equivalent rates. Thus, the input to and the output from each condition group are equal. From a disaggregated age-distribution perspective, 7 km pipes shifted for all ages is equivalent to the one percent of the network annually replaced. Therefore, both aggregated and disaggregated age-distributions of Network A remain the same as the initial condition over the simulation period. For this reason, the results of SD simulations are identical with the results of AB-SD simulations in the proactive 1% renewal strategy for Network A.

Figure 2-12b shows capital expenditures on the left y-axis and operational expenditures on the right y-axis, over the 100-year simulation period. Total capital expenditures are zero over the simulation period in the do-nothing scenario, while $7 million per year is invested in replacing deteriorated pipes in the proactive scenario. As the aggregated and disaggregated age-distributions are identical, the CapEx is constant over the entire simulation period in both scenarios. The trend of annual operational expenditures follows the network average age curve, as it is a dependent variable of the network average age. In the do-nothing scenario, annual operational expenditures increase from $44 to $67.6 in the SD simulation and to $70 million in the AB-SD simulation with the same increasing trend of network average age. In the proactive 1% annual renewal rate scenario, operational expenditures remain at $44 million due to the constant network average age for the entire simulation period.

To attain a self-financially sustainable condition, all capital and operational expenditures should be covered by the revenue generated by water user fees. Figure 2-12c shows water user fees that are set to gain zero fund balance over the 100-year simulation period. The results suggest that if we do not proactively invest in replacing deteriorated pipes, water consumers will have to pay more in time to cover escalating operational costs. By year 100, water consumers should pay \$8.3 per m^3 of water in the do-nothing scenario and more than 50% in the 1% annual renewal rate scenario, which is \$5.4 per m^3.



(a) (b)

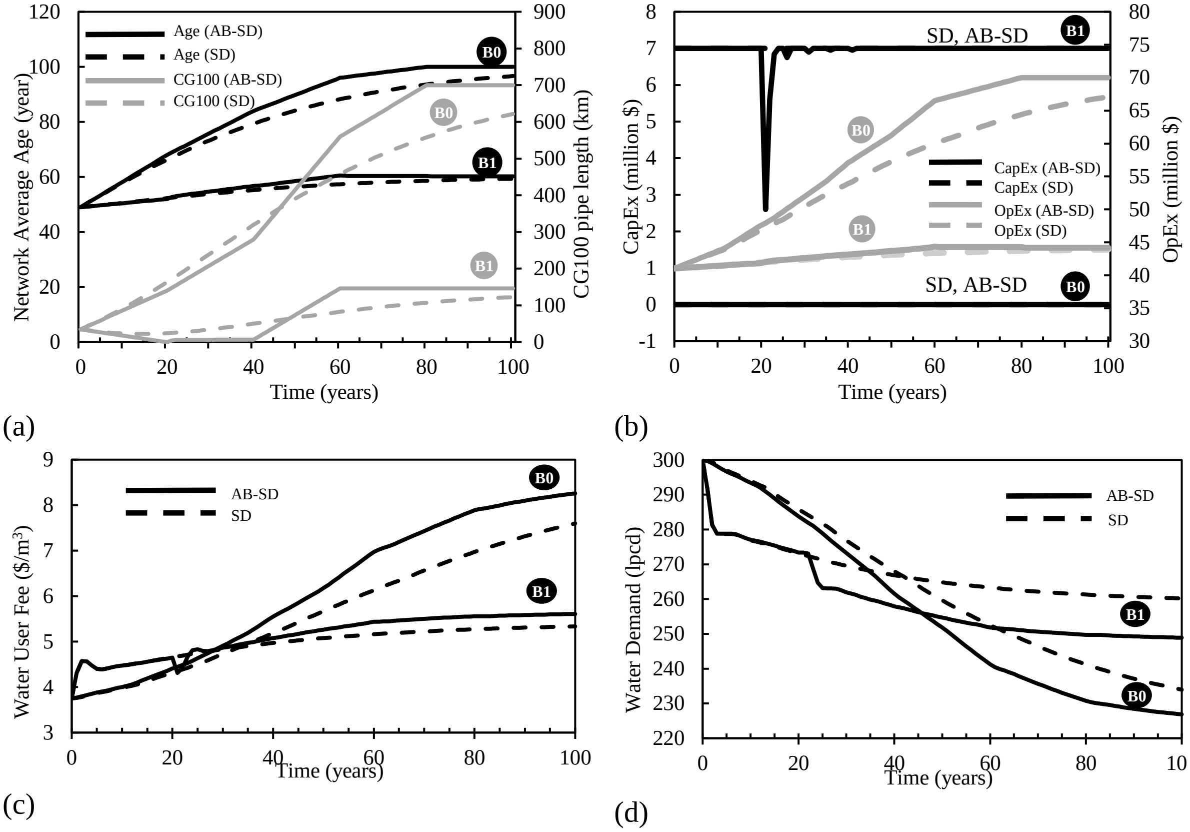
(c) (d)

Figure 2-12- Simulation results for Network A

Figure 2-12d illustrates water demand over the long-term simulation period. All curves trend down as water demand behaviour is counter to water user fees. Thus, water consumers will conserve water with price increase. Figure 2-12d also shows that people conserve more water, to reduce their water bills, in the do-nothing scenario compared to the proactive 1% annual renewal rate scenario.

The water demand decreases from 300 lpcd, at the initial point, to 226.1 lpcd, in the do-nothing scenario, and to 255.7 lpcd, in the proactive renewal scenario at the end of the 100 years. The discrepancy of SD and AB-SD simulation results, regarding water user fees and water demands, is related to feedback effects between the aggregate and disaggregate inventory age distributions, as explained above.

The initial network conditions of networks B and C differ when one views the networks from a disaggregate perspective, although they have identical aggregate age distributions (Figure 2-10 and Figure 2-11). Figure 2-13 and Figure 2-14 present results relevant to Networks B and C, respectively.



(a)

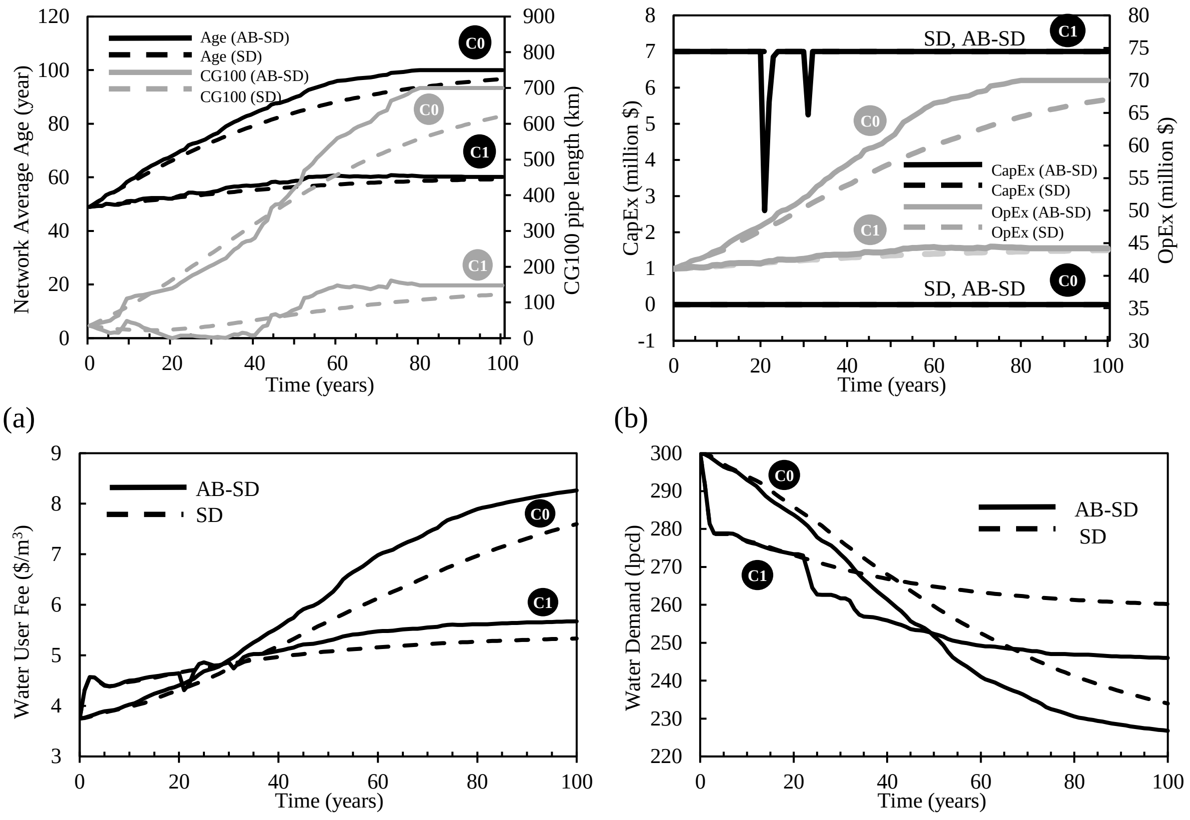
(b)

(c)

(d)

Figure 2-13- Simulation results for Network B

Figure 2-13a and Figure 2-14a show an aggressive increasing trend in network average age and ICG100 deteriorated pipes in the do-nothing scenario compared to ones related to the proactive renewal scenario. The network average age and the deteriorated pipes in CG100 reach their maximum possible values at year 80. The results of operational expenditures verified this behaviour by following the same trend as the network average age (Figure 2-13b and Figure 2-14b). As expected, the capital expenditure is flat at zero in the do-nothing scenario due to no capital works done. Although the results of SD model simulation show constant 7 km replacement activity per year in the proactive renewal scenario, the AB-SD model simulation reveals a sharp drop in year 21 and a few small ones in the following years, indicating the lack of sufficient deteriorated pipes in CG100 to be selected for replacing. The drops demonstrate the ability of the AB-SD model to capture component-level information, which the SD model is unable to do.



(a)

(b)

(c)

(d)

Figure 2-14- Simulation results for Network C

Figure 2-13c and Figure 2-14c show water user fees over the simulation period for both renewal scenarios. Water users will pay more in the long-term if no replacement action is performed in the networks. These figures show that the annual water user fee generally increases from \$3.75 per m^3 to \$8.26 per m^3, in the do-nothing scenario, and \$5.60 per m^3, in the proactive renewal scenario, by year 100.

Figure 2-13d and Figure 2-14d show a decreasing trend in water demand, reflecting the contrary behaviour of user fee changes. Initial water demand of 300 lpcd ends up as 227 lpcd, for the do-nothing scenario, and 248.9 lpcd, for the proactive renewal scenario, at year 100.

Other than the similarity in general trends of the performance indicators for Networks B and C (Figure 2-13 and Figure 2-14), they converge to the same values approaching the end of the simulation period, until they end up at the same values. A comparison between the corresponding curves reveals that more heterogeneousness in disaggregate inventory profile only imposes more fluctuations in the early years, which are diminished over the simulation time.

2.7. Discussion

The desired long-term performance for a water distribution network is to achieve: (1) better physical condition, reflected in lower network average age consisting of fewer deteriorated pipes; (2) lower network expenditures from the utilities' perspective, and; (3) lower user fees and higher water demand from consumers' perspective. The simulation results show that the AB-SD model broadly outputs a higher network average age, more highly-deteriorated pipes (i.e., CG100 pipes), higher operational expenditures, higher user fees, and lower water demand. It implies that the integrated planning approach using the AB-SD model conservatively forecasts long-term performance for water distribution networks compared to the SD model, which only considers the network-level perspective. Hence, ignoring interactions between the strategic, tactical, and operational levels in an integrated planning approach may lead to overestimating the network indicators and cause unexpected infrastructure backlog in the future. Reviewing all results (Figure 2-12, Figure 2-13, and Figure 2-14) underlines that the results of AB-SD and SD models follow the same trends over the simulation period. Although they diverge to different values by 100 years in some scenarios, they closely agree for the first 20 years and show almost the same values for all performance indicators. Table 2-1 provides the variation of the performance indicators using the AB-SD simulation model compared to the SD strategic model by the end of 100 years. The changes in all the performance indicators are less than 10% by year 100, which is acceptable as the uncertainty of simulation results increases through the simulation time.

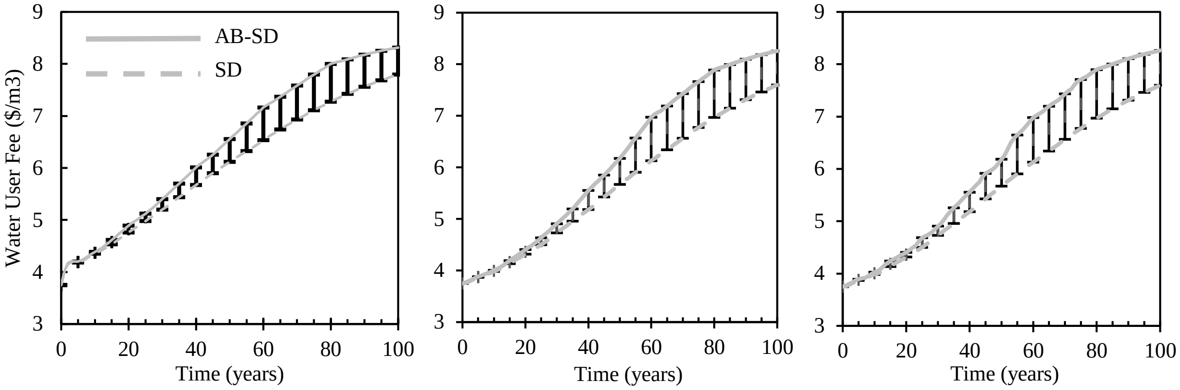
Table 2-1- Change of performance indicators using AB-SD model vs. SD model

Performance Indicators	Simulation Scenarios					
	A0	A1	B0	B1	C0	C1
Network Average Age (year)	2.65 ↑ 3%	0.00 ↑ 0%	3.33 ↑ 3%	0.86 ↑ 1%	3.33 ↑ 3%	0.90 ↑ 2%
CapEx (million$)	0.00 ▬ 0%	0.00 ↑ 0%	0.00 ▬ 0%	0.00 ▬ 0%	0.00 ▬ 0%	0.00 ▬ 0%
OpEx (million$)	2.32 ↑ 3%	0.00 ↑ 0%	2.91 ↑ 4%	0.27 ↑ 1%	2.91 ↑ 4%	0.29 ↑ 1%
Accumulated CapEx (billion$)	0.00 ▬ 0%	0.00 ↑ 0%	0.00 ▬ 0%	-6.40 ↓ -1%	0.00 ▬ 0%	-7.70 ↓ -1%
Accumulated OpEx (billion$)	0.26 ↑ 4%	0.00 ↑ 0%	0.33 ↑ 6%	0.04 ↑ 1%	0.34 ↑ 6%	0.05 ↑ 1%
Water User Fees ($/m3)	0.52 ↑ 7%	-0.01 ↑ 0%	0.66 ↑ 8%	0.27 ↑ 5%	0.67 ↑ 9%	0.34 ↑ 6%
Water Demand (lpcd)	-5.42 ↓ -2%	0.31 ↑ 0%	-7.09 ↓ -3%	-11.29 ↓ -4%	-7.19 ↓ -3%	-14.20 ↓ -5%

The advantage of the integrated approach using AB-SD model is to address the planning needs at the network- and component-levels, simultaneously, to support and align the decision-making processes at both simulation levels. The SD model alone can not comply with these requirements.

2.8. Sensitivity Analysis for PDCA Cycle

Uncertainty is inevitable in forecasting models. Forecasts would be different from the numbers that occur. Thus, forecasting is impossible yet unavoidable. Water utilities, planners, and policy-makers need to quantify the performance of water distribution networks for better decision-making regarding prospective costs and benefits in various scenarios. Uncertainty is often growing over time in a forecasting model. For instance, Figure 2-15 shows the divergence between water fees forecasted using the SD model and the AB-SD model over 100 years for all three networks.



(a) Network A (b) Network B (c) Network C

Figure 2-15- Uncertainty in water user fee forecasting over 100 years in Do-nothing scenario

In the AB-SD model, the network-level SD simulations are periodically checked and adjusted using the results of component-level AB simulations. A 5-year period in Section 2.4.3 is used to get feedback from the component-level to the network-level simulations, and vice versa. Figure 2-16 presents the sensitivity analysis performed to determine an appropriate feedback cycle in the AB-SD model. A number of simulations are performed on Network B using the SD model, without any feedback between network and segment levels, and using the AB-SD model, with a feedback cycle every 2, 5, 10, 50, and 100 years. Two performance indicators of water user fee (Figure 2-16a), and network average age (Figure 2-16b) are plotted to demonstrate the results provided. The simulation results show that the AB-SD model with a 5-year feedback cycle (solid line) forecasts the highest water user fees and the highest network average age over the 100 years. On the other hand, the SD model (dashed line) outputs the lowest results for both performance indicators. Other simulations with different feedback cycles fall between these two curves. Hence, five years is the optimum feedback cycle for interacting between network- and component-level simulations. Generally, the strategic planning using the SD model, without any interaction with the component-level, overestimates the long-term performance of water distribution networks. In contrast, the AB-SD model with a 5-year feedback cycle conservatively forecasts it.

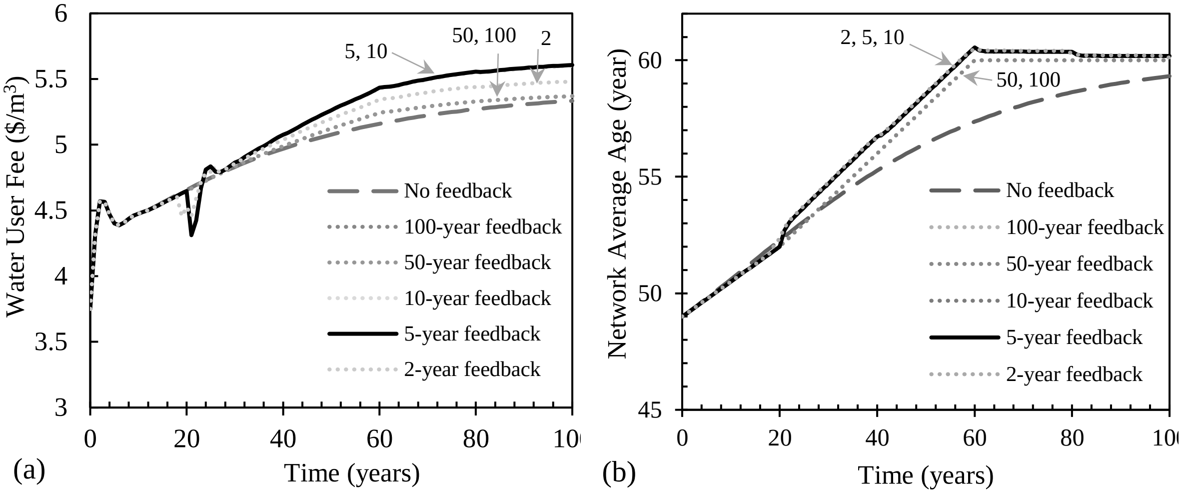


Figure 2-16- Sensitivity analysis to determine efficient feedback cycle

2.9. Conclusions

This study set out to develop an integrated simulation framework to forecast the long-term performance of water distribution networks. The literature review has identified that no decision support system or simulation model has been developed to integrate decision-making processes at both network and component levels.

Rehan et al. (2011) applied the system dynamics simulation method to capture the interconnections and feedback loops among system components in water distribution networks. However, it is limited to the strategic level without having any interactions with the lower levels of planning, i.e., tactical and operational. This study couples an agent-based simulation method with the system dynamics model to provide a platform to integrate strategic, tactical, and operational plans for forecasting the long-term performance of water distribution networks. This integrated model can be used to mitigate the organizational-silos problem in water utilities. The model can interpret long-term strategic goals for developing multi-year capital programs to drive renewal projects, and then getting feedback to tweak strategic plans. Hence, the proposed novel AB-SD methodology is deemed to be compliant with infrastructure asset management guidelines, such as ISO 55000 and IIMM, for developing an integrated asset management plan.

The results of the AB-SD model display similar trends to the SD model for all performance indicators over 100 years. Although they diverge over the 100-year simulation period, it is trivial as the presence of ever-growing uncertainty is inherent in forecasting models. Nevertheless, both models output almost the same results for the first twenty-year. Comparing the results found that the SD model optimistically forecasts the long-term financial performance of water distribution networks, whereas the hybrid AB-SD method pessimistically forecasts it, incorporating a feedback mechanism between network- and component-levels. Further analysis of the feedback cycle reveals that updating long-term strategic plans (SD model) every five years using feedbacks from component-level (AB model) is deemed to be the most efficient method for developing an integrated asset management plan.

Chapter 3.

Development of a Hybrid Agent-based and System Dynamics Model for Water Distribution Networks

Abstract

Utility managers face challenges in developing capital programs for water distribution networks due to limited capital budgets and a large number of degraded pipes. An integrated long-term planning approach is essential to address the current needs of water infrastructure for capital investments and eliminate infrastructure backlog over a reasonable period. This study develops a novel Agent-based modelling approach coupled with System Dynamics (AB-SD) model to integrate short-term capital programming with long-term strategic plans to fulfill short- and long-term managerial policies simultaneously. This is the first know application of agent-based modelling to the management of water distribution networks. The model is implemented on three artificial water distribution networks to demonstrate how it can address both component-centric and network-centric decisions and simulate the interactions between component and network planning levels.

Keywords: capital program, water infrastructure, agent-based, system dynamics, risk analysis, decision support system

3.1. Introduction

Canadian water infrastructure needs more than $50 billion for immediate renewal action on water and wastewater infrastructure assets in poor or very poor condition to sustain the current state of urban water services (Canadian Infrastructure Report Card 2016). Moreover, a larger proportion of water infrastructure in fair condition requires close attention as they are approaching the end of their service life in the following decades. Canadian Infrastructure Report Card (2019) highlights that 27% of water distribution networks are in fair or worse condition, of which two-thirds are in fair condition. However, the network is expected to age over the next decade and fall into poor or very poor condition.

Immediate actions are required to replace failed water mains and bring them back to the service for maintaining the current levels of service. Water fees are set to generate sufficient revenue to cover expected operational and capital expenses over a multi-year planning period to obtain a financially sustainable system. Thus, water user fees are projected with respect to the physical condition and failure rate of a water distribution network over the planning period. Asset managers consider flexibility in annual capital budgeting to cover the uncertainty of failure rates to accommodate all potential capital works. They usually develop an asset management plan to outline the asset activities and programs in a 10-20 year planning outlook (IIMM 2011). A wave of deteriorated water mains beyond this planning window may cause a significant infrastructure deficit due to a surge in failure rates. A successful capital program needs to be integrated with the long-term strategic plan to eliminate the current infrastructure backlog and avoid growing infrastructure deficit in water distribution networks. This capital program can support both reactive renewal (replacing water mains reaching the end of their service lives) and proactive renewal strategies (rehabilitating deteriorated water mains to extend their remaining service lives).

Most earlier studies investigated the optimal replacement time for individual water mains to minimize the total network costs, including capital and operational costs (Hong et al. 2006; Loganathan et al. 2002; Luong and Nagarur 2001; Shamir and Howard 1979; Walski 1987). Dridi et al. (2008) developed a GA-based optimization model to locate and schedule any pipes that need to be replaced within a planning period. The model is combined with a hydraulic simulator, i.e., Epanet2.0, and a probabilistic break model to simulate structural deterioration of pipes. Nafi and Kleiner (2010) proposed a GA optimization methodology to efficiently schedule water mains replacement activities with limited financial resources in a determined planning period. It considers the impact of economies of scale and roadwork coordination on total capital cost. Salman et al. (2013) proposed a reliability-based methodology to develop capital programs for water distribution networks depends mainly on limited capital budget and planning time. Their model optimally clusters water mains into capital groups subject to the acceptable size of group and rehabilitation method. Roshani and Filion (2014) developed an event-based approach to optimally schedule watermain capital works (rehabilitation and replacement) in water distribution networks. The optimization problem was defined as a multi-objective problem of minimizing both capital and operational costs by seeking the best scheduling to rehabilitate pipes. Li et al. (2015) demonstrated that utilizing a replacement decision optimization method for group scheduling (RDOM-GS) can improve replacement planning significantly and reduce costs and service interruptions. All of the studies reviewed here support the development of capital programs for water distribution networks without having any interactions with a long-term strategic plan.

Chapter 2 highlighted the lack of a Decision Support System (DSS) that is capable of integrating network-level (i.e., strategic) and component-level (i.e., tactical and operational) plans for water distribution systems. A hybrid system modelling framework has been introduced to provide an integrated DSS using Agent-Based and System Dynamics (AB-SD) modelling methods. This integrated DSS provides a platform to combine capital programming at the component-level with long-term strategic planning at the network-level.

The goal of this chapter is to demonstrate how the hybrid AB-SD model can be used to develop capital programs aligned with the long-term strategic plan for water distribution networks. The salient objectives of this study are: (1) to develop the AB-SD model and its associated computational modules, and (2) to demonstrate how it can be implemented in water distribution networks to address: component-centric decisions, such as pipe renewal schedule and optimal replacement/rehabilitation alternatives; and network-centric decisions, such as annual water fees and network rehabilitation rate. Three artificial water distribution networks are designed to validate the AB-SD model for the development of multi-year capital programs.

The following section provides a detailed discussion of the necessity and benefits of including a bottom-up modelling approach using the agent-based modelling method in the simulation of water distribution networks. A detained hybrid AB-SD model is developed in Section 3.3. Validation exercises are presented in Section 3.4 followed by a discussion in Section 3.5. Finally, this chapter is concluded by summarizing the outcomes in Section 3.6.

3.2. Water Distribution Systems and Agent-based modelling

The management system of water distribution networks consists of numerous interconnected components, from social-political stakeholders, and financial decision-makers, to physical assets. Rehan et al. (2013) developed a causal loop diagram to illustrate the interactions among social, financial, and physical components in the management system of water distribution networks. They utilized a system dynamics model to mathematically realize the causal loop diagram for water distribution systems (Rehan et al. 2015). Although their system dynamics model was a novel contribution in capturing dynamic interactions among the water system's components over time, it is limited to decision-making processes that occur at the strategic level by policy-makers. Hence, the system dynamics model is incapable of developing capital programs that answer three questions of which deteriorated pipe segments, how, and when needs to be replaced.

Decisions regarding a water main are made using simple rules and interactions with other system components. For example, a water main is selected for replacing if it is more critical and has higher priority compared to other candidates. This selection occurs if there is a capital budget available to cover associated replacing expenses. Hence, any decision on whether to select a water main or not for replacement depends on the condition of other mains as well as the budget constraints. The agent-based modelling method can simulate the behaviour of system components and their interactions for water distribution networks to address asset-centric requirements in developing capital programs.

A typical agent-based simulation model has three main components (Macal and North 2010):

i. A set of *Agents*
ii. Agent *Interacting relationships*
iii. The agents' *Environment*

Agents are the decision-making entities and have a set of attributes, behaviours, and actions (North and Macal 2007). Agent attributes that specify the state of an agent are classified into two groups: static and dynamic. The value of static attributes remains constant while that of dynamic attributes may alter over the simulation period. Dynamic attributes can be time-dependent (i.e., changing by time), action-dependent (i.e., changing in response to other agent actions), or both time- and action-dependent. A series of decision rules allows an agent to capture required information from internal (agent's self-attributes) or external (other agents' attributes or the model environment) sources, process the inputs, and then output an action or an effect on the outside environment. This process is identified as the agent behaviour, and its output denotes the agent action. The agent behaviour link between agent inputs and outputs, and it can be anything from simple rules/functions to complex simulation models.

Agents are interacting with each other based on pre-defined rules. These rules are specifying the connectivity between neighboring agents, and how they are mutually influencing each other (i.e., agent-based model's topology). Thus, a change in an agent's behaviour triggers a series of behavioural changes in other agents over the interacting rules, which in turn influences its behaviour.

Agents are interacting with the model's environment in addition to agent-agent interactions. The model environment provides information from external sources, such as spatial location, regulatory rules, and technical considerations.

The objective of this study is to develop an integrated model for water infrastructure asset management to integrate capital programming, using the Agent-Based (AB) model, with long-term strategic planning processes, using the System Dynamics (SD) model, for water distribution networks. This hybrid AB-SD simulation model considers the AB simulation method as the prime modelling paradigm in which the SD model is embedded in an autonomous agent. The following sections elaborate more on the components of the AB-SD model.

3.3. Agent-Based and System Dynamics (AB-SD) Model

The first steps of developing an agent-based model are to define the agents, their interactions, and behaviours. The hybrid AB-SD model recognizes three primary agent types: Master Agent, at the network-level, and Segment and Asset-Manager Agents at the component-level. Table 3-1 summarizes these agents along with their attributes, whether they are static or dynamic, their dependency, and units.

Table 3-1- Agent attributes in the AB-SD model

Agent	Static attribute (unit)	Dynamic attributes (unit, dependency[*])
Master	Population (person) Minimum Water Demand (litre/capita/day) Water Price Elasticity of Demand (%/%) Pipe Deterioration Rates (km/year)	Renewal Rate (% of network/year, A) Pipe Length of Condition Groups (km, T) Annual Renewal length (km/year, T) Fund Balance ($, T) Revenue ($/year, T) Capital Expense ($/year, T) Operational Expense ($/year, T) Water User Fee ($/m3, T) Capital Unit Cost ($/m, A) Operational Unit Cost ($/m, A) Water Demand (litre/capita/day, T) Total Water Consumption (m^3, T) Network Average Age (year, T)
Segment	Physical attributes: - Diameter (mm) - Length (m) - Material Location attributes: - Land use - Geographic Coordinates - Natural/Artificial Accessibility Obstacle # of Service Connections # of Connected Fire Hydrants Criticality Tier/Class	Age (year, TA) Installation date (year, A) Criticality Index (- , A) Reliability Index (- , TA) Priority Index (- , TA) Feasible Renewal Techniques (- , A) Renewal Action (- , A) Renewal Technique (- , A) Renewal Cost ($, A)
Asset Manager	Annual Capital Budget ($/year) Intervention policies	Annual Capital Expense ($/year, A) Capital Activities (- , A) Annual Capital Unit Cost ($/m, A)

[*] T: time-dependent, A: action-dependent, TA: time- and action- dependent

3.3.1. Agent definitions

Master Agent is a single agent that develops a long-term plan based on the broad perspective of a water distribution network. It requires only a basic set of information to analyze and evaluate the impact of different renewal strategies on the performance of water distribution networks from a high-level planning point of view. The decisions in Master agent are formed through continuous interaction among the physical asset, finance, and consumer sectors. The SD model is deemed to be an appropriate modelling approach to accommodate this dynamic, interactive simulation concept. Therefore, the behaviour of the master agent is defined using an SD model adopted from Rehan et al. (2011). An SD model has four primary elements: stocks, flows, dynamic variables, and parameters. All stocks, flows, and variables represent dynamic attributes, wherein parameters represent static attributes. Stocks are accumulating the impacts of the system on a variable over the simulation time. Examples of stocks are water-user-fee, inventory of pipes, water demand, and fund balance. Flows cause changes in stocks over time or promptly by either increasing (inflow) or decreasing (outflow) the stock value. Examples of flows are capital expenditure, operational expenditure, and revenue that affect the stock of fund balance. Table 3-1 lists the attributes of the Master agent. The behaviour of the master agent is forecasting the long-term performance of a water distribution network, including the physical condition of the network, financial measures, and water consumption indicators. An agent in agent-based modelling method may be adaptive, which implies that its behaviour can be modified using a set of rules and learning from previous actions (North and Macal 2007). The master agent is designed as an adaptive agent of which behaviour is periodically adjusted by feedback received from other agents. Section 3.3.2 provides more details about this feedback mechanism.

Segment Agent is the simplest agent in the AB-SD model and represents a watermain pipe segment with a valve at each end. Therefore, a population of segment agents appears in the model. The value of some segment's attributes is easily determined by direct measurement. For example, segment dimensions, including pipe diameter and length, are intrinsic characteristics of a segment and measured directly without any relationship with other attributes. Some other attributes are determined in connection with other attributes using either a simple mathematical function or a computational algorithm. For example, the age of a segment is a simple function of the installation date and simulation time, while the list of feasible renewal methods is generated by checking with a set of decision rules.

Segment agents make some decisions independently. For instance, a segment agent decides whether a replacement or rehabilitation method is technically feasible or not, regardless of the state, behaviour, or action of other agents. Nevertheless, there are some decisions made for a segment agent in interactions with other agents. For example, a pipe segment is flagged for a renewal action if there is an available budget for capital works; furthermore, the type of renewal action is specified in compliance with the intervention policies.

The static and dynamic attributes designed for Segment agents are presented in Table 3-1. Two behavioural modules are utilized in segment agents to specify the attributes related to risk management and renewal technique selection. Sections a) and 3.3.3 expound on these behavioural modules.

Asset-Manager Agent represents the decision-maker who allocates capital budgets for replacing or rehabilitating water mains to operate and maintain the water distribution networks most efficiently over a multi-year planning period. This agent decides which segment and how it should be replaced or rehabilitated subject to available financial resources and technical constraints. This process is taken place according to rules set by intervention policies. A population of asset-manager agents exists in the simulation model that each one represents the capital plan for a given year. Asset-Manager agents utilize a capital budgeting behavioural module to allocate limited financial resources to candidate segments. Section 3.3.3 c) provides more details about how the capital budgeting works.

3.3.2. Agent interactive relationships

Agent interactions simulate feedback effects in a dynamic system and can be either inner-agent or inter-agent types. Figure 3-1 presents the agent interactions in the AB-SD model for water distribution networks.

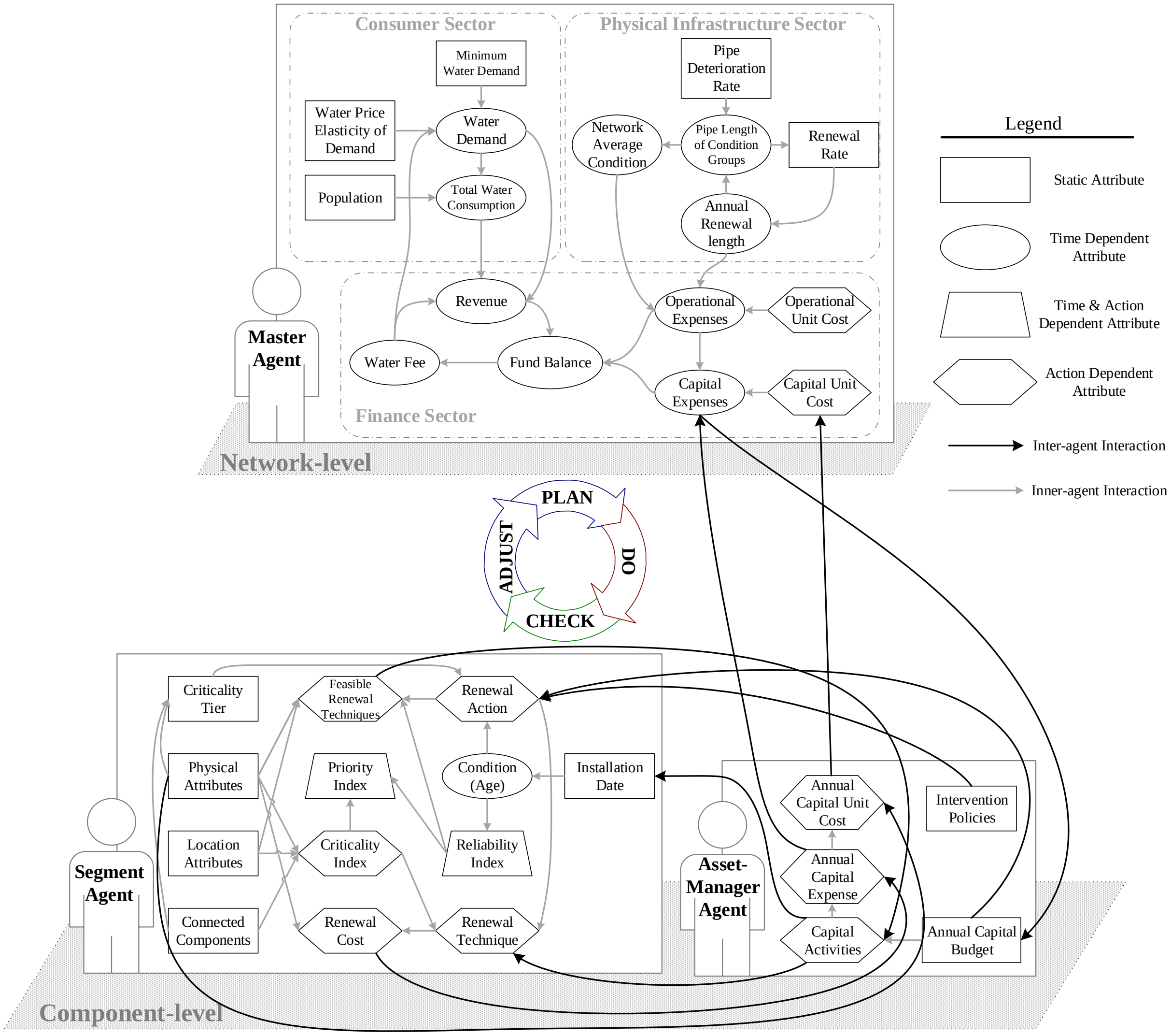


Figure 3-1- Agent interactions in the AB-SD model

In inner-agent interactions, an attribute of an agent impacts another attribute of the same agent. For example, the *Age* value of a segment agent is used to calculate its *Reliability Index* through the age-reliability interaction. Grey arrows represent inner-agent interactions in Figure 3-1. Inter-agent interactions occur between two separate agents in which an attribute of an agent influences an attribute of a different agent. For example, the *Renewal Cost* of a segment agent is added to the *Annual Capital Expense* of an asset-manager agent. Figure 3-1 illustrates inter-agent interactions with black arrows.

There are four interaction sets in the model: (1) within network-level interactions, (2) the interactions passing down the information from network-level to component-level, (3) within component-level interactions, and (4) the interactions passing the information from component-level up to network-level. A Plan-Do-Check-Adjust (PDCA) mechanism is developed to regulate the sequence of these interaction sets. It implies that only one interaction set is executing at a time, while other sets are idle. Indeed, the interactions within each level and between the levels are operating in phases.

At the Plan step, all inner-interactions of the Master agent are active (i.e., interaction set 1), and the simulation of the water distribution system is used to develop a long-term strategic plan at the network-level. At the Do step, the downward inter-interactions (i.e., interaction set 2) subsequently pass required information for the component-level agents from the Master agent, as the initial conditions of the simulation at the component level. This action then drives all component-level interactions (i.e., interaction set 3) to simulate the water system at the component-level to create a multi-year capital plan. The results of these two types of simulations are compared at the Check step, using the upward inter-interactions between network- and component-levels (i.e., interaction set 4). In the Adjust step, the long-term strategic plan is adjusted to be aligned with the capital plan. The initial conditions of the next SD simulation in Master agent, i.e., the next PDCA cycle, are set according to the new status of the system at the end of the previous PDCA cycle.

3.3.3. Agent Behavioural Modules

Different computational modelling modules are embedded in the agents to simulate their corresponding behaviours. Figure 3-2 shows the main behavioural modules relating to each agent. As discussed earlier, the behaviour of the Master agent (i.e., strategic planning) is simulated using an SD model at the network-level. Risk management and renewal technique selection are two main behavioural modules used to determine the actions of Segment agents. Capital budget management is also used by the Asset-Manager agent to allocate the limited capital budget among potential capital works.

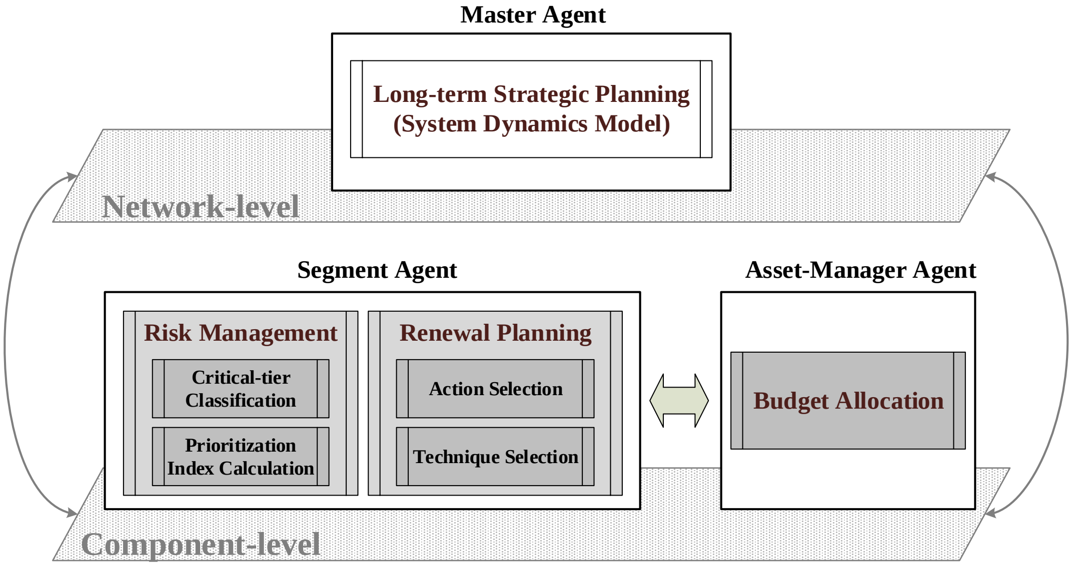


Figure 3-2- Computational modules to simulate agents' behaviour

a) Risk Management

The purpose of risk management is to prioritize deteriorated pipes for renewal. Two pillars of the risk analysis for a pipe are: (1) the likelihood of pipe failure (i.e., pipe reliability assessment), and (2) the consequence of pipe failure (i.e., pipe criticality assessment). Water mains can be classified into four broad groups:

i. Transmission Mains: which transport water from distant water supply sources such as treatment plants or reservoirs dams to centralized supply points of distribution such as water towers or pumping stations. Transmission mains not directly supplying water consumers; therefore, there are no service connections attach to a transmission watermain.

ii. Primary Feeder Mains: which convey water from centralized supply points to water service zones. These water mains also do not supply water to the end-users.

iii. Secondary Feeder Mains: which play the same role as primary feeder mains except supplying some water consumers either with high water demands, such as factories demanding large quantities of water, or ones without access to distributed mains.

iv. Distribution Mains: which deliver water to water consumers. These are typically the smallest mains in the water supply system.

The sizing of water mains for each category depends on the size of a network and pertinent hydraulic characteristics. However, the size range of transmission, primary feeder, secondary feeder, and distribution mains are generally in descending order. Table 3-2 provides the size range of each watermain group used in this study.

Table 3-2- Typical sizes for water mains

Water main	**Diameter (mm)**
Transmission mains	$D > 600$
Primary Feeder mains	$450 < D \leq 600$
Secondary Feeder mains	$350 < D \leq 450$
Distribution mains	$150 < D \leq 350$

The size of service connections is also a good rule of thumb to quantify the impact of service interruption on water consumers. Service connections classify into four groups: (1) small connection: deliver water to residential users, (2) medium connection: deliver water to small commercial and industrial users, (3) lager connection: deliver water to large commercial and industrial users, and (4) extra-large connection: deliver water to special users with high water demand, such as large manufacturing plants.

Table 3-3- Typical sizes for service connections

Service Connection	**Diameter (mm)**
Extra-large	$d > 150$
Large	$50 \leq d < 150$
Medium	$40 \leq d < 50$
Small	$d < 40$

Project Management Institute (PMI) recommends a six-step process of risk management planning, risk identification, qualitative analysis, quantitative analysis, response planning, and risk control for the risk management of a project (PMI 2013). This process is subjective and depends on the client's objectives, expectations, and project terms and conditions. In this study, two-phase risk management is proposed to conduct the risk analysis, and consequently, the prioritization process.

The first phase entails a critical-tier classification process to segregate segments according to their importance. Four critical tiers are defined as follows:

- **Tier-one** consists of segments whose failure has the lowest consequences. The maintenance strategy for this type of pipes is “run to failure”. Distribution mains providing service to residential consumers fall into this category.
- **Tier-two**, the second critical class, causes considerable damage upon failure. The outage of this type of water main affects small businesses in addition to residential users. Tier-two consists of both distribution and secondary feeder mains that serve small commercial and industrial users. Although more water consumers will be affected by the failure of a tier-two pipe, the consequences are limited.
- **Tier-three**, the third critical class, induces extensive damage upon failure. Tier-three consists of both distribution and secondary feeder mains that serve large commercial and industrial users. In addition to the service interruption of large businesses, the failure of a tier-three main would interrupt the water service for a subdivision of the network.
- **Tier-four** includes the most-critical mains with the highest consequences for failure. The service interruption in the failure event of a tier-four pipe affects either the whole network or a vast service area. Therefore, the failure of a tier-four main will have catastrophic consequences, and immediate action needs to be taken to bring it back to the service.

Different renewal strategies can be implemented for each critical-tier. In this study, a proactive renewal strategy is pursued for Tier-four, Tier-three, and Tier-two in order of priority, whereas the Tier-one mains can run to failure. Figure 3-3 illustrates the algorithm used to classify a pipe segment into critical-tiers based on its size and size of the meter installed on associated service connections.

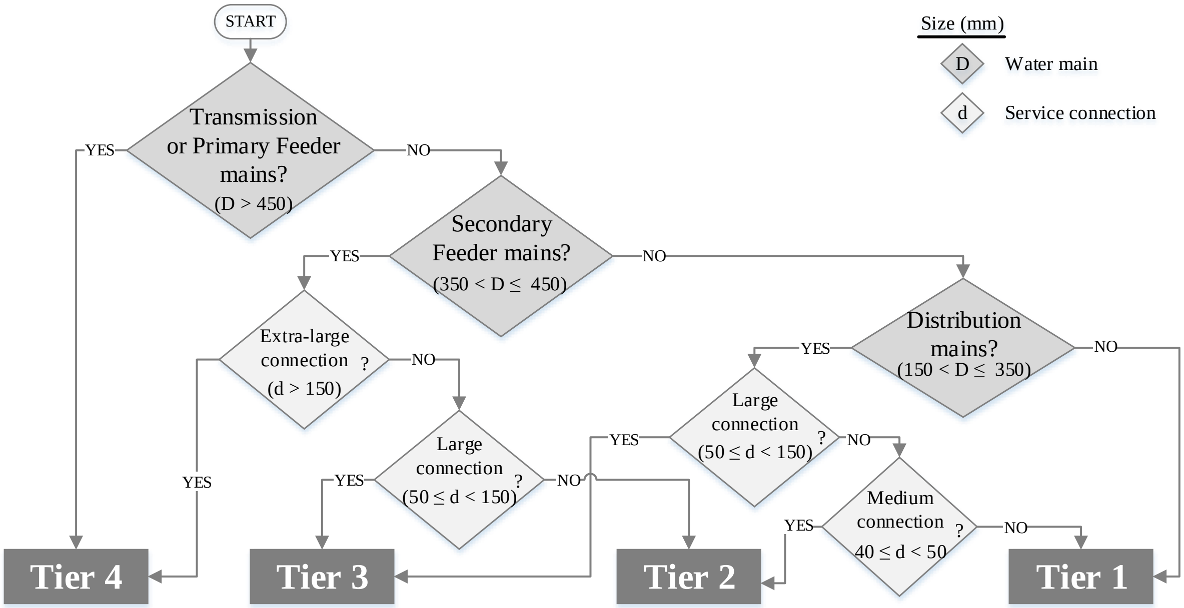


Figure 3-3- Preliminary criticality classification methodology

The second phase entails the prioritization of pipe segments within each critical tier based on coupling the probability and consequence of failure.

Reliability is another way to describe the probability of pipe failure. The reliability of a system or a component is the probability of its proper functioning within specified limits for a specified time without failure. The failure of a water main does not have an exact definition; however, practitioners often identify the failure state for a water main as one that requires a physical intervention, such as repair or replacement (Knight et al. 2018). A segment's reliability exponentially declines with age. Mathematically, the Reliability Index (*RI*) is a negative exponential function of time assuming the average failure rate of a water main (λ) is constant and independent of time (t) (Billinton and Allan 1992).

$$RI(t) = e^{-\lambda t} \qquad \text{Eq. 3-1}$$

Folkman (2018) calculated water main break rates by collecting and analyzing the data on water main failures across pubic and private water utilities in the USA and Canada. This study uses the average failure rates of Canadian utilities reported by Folkman (2018). Table 3-4 provides the value of λ broken down by pipe material.

Table 3-4- Average failure rates (λ) for water mains, adopted from Folkman (2018)

Pipe Material	Failure Rate (failures/100 km/yr)
Polyvinyl Chloride (PVC)	0.434961
Asbestos Cement (AC)	4.660296
Cast Iron (CI)	21.74805
Concrete Pressure Pipe (CPP)	0.559235
Ductile Iron (DI)	9.444866
Steel	2.423354
Other	8.326395

Identification of critical factors and then quantifying their corresponding scores and weights are two main steps in criticality analysis (PMI 2013). The criticality models estimate either actual or relative damage costs caused by the failure of a water main, which incurred by the water utility, consumers, and surrounding area (e.g., roads, traffic, businesses, and environment). Salman et al. (2010) presented a model quantifying the impact of a watermain failure in terms of economic, operational, social, and environmental factors. Kleiner and Colombo (2014) investigated the consequence of failure for large-diameter iron water mains in the form of direct, indirect, and social/environmental costs. Large et al. (2014) recognized water consumers and the users of neighbor infrastructure as the vulnerable elements impacted in the failure events.

The criticality assessment is often carried out according to expert knowledge and engineering experience. In this study, the framework proposed by Kleiner and Colombo (2014) is adopted to quantify the consequences of watermain failure. Table 3-5 lists the criteria that contribute to evaluating the consequences of a watermain failure along with the weights used in this study.

Table 3-5- Criticality components of water mains (adopted from Kleiner and Colombo 2014)

Cost	Criticality Criterion	Weight	Factor						
			PS	LOC	MWM	TWM	P	FH	M
Direct	1. Emergency repair/ rehabilitation	w_1	$\alpha_{1,1}$	$\alpha_{1,2}$	$\alpha_{1,3}$	$\alpha_{1,4}$	$\alpha_{1,5}$	$\alpha_{1,6}$	$\alpha_{1,7}$
	2. Damage to property	w_2	$\alpha_{2,1}$	$\alpha_{2,2}$	$\alpha_{2,3}$	$\alpha_{2,4}$	$\alpha_{2,5}$	$\alpha_{2,6}$	$\alpha_{2,7}$
	3. Water loss	w_3	$\alpha_{3,1}$	$\alpha_{3,2}$	$\alpha_{3,3}$	$\alpha_{3,4}$	$\alpha_{3,5}$	$\alpha_{3,6}$	$\alpha_{3,7}$
	4. Liability	w_4	$\alpha_{4,1}$	$\alpha_{4,2}$	$\alpha_{4,3}$	$\alpha_{4,4}$	$\alpha_{4,5}$	$\alpha_{4,6}$	$\alpha_{4,7}$
Indirect	5. Business/ production loss	w_5	$\alpha_{5,1}$	$\alpha_{5,2}$	$\alpha_{5,3}$	$\alpha_{5,4}$	$\alpha_{5,5}$	$\alpha_{5,6}$	$\alpha_{5,7}$
	6. Impact on adjacent infrastructure	w_6	$\alpha_{6,1}$	$\alpha_{6,2}$	$\alpha_{6,3}$	$\alpha_{6,4}$	$\alpha_{6,5}$	$\alpha_{6,6}$	$\alpha_{6,7}$
	7. Fire loss	w_7	$\alpha_{7,1}$	$\alpha_{7,2}$	$\alpha_{7,3}$	$\alpha_{7,4}$	$\alpha_{7,5}$	$\alpha_{7,6}$	$\alpha_{7,7}$
Social/ Environmental	8. Service disruption	w_8	$\alpha_{8,1}$	$\alpha_{8,2}$	$\alpha_{8,3}$	$\alpha_{8,4}$	$\alpha_{8,5}$	$\alpha_{8,6}$	$\alpha_{8,7}$
	9. Traffic disruption	w_9	$\alpha_{9,1}$	$\alpha_{9,2}$	$\alpha_{9,3}$	$\alpha_{9,4}$	$\alpha_{9,5}$	$\alpha_{9,6}$	$\alpha_{9,7}$
	10. Special facilities	w_{10}	$\alpha_{10,1}$	$\alpha_{10,2}$	$\alpha_{10,3}$	$\alpha_{10,4}$	$\alpha_{10,5}$	$\alpha_{10,6}$	$\alpha_{10,7}$
	11. Illness due to contamination	w_{11}	$\alpha_{11,1}$	$\alpha_{11,2}$	$\alpha_{11,3}$	$\alpha_{11,4}$	$\alpha_{11,5}$	$\alpha_{11,6}$	$\alpha_{11,7}$
	12. Impact on environment	w_{12}	$\alpha_{12,1}$	$\alpha_{12,2}$	$\alpha_{12,3}$	$\alpha_{12,4}$	$\alpha_{12,5}$	$\alpha_{12,6}$	$\alpha_{12,7}$

PS: Pipe Size, LOC: Location (Land use), MWM: Max Water Meter, TWM: Total Water Meter, P: Proximity to water bodies, FH: Fire Hydrant, M: Material

The Analytical Hierarchy Process (AHP) is applied to calculate the weights (w_i) of each criterion through a pair-wise comparison (Al-Harbi 2001). Each criterion is assumed to be a linear function of seven characteristics related to water mains: pipe size, location (land use), maximum water meter, total water meters, proximity to water-bodies, fire-hydrant, and pipe material. These linear relationships are structured using coefficient factors (α_{ij}), whose values vary between 0 and 1. The value of α is 0 if no correlation exists between a criterion and the pertinent factor. Thus, the summation of the criteria weights and the summation of coefficient factors in each criterion must equal one (Eq. 3-2 and Eq. 3-3).

$$\sum_{i=1}^{n} w_i = 1$$

Eq. 3-2

$$\sum_{j=1}^{m} \alpha_{ij} = 1 \quad where \quad i \in \{1,\ldots,12\}$$

Eq. 3-3

In this study, the matrix of w_i and α_{ij} is calculated as follows:

$$w_i = \begin{bmatrix} 0.30 \\ 0.10 \\ 0.05 \\ 0.05 \\ 0.02 \\ 0.03 \\ 0.05 \\ 0.20 \\ 0.05 \\ 0.03 \\ 0.02 \\ 0.10 \end{bmatrix}, \qquad \alpha_{i,j} = \begin{bmatrix} 0.6 & 0.25 & 0 & 0 & 0 & 0 & 0.15 \\ 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.4 & 0.6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0.6 & 0.4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0.5 & 0 & 0 & 0.5 & 0 & 0 & 0 \\ 0.2 & 0.8 & 0 & 0 & 0 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 & 0 & 0 \\ 0.3 & 0 & 0 & 0 & 0.7 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0.5 & 0 & 0 \end{bmatrix}$$

Eq. 3-4

The criticality index (CI) of a watermain is determined as follows:

Eq. 3-5

$$CI = \sum_{i=1}^{n} \sum_{i=1}^{m} w_i \left(\alpha_{ij} \times NS_j \right)$$

where n is the number of criteria, m is the number of factors, NS_j is the normalized score of the critical factor.

Risk is the product of probability and the consequences of failure. Hence, the Priority Index (PI) is formulated as Eq. 3-6 to rank pipe segments:

$$PI = CI \times (1 - RI)$$

Eq. 3-6

The value of PI ranges between 0 to 1, where 0 means the lowest priority (or lowest risk) and 1 means the highest priority (or highest risk).

As discussed earlier, criticality and reliability assessment is subjective processes. This implies that one can substitute any other suitable risk analysis methodology for the approach proposed here.

b) Selection of renewal techniques

Capital works in water distribution networks consist of three main actions: repair, rehabilitate, and replace (Matthews et al. 2013). The scope of the current study is limited to replacement and rehabilitation activities. Open-cut and trenchless technologies are two broad categories of water main replacement/rehabilitation methods to retrieve the structural integrity of water mains. Trenchless technology is a method to install, replace, or rehabilitate a pipe without or with minimal excavation. These technologies include Micro-Tunneling (MT), Horizontal Directional Drilling (HDD), pipe bursting, cured-in-place pipe (CIPP), slip lining, and close-fit slip lining.

The primary purpose of water pipe renewal is to return the functionality of a target component to near-original condition and performance (USEPA 2007). This module determines feasible replacement techniques and ranks them according to the given criteria. The developed methodology of selecting renewal techniques is shown in Figure 3-4.

Figure 3-4- Renewal technique selection algorithm

In the first step, the rules, conditions, and methodologies to select renewal techniques need to be defined by the user or adopted from best practices, such as AWWA manual for Rehabilitation of Water Mains (AWWA-M28 2014) or Canadian InfraGuide (FCM and NRC 2003). Researchers have also proposed several methodologies to support decision-making processes to select either the most appropriate technique or a set of feasible techniques to replace or rehabilitate water mains (Allouche et al. 2000; Ammar et al. 2012; Aşchilean et al. 2017; Deb 2002; Hong et al. 2006; Matthews 2010; Salman et al. 2013). In the second step, the module evaluates the technical feasibility of renewal techniques subject to the defined technical considerations and limitations. For example, micro-tunnelling replacement technique is typically utilized for pipe lengths up to 200m (FCM and NRC 2003), or up to 460m in special cases (Najafi and Gokhale 2005); water mains with flow problems must be upsized and replaced by brand-new pipes (i.e., new installation); if a water main has more than 20 service connections per 100 meters of length, open-cut is the most cost-effective replacing method (Najafi and Gokhale 2005).

In the third step, a preference evaluation is carried out to rank feasible renewal techniques through the weighting criteria. Replacement/rehabilitation cost, impacts on the environment, and engineering preference are three core criteria for prioritizing the techniques. Except for the first criterion, which is a quantitative measure that can be readily calculated with unit costs, the two other criteria are intrinsically qualitative matters. The criterion of "impacts on the environment" reflects the adverse residual effects of the construction phase using a renewal technique. The chemical, physical or biological damage level to the soil, water, and air are in a close relationship with whether open-cut or trenchless technologies are used (Salman et al. 2013; Zayeda et al. 2011). Moreover, the open-cut method, compared to trenchless technologies, has more noise pollution, more traffic interruptions, and other social costs (Zayeda et al. 2011). Engineering practitioners are struggling with a trade-off between reluctance to accept the risk associated with new technologies, and the willingness to experience new renewal method to expand their own business (Salman 2011). This study employs a simple scoring system to quantify all three criteria. A 9-grade scale is used to normalize the contributing factors, where 1.0 represents the least utility, and 9.0 represents the most utility in respect of each criterion.

c) Budget allocation

Asset-Manager Agent addresses the selection of renewal candidates for each year, considering a limited financial resource. The annual capital budgets, established by the SD module in *Master Agent*, govern the budget-allocating process. Although a proactive renewal strategy is implemented for water mains in tiers four, three, and two, it must be coupled with an active renewal strategy to address those that reach the end of their service life, as a failure indicator. The following steps used for capital budget allocation in this study:

(1) Compare the total annual capital budgets suggested by the SD module with total potential renewal costs for a multi-year capital program. If the total annual capital budgets for the whole planning period is less than the total potential renewal costs, then the annual capital budgets recommended by the SD module are used in the selection of renewal activities for each year. Otherwise, the total annual capital budgets are uniformly distributed to have capital works in every year over the capital planning period;

(2) Divide all renewal candidates into either the proactive group, for those still in operation, and the active group, for those that have reached the failure threshold;

(3) Sort all renewal candidates in descending order of PI values within each critical tier;

(4) Select the candidates from the active group and then from the proactive group. The selection process within each group is performed from the top to bottom of sorted tier lists, with the priority order of tier-four to tier-one. This action continues until all annual capital budget is spent.

3.4. Model Validation

The AB-SD model can be applied to a real water distribution network with intrinsic complexity and heterogeneity. However, validation exercises are essential to ensure whether the model represents and correctly reproduces the behaviour of capital programing for water distribution networks.

Many factors contribute to finding answers for the three pertinent questions about linear assets: Which water main should be replaced or rehabilitated, When, and How. This section focus on only three contributing factors in the development of capital programs. These factors are (1) age, (2) size, and (3) location. Figure 3-5 illustrates three artificial water distribution networks (A to C). Each network is composed of 144 water mains with the same 75-meter length.

Age is the only variable in Network A. It implies that all characteristics of Network A’s components are identical except for age. The network is divided into four zones of 90 years old (Zone

1), 70 years old (Zone 2), 50 years old (Zone 3), and 30 years old (Zone 4). Network A is designed to validate the impact of pipe age on the selection process for capital works.

The pipe sizes differ from one another in Network B, while all other characteristics are identical. The age of all segments in Network B is 90. Network B is designed to investigate the impact of criticality features on the selection process for capital works.

Network C combines the characteristics of Networks A and B, with an added natural obstacle (i.e., a river here) crossing over some segments, thereby restricting pipe accessibility. The reason for the example of Network C is to validate if the model is selecting the correct renewal technique. As discussed before in Section 3.3.3c, the AB-SD model is adaptive to any decision-making system and rules defined by the user for selecting an appropriate renewal technique. In this validation study, the trenchless technique (TT) option is selected as a replacing technique for a segment if and only if it is crossing over by a natural or artificial accessibility obstacle, such as a river in Network C; otherwise, Open-Cut (OC) is the option.

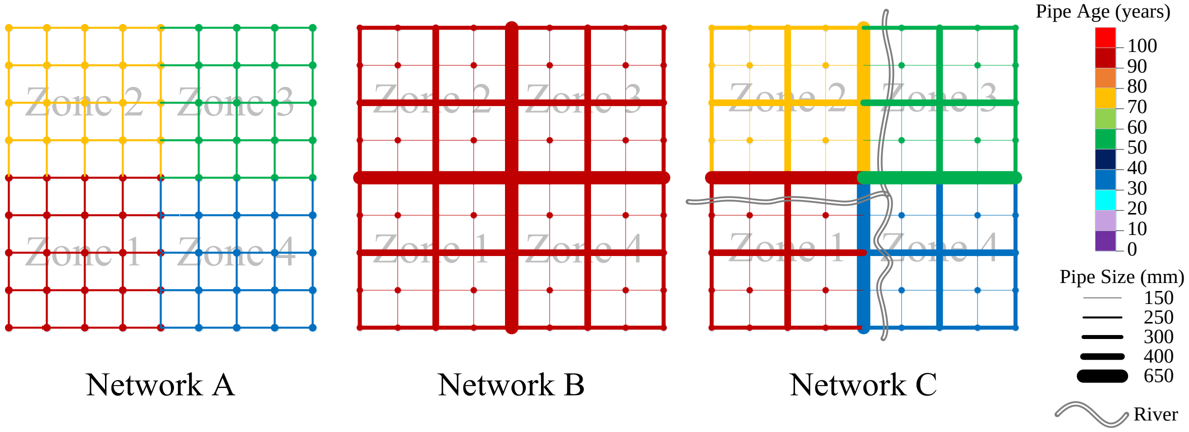


Figure 3-5- Regular pipeline networks for the AB-SD model validation

Table 3-6 tabulates other assumptions used in the simulation of the system to develop long-term strategic plans and short-term capital programs. The renewal strategy pursued in the current study is to replace 1% of the total network length per annum (i.e., a 1% annual replacement rate strategy).

Assuming 100-year service life for all segments, the entire network will be renewed by the end of year 100.

The objective of the SD model at the network-level is to achieve financial sustainability over the long-term. To this end, water user-fees are set to generate sufficient revenue to cover operational and capital expenditures (i.e., obtaining zero fund balance). Since all networks have different initial operational expenses, their respective initial user fees are adjusted to satisfy the zero-fund-balance policy as an initial condition for all three networks. Table 3-6 presents the initial user fees assumed for each network.

Table 3-6- Validation test assumptions

Long-term strategic planning		**Short-term capital programing**	
Parameter	Value	Parameter	Value
Long-term period	100 years	Short-term period	5 years
Annual Renewal Rate	1 % of the total network length	Average service life	100 years
Capital unit cost (1)	1000 \$/m (A), 1178 \$/m (B&C)	Renewal unit cost (2)	4 \$/mm diameter/m
Operational unit cost (1)	50 \$/m	Pipe length	75 m
Population	2500 persons		
Initial Water demand (1)	300 liter/cap/day		
Min Water demand (1)	200 liter/cap/day		
Initial water fee	3.13 \$/m^3 (A) 4.41 \$/m^3 (B) 3.20 \$/m^3 (C)		

(1) Rehan et al. (2011), (2) Zhao and Rajani (2002)

Each water main in Network A is a distribution main with 250 mm diameter and connects to a medium-size service connection. Thus, all water mains are identified as the second critical-tier. Networks B and C consist of four groups of pipe diameters, 650, 400, 300, and 150 mm, connected to extra-large, large, medium, and small service connections, respectively. According to the preliminary criticality classification algorithm (Section 3.3.3a), water mains with diameters of 650, 400, 300, and 150 mm in Networks B and C, are classified as Tier-four, Tier-three, Tier-two, and Tier one, respectively. Figure 3-6 presents the critical-tier-map of all three networks.

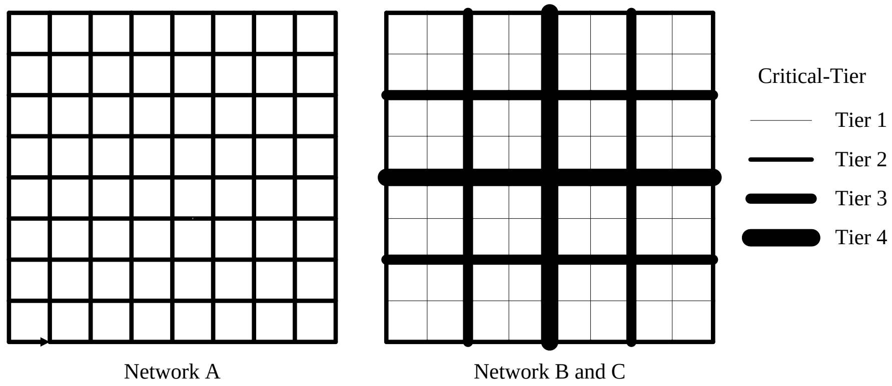


Figure 3-6- Critical-tier map of sample networks

Age is the only variable in Network A, and all other characteristics of water mains are identical. Therefore, it is expected that the selection processes of deteriorated mains is executed according to their ages. Figure 3-7 illustrates six snapshots of the network over a 100-year planning time span. The results show that pipes are selected for replacement from the oldest zone in the bottom-left, i.e., Zone 1, clockwise toward the youngest zone in the bottom-right of the network, i.e., Zone 4. Thus, the age variable is the determinant of PI values as the selection progress for capital works is only age-based.

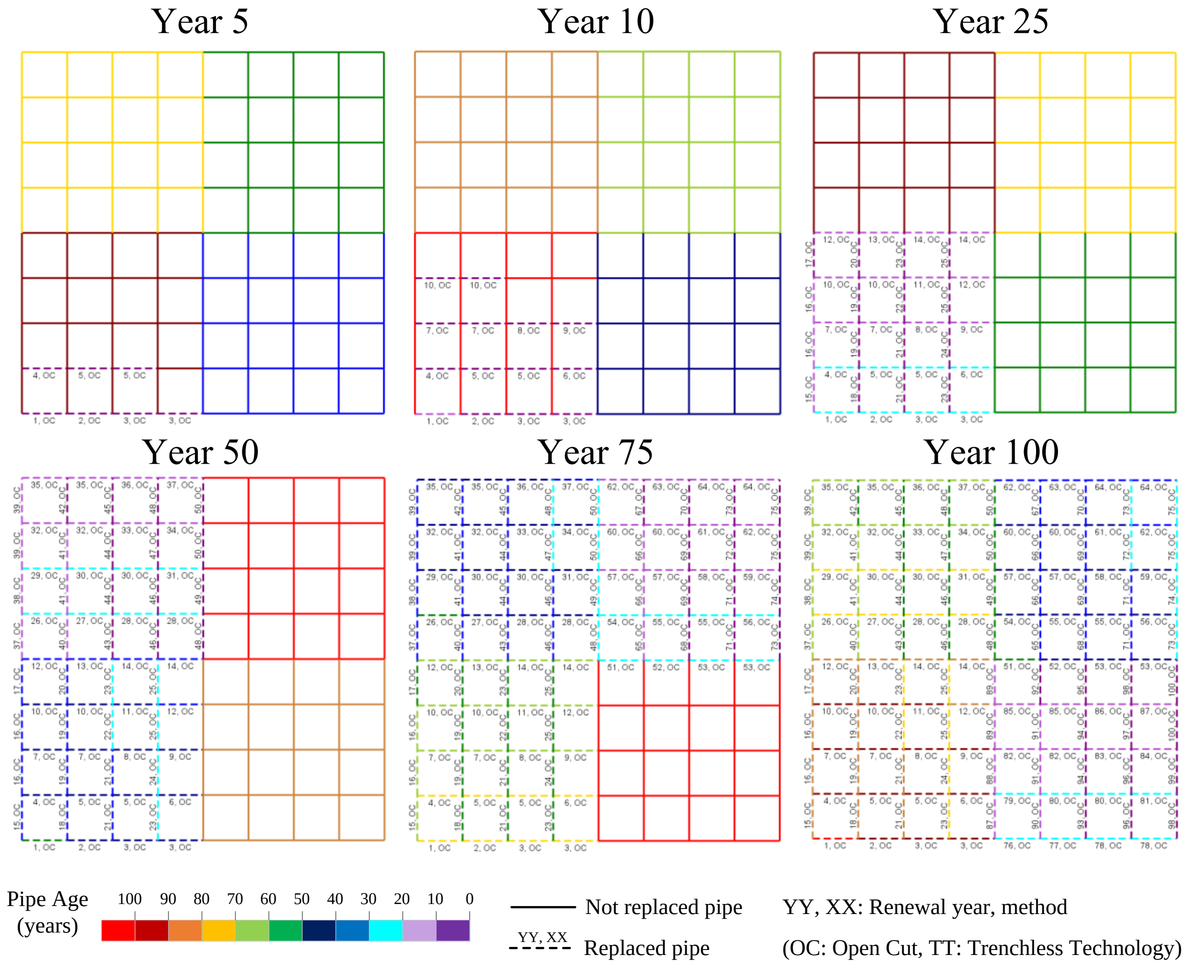


Figure 3-7- Renewal program for Network A

Figure 3-8 presents the progress of selecting deteriorated pipes in Network B. Pipe diameter is a dominant variable in the prioritization of capital activities in this network, as other features are assumed the same for all segments. The network includes four different pipe diameters, 650, 400, 300, and 150 mm, connected, respectively, to extra-large, large, medium, and small water meters. As shown in Figure 3-6, the critical-tier-map of Network B is coincident with the network size-map (Figure 3-5). Therefore, it is expected to select all segments in tier-four first, and then ones belonging to tier-three, tier-two, and tier-one, sequentially.

For the first round of capital planning (i.e., the first 5-year program), only three segments of tier-four have been selected. The selection of segments in tier-four continues until no one remained in this category. After depletion of all candidate segments in tier-four by year 25, the capital budget is allocated to the next critical-tier (i.e., tier-three). Comparison between the snapshots of Network B at years 50 and 75, highlights a shift from the selection of tier-three to tier-two segments. The last two snapshots show the selection of tier-one segments starting upon the depletion of tier-two pipes. Hence, the simulation results confirm that the pipe diameter is the determinant of capital planning for Network B.

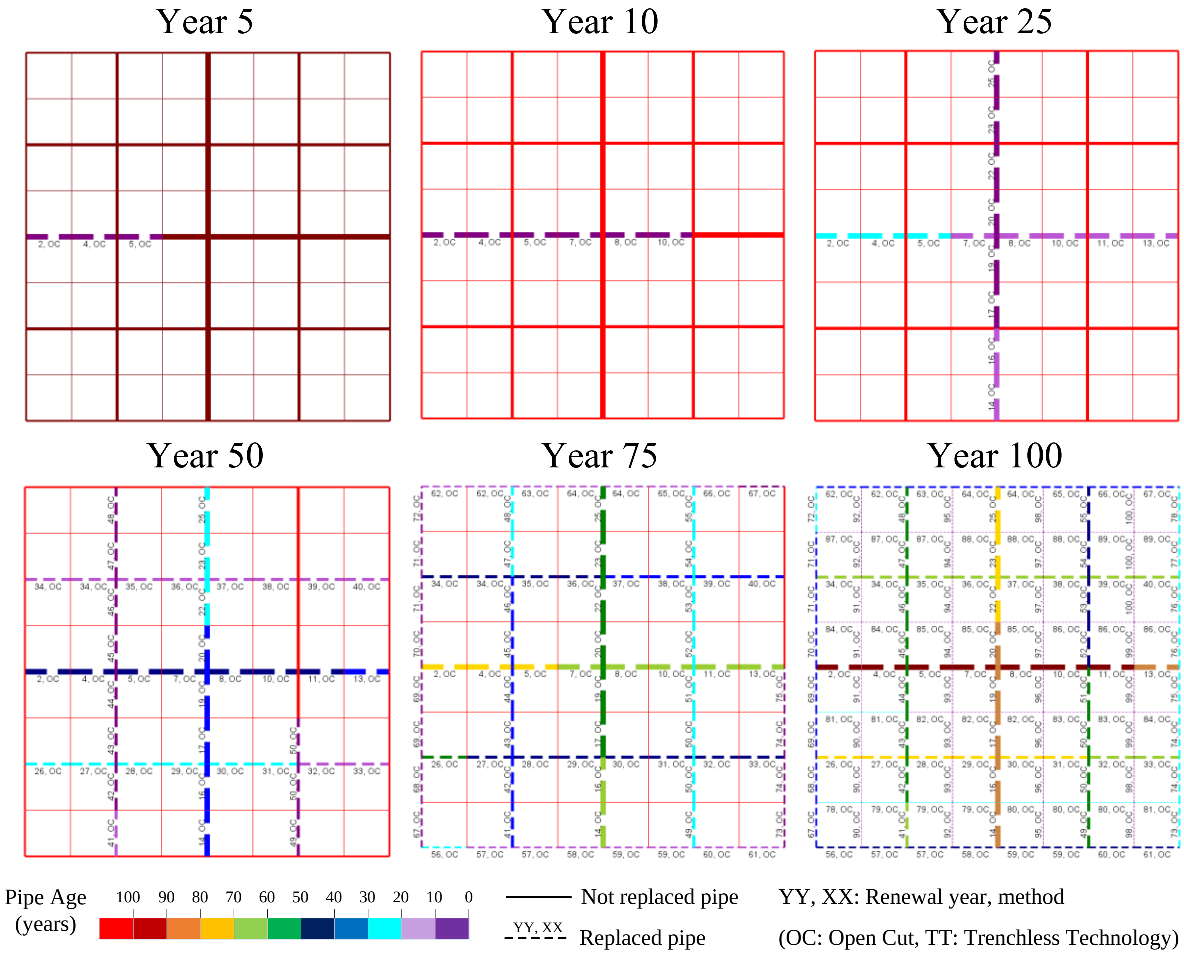


Figure 3-8- Renewal program for Network B

Age and pipe-size are two variables playing a pivotal role in the development of capital plans for Network C. The results confirm that the deteriorated pipes are flagged for replacement starting in Zone 1, with priority given to the higher tier classes (Figure 3-9).

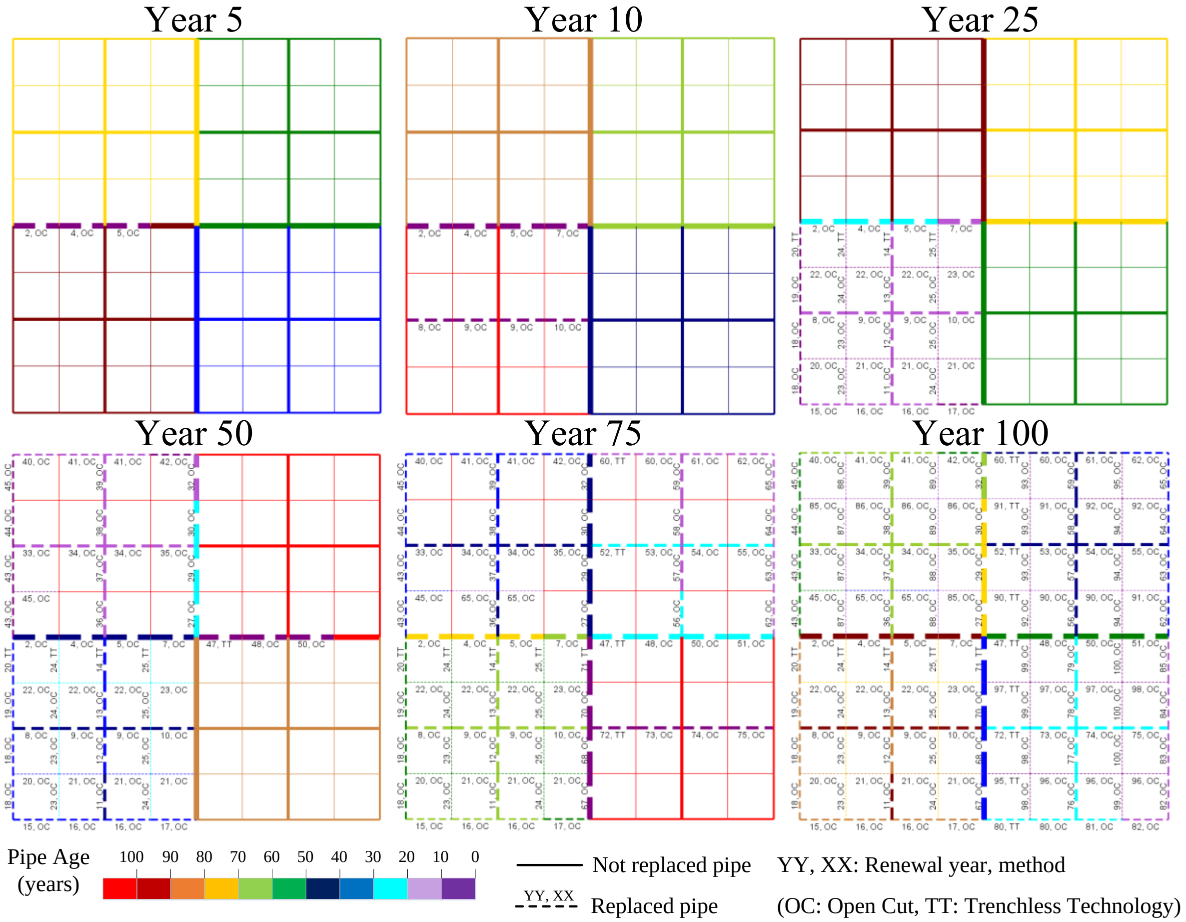


Figure 3-9- Renewal program for Network C

The model selects the oldest segments in the highest critical-tier in the first 5-year capital plan. The Year 10 snapshot shows that the next critical-tier segments are flagged for replacement after no tier-four segments remain in the deteriorated candidates (i.e., pipes over 80 years old). By year 10, all segments in zone 1 have reached the failure threshold, i.e., 100 years, meaning they are falling in the group of failed mains that needs immediate actions (i.e., active renewal strategy). Therefore, all tier-two and tier-one mains are also selected by the year 25. By year 50, both Zones 2 and 3 have reached the nominal failure point. Thus, the priority of selection is respectively given to tier-four, tier-three, tier-two, and finally tier-one for all mains in both zones. Ultimately, all segments will be replaced by year 100 as the renewal strategy has been set to do so. Notice that the model selects the trenchless technology method for all segments crossing under the hypothetical river as an appropriate replacement method.

3.5. Discussion

The objective of long-term strategic planning at the network level is to achieve financial sustainability state. The system dynamics (SD) model attains this objective by setting water user fees through simulating the interactions among the system components in the physical, financial, and social sectors. The objective of capital programming at the component-level is to allocate a limited capital budget among potential capital works efficiently. The agent-based model accomplishes this objective by specifying which segment needs to be flagged for capital works in a given year, and what is the most suitable technique to do so. The goal of the AB-SD model is to integrated network- and component planning levels to align the objectives of long-term strategic plans with capital programs.

This section discusses the financial performance indicators for Network C, as an example, from both network-level (SD model) and combined perspectives (AB-SD model). A general overview of all figures indicates that the results out of both models follow the same trends (Figure 3-10).

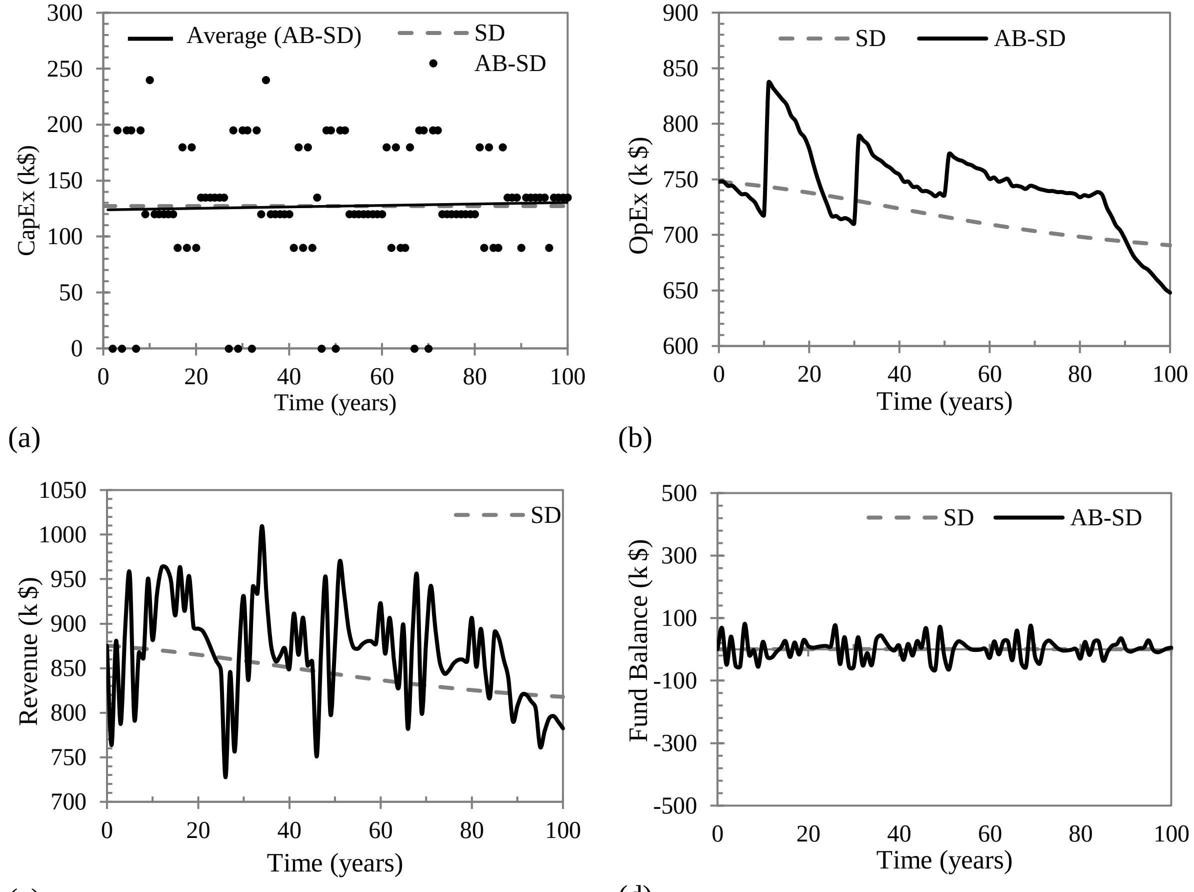
Figure 3-10a compares the capital expenditures of Network C, using SD and AB-SD models. In the SD model, the annual length of capital works is a continuous variable. It implies that the annual renewal rate can be any real number from zero to 1% of the total length of the network. However, the segment selection in the AB-SD model is dealing with 75m-length segments at the component-level. Thus, the AB-SD model can only pick a discrete number of pipes with a certain length, and consequently, certain capital expenses. Although there is a variation in capital expenditures for the AB-SD model, its general trend follows the SD model’s results, as the AB-SD average capital expenditure lies on top of the SD’s results. The replacement cost of a 75 m tier-four water main with

650 mm diameter is $195k, which is over the annual capital budget of $127.2k. Capital budgets need to be accumulated over a few years to afford the replacement cost of this type of pipes. Therefore, zero CapEx at some points indicates the lack of sufficient funds to replace a large diameter pipe.

Figure 3-10b presents the operational expenditures of the network over the 100-year planning period. Operational expenditure is a function of the network average age, calculated as follows:

$$Network\ Average\ Age = \frac{\sum_i \left(Pipe\ Length\right)_i \times age}{\sum_i \left(Pipe\ Length\right)_i} \qquad \text{Eq. 3-7}$$

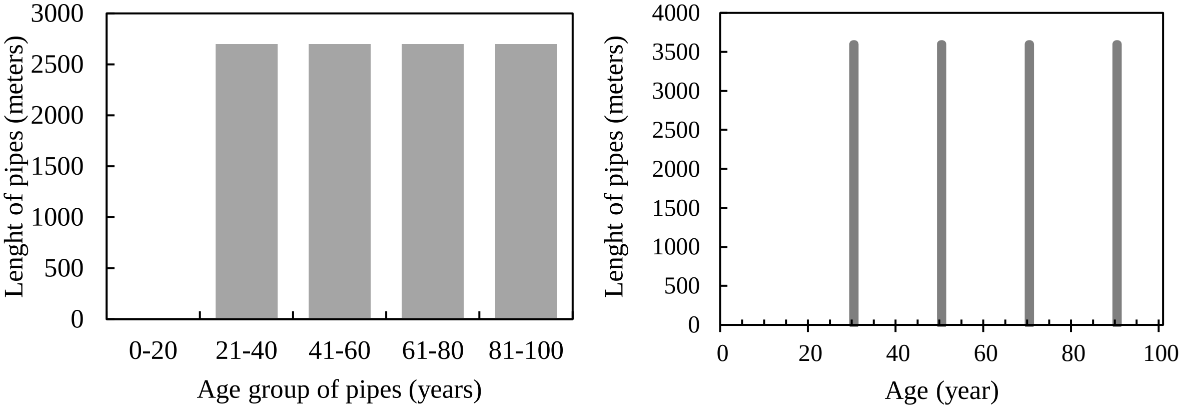
where *i* is the group-age of 0-20, 21-40, 41-60, 61-80, or 81-100 at the SD model.



(a) (b) (c) (d)

Figure 3-10- Simulation results for the long-term financial performance of Network C

Figure 3-11 provides the initial age-distributions of Network C from aggregated (SD model) and disaggregated (AB model) perspectives. The SD model considers the average age of each group to calculate the network average age, while the AB model uses the actual age for pipes in each year. In the hybrid AB-SD model, the aggregated age-distribution is periodically updated from actual disaggregated age-distribution. Therefore, by the next ten years, for example, a large quantity of watermain with 30, 50, and 70 years old move to the older age-groups that causes a jump in the network average age. Three spikes in year 10, 30, and 50 in Figure 3-10b indicates these inventory shifts from a younger age-group to an older one.

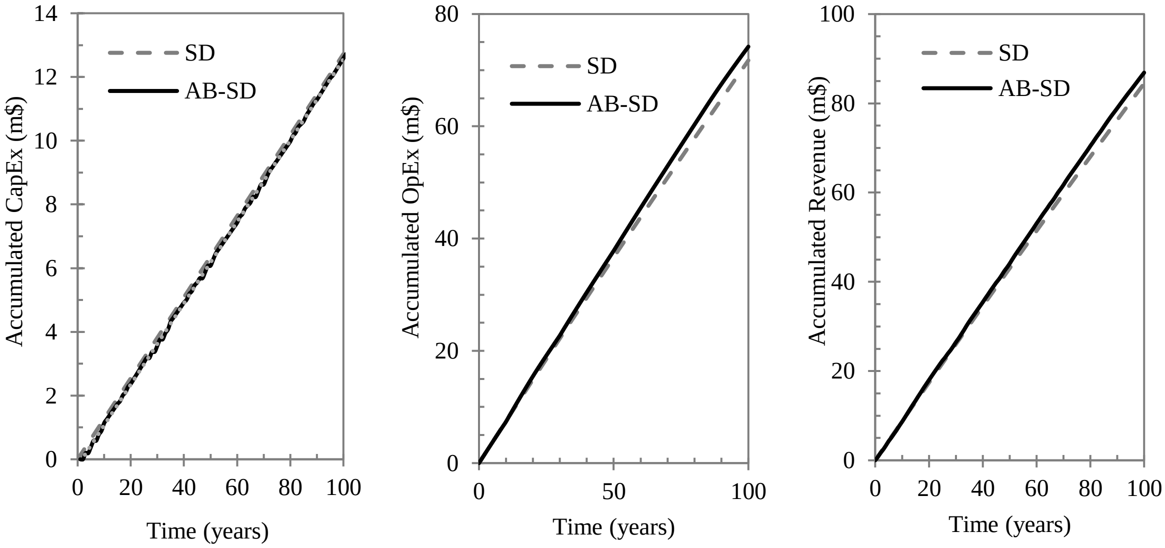


(a) aggregated (b) disaggregated

Figure 3-11- Initial age-distribution of Network C

Figure 3-10c presents the revenue required to cover CapEx and OpEx to comply with the financial sustainability objective. The fluctuation of CapEx and OpEx induces ineluctable variation in revenue. Figure 3-10d provides the simulation results of fund balance over the 100-year simulation period. The results of fund balance prove the fact that the AB-SD model attempts to converge the objectives of financial sustainability and capital programming over the simulation period despite variation induced to the system.

Figure 3-12 compares the accumulated CapEx, OpEx, and revenue of the SD and AB-SD simulation models. As discussed in Chapter 2, the SD model underestimates the total operational expenditures, as well as, the total revenue required while investing the same amount in capital works over the 100-year simulation. The SD model shows 3.41% and 2.86% less accumulated OpEx and revenue, respectively, by the end of the planning period.



(a) (b) (c)

Figure 3-12- Simulation results for revenue of Network C

3.6. Conclusions

This study set out to develop an effective integrated decision support system to align decision-making processes running at both network- and component-levels for water distribution networks. The findings have shown that the hybrid Agent-Based and System Dynamics (AB-SD) simulation model can amalgamate long-term strategic planning processes with decisions made for the individual system’s components to develop capital programs.

This study creates three hypothetical distribution networks to demonstrate the top-down planning approach integrated with the bottom-up planning approach in water distribution systems to address renewal planning pertinent questions. The validation results show that the hybrid model successfully interprets the high-level renewal policies for decision-making processes at the component-level to develop annual renewal plans.

The development of a risk management system, replacement/rehabilitation technique selection, and budget management is beyond the scope of this study. Thus, preliminary algorithms have been used to develop the AB-SD model and conduct validation exercises. However, the AB-SD model is adaptable to any advanced algorithms and processes for risk analysis, prioritization process, budget allocation, and technical analysis.

Chapter 4.

Optimal Group Replacement Scheduling for Water Distribution Networks

Abstract

In past decades, many efforts have been made to optimize the allocation of limited financial resources to the candidates for replacement in water distribution networks. They mostly focus on scheduling individual pipes rather than pipes in a group. Scheduling replacement in groups has the potential to provide benefits of the reduction in direct costs, including construction, procurement, and mobilization costs, and indirect costs, such as traffic interruption, service interruption, and social costs. This study develops an integrated decision support system using a hybrid Agent-Based and System Dynamics (AB-SD) simulation method to implement optimal group scheduling of replacement works. A bi-level heuristic optimization algorithm is developed to enhance both exploration and exploitation capabilities of problem-solving by search. A case study demonstrates that optimal grouping strategy can improve the long-term performance of water distribution networks and reduce costs and level of risk.

Keywords: water distribution network, group scheduling, benefit-cost optimization, agent-based, system dynamics, k-Means clustering, genetic algorithm

4.1. Introduction

Urban physical infrastructure, such as roads, bridges, electrical grids, buildings, recreational facilities, water pipes, and sewers, all naturally deteriorate over their service life. This deterioration process is inevitable. However, the utilization and environmental conditions of an infrastructure system can accelerate or decelerate the physical deterioration process (Rajani and Kleiner 2001).

New pipes have low breakage rates and, consequently, are less likely to need pipe flushing or emergency repairs. However, their maintenance and operational expenditures exponentially increase over time as they age (Kleiner et al. 2001; Shamir and Howard 1979). An increase in repair frequency, service interruption, water leakage, damage to adjacent infrastructure, and reduction in water quality cause the replacement of a water main to be a cost-effective decision in time. Water utility managers often face challenges in finding an optimal schedule to replace pipes in water distribution networks. Renewal scheduling constraints, such as limited capital budget, exacerbate these challenges.

Most research models and decision-support systems over past decades focus on optimal renewal scheduling of individual pipes. Kleiner et al. (1998a; b) introduced an optimization approach using dynamic programming to determine the optimal time and the rehabilitation alternative for each pipe to minimize corresponding life-cycle costs. They then developed a decision-support tool to implement the approach to discover the most cost-effective renewal strategy for each pipe, considering the performance of the whole system financially as well as hydraulically (Kleiner et al. 2001). Dandy and Engelhardt (2001) employed a genetic algorithm optimization to find the optimal schedule for replacing pipes to minimize the total cost of the water distribution system, including both direct and indirect costs. Xu et al. (2013) developed a break rate prediction model for water distribution networks to determine the optimal replacement time of a main. Reviewing these studies and similar ones (Hong et al. 2006; Loganathan et al. 2002; Luong and Nagarur 2001; Shamir and Howard 1979) reveals that they have focused on the optimal schedule of the replacement of individual water mains. Decision-support systems developed to aid water utilities, such as UtilNets (Hadzilacos et al. 2000), PARMS (Burn et al. 2003; Moglia et al. 2006), CARE-W (Saegrov 2005), and AWARE-P (Leitão et al. 2016), are also looking for the best solutions to allocate limited financial resources to individual renewal candidates in a most cost-effective time.

Deteriorated water mains are usually grouped in capital projects in best practices to take advantage of the reduction in direct costs, including construction, procurement, and mobilization costs, and indirect costs, such as traffic interruption, service interruption, and social costs. Kleiner et al. (2010) and Nafi and Kleiner (2010) formulated the effects of group pipe replacement on total costs for the first time. They investigated the potential savings entitled by scheduling the replacement of pipes in a group, in terms of mobilization cost savings, quantity discounts, and the coordination of pipe replacement with scheduled roadwork. A similar study proposed a methodology to optimally synchronize the renewal cycle of water mains with pavements (Kleiner 2013). Roshani and Filion (2014) developed an event-based approach to optimize the scheduling of rehabilitation activities, including pipe replacement, duplication, lining, and new pipe installation. Their model calculates the rehabilitation cost of water mains incorporating adjacency discount, which is applied if the reconstruction of the road and its buried water main are scheduled concurrently, and quantity discount, which is entitled if a number of connected piped are rehabilitated in the same year. Salman et al. (2013) defined a performance index reflecting the reliability and criticality of a group of pipes. They developed a rehabilitation-planning model to efficiently schedule work-packages within limited budgets and planning time to maximize the total performance of renewal groups. They defined the performance of water distribution networks as risk reduction. Li et al. (2015) demonstrate that utilizing a replacement decision optimization method for group scheduling can improve replacement planning significantly by reducing costs and service interruptions. They showed that applying the group scheduling strategy on a medium-sized water network led to an approximate reduction of 10% and 25% in capital expenditure and service interruption time, respectively. The benefits of grouping renewal strategy and potential cost savings are also investigated by Rokstad and Ugarelli (2015) using a greedy heuristic algorithm. Their methodology is applied to a medium-sized water distribution system with 430 components.

All the aforementioned studies are applicable to small networks with a limited number of pipe segments. An exception is Rokstad and Ugarelli (2015), who developed a greedy heuristic algorithm with an element of randomness to avoid the computational burden of combinatorial optimization problems. However, their model is confined to the assumption of grouping only connected water mains. Another issue is that they produce optimized action plans for capital activities based on component-level analyses without any interaction with the strategic level of planning to ensure the fulfillment of long-term policy levers.

Chapter 3 develops the first known application of the Agent-Based modelling method coupled with System Dynamics simulation method (AB-SD) to integrate long-term strategic planning, based on a network-level perspective, and short-term capital programming, based on a component-level perspective. The objectives of this chapter are to advance the AB-SD model (1) to develop most-efficient capital programs that benefited from grouping water mains for replacement actions, and (2) to investigate the impact of group renewal strategy on the long-term performance of water distribution networks. The classical optimization methods are computationally exhaustive since the solution space to explore for the optimal groups of water mains is extremely large in a real-sized water distribution network. Thus, a bi-level optimization methodology based on Genetic Algorithm (GA) is developed to enable the model to search the solution space efficiently. The next section discusses the benefits of grouping capital works in water distribution networks. The advanced AB-SD model is described afterward. It is followed by a model demonstration on three artificial water networks for validation exercises. The simulation results are discussed and the main takeaways summarized.

4.2. Grouping Capital Works in Water Distribution Networks

The failure of a water main occurs when it cannot fulfill the intended objectives (Rausand and Høyland 2003). Although there are different aspects of failure defined for water pipes in the literature (Kleiner and Rajani 2001; Rajani and Kleiner 2001; Rokstad and Ugarelli 2015), in broad terms, the probability of failure exponentially increases with pipe age (Billinton and Allan 1992). Risk, which is a product of probability and consequence of failure, also increases as pipe ages. Replacing a degraded pipe reduces associated risk drastically, and consequently, mitigates the total risk of the entire water distribution network. Thus, replacing a deteriorated pipe provides benefits to the system in terms of risk reduction, offset by the cost of the replacement.

Furthermore, the renewal cost can be discounted through grouping capital works with a common renewal practice. Utility managers often face limited budgets to address renewal needs in water infrastructure systems. The best renewal decisions are ones gain more benefits (i.e., risk reduction) in return for capital costs, which can also be discounted by grouping capital works. Therefore, the optimization of renewal decisions aims at maximizing the total benefit/cost ratio of capital works. The following sections formulate the benefit (i.e., risk reduction) and the cost of replacing a group of pipes in a work-package.

4.2.1. Group replacement benefit

The replacement benefit is defined as the amount of risk reduction due to replacing a water main. Pipes in a water distribution network have different levels of criticality. For example, a failure in a transmission line may interrupt water service delivery to the consumers of the entire network. However, the failure of a distribution main that serves a residential area may have limited effects. Therefore, these two mains have different levels of criticality.

Section 3.3.3a) devises a critical-tier classification algorithm to categorized water mains according to their role in the water distribution network. Water mains are listed into four criticality-tiers (i.e., tiers four to one) depending on their functionality in the network (transmission, feeder, or distribution mains) and their impacts on service interruption (size of service connections). Utility managers may implement different renewal strategies for each critical-tier. In this study, water mains in Tier-four to Tier-one are selected for replacement in order of preference. A Tier Preference (TP) coefficient is defined to quantify the critical-tier preferences. Table 4-1 shows the coefficients used in this study

Table 4-1- Risk Preference Coefficient for critical-tiers

Critical-tier	Tier-four	Tier-three	Tier-two	Tier-one
Tier Preference (TP) Coefficient	1	0.7	0.3	0.1

Priority Index (PI) is defined to quantify the failure risk of a pipe segment. The value of PI can be any number from 0 to 1, indicating the lowest and the highest priority, respectively. PI is a normalized measurement of risk by multiplying probability and consequence of failure (Eq. 3-6). Section 3.3.3a provides the details on how to calculate PI for a pipe segment.

The benefit (B_i) derived from the replacement of pipe segment i is defined as follows:

$$B_i = TP_i \times PI_i \times l_i \qquad \text{Eq. 4-1}$$

where l_i is the length of pipe segment i.

Hence, the total benefit of replacing n segments in work-package g (WPB_g) is,

$$WPB_g = \sum_{i=1}^{n} B_i = \sum_{i=1}^{n} \left(TP_i \times PI_i \times l_i \right) \qquad \text{Eq. 4-2}$$

4.2.2. Group replacement cost

The capital cost for replacing deteriorated water mains consists of various components such as new pipe procurement, installation labor, overhead expenses (engineering design, inviting tenders, and contacting), mobilization, and bypass system operation. Although the physical dimensions of a water main, (i.e., its length and diameter) are the primary drivers of the total replacement cost, practitioners often take advantage of the potential discounts associated with grouping replacement activities. Nafi and Kleiner (2010), Li et al. (2015), Rokstad and Ugareli (2015) demonstrate how such grouping can reduce total capital costs through savings in mobilization, setup costs, and discounts from economies of scale.

Clark et al. (2002) provided a cost estimate for new installations and pipe replacements by breaking it down into various cost categories: base installed pipe, trenching and excavation, embedment, backfill and compaction, pipe accessories (i.e., valves, fittings, and hydrants), dewatering, sheeting and shoring, pavement removal and replacement, utility interference, and traffic control. Quiroga et al. (2007) showed that the total cost of construction incorporates material, labor, equipment, and transportation category costs. They stated that equipment and transportation cost components may be estimated as fractions of labor and material costs.

The replacement cost of segment i denoted by RC_i can be broadly formulated as the summation of the constructional costs (RC_i^{con}) and including material procurement, earth work (e.g., excavation, backfill, sheeting and shoring), pipe installation, and skilled labor costs, and logistical costs (RC_i^{lgx}) including mobilization, traffic control, and construction site setup (e.g., right of way and permit) costs.

$$RC_i = RC_i^{con} + RC_i^{lgx} \qquad \text{Eq. 4-3}$$

Assume that the logistical costs of pipe segment *i* is proportional to the total replacement unit cost (UC_i), therefore

$$RC_i^{con} = \left(1-\alpha\right)\cdot UC_i \cdot d_i \cdot l_i \qquad \text{Eq. 4-4}$$

$$RC_i^{lgx} = \alpha \cdot UC_i \cdot d_i \cdot l_i \qquad \text{Eq. 4-5}$$

where α is the proportion of logistical costs to total costs, d_i and l_i are the diameter and length of segment *i*, respectively.

Every pipe segment is identified by two nodes at each end in the geospatial map of water distribution networks. The logistical cost associated with a pipe segment is presumed to be divided equally between these two nodes. Thus, the total logistical cost of a work-package with *n* segments in a fully disconnected layout, where no nodes are connected to another node at all, the share of each node is calculated as follows,

$$\sum_{i=1}^{n} RC_i^{lgx} = \sum_{i=1}^{n} \alpha \cdot UC_i \cdot d_i \cdot l_i \qquad \text{Eq. 4-6}$$

Spatially close water mains often share logistical costs (Nafi and Kleiner 2010). It is presumed that if two contiguous segments share a node and are replaced at the same time in a work-package, then only one unit of logistical cost is levied (i.e., the average of logistical costs for connected nodes). Thus, the total logistical cost of a work-package with *m* nodes and *n* segments is,

$$\sum_{i=1}^{n} RC_i^{lgx} = m \times \frac{\sum_{i=1}^{n} \alpha \cdot UC_i \cdot d_i \cdot l_i}{2n} \qquad \text{Eq. 4-7}$$

The total replacement cost of a work-package with some shared nodes is, therefore,

$$WPC = \sum_{i=1}^{n} \left[\left(1-\alpha\right) UC_i \cdot d_i \cdot l_i + \frac{m}{2n} \cdot \alpha \cdot UC_i \cdot d_i \cdot l_i \right] \qquad \text{Eq. 4-8}$$

Another cost advantage of grouping capital works is the effect of economies of scale on the number of capital works. Construction efficiency often increases with an increase in the size and scale of a capital project. Fixed components of construction costs, such as machinery and overhead costs, are spread out over more pipe length. Therefore, the unit cost of replacement is discounted. For example, a boring machinery cost is a one-time fixed cost levied in a renewal project using HDD technique. The unit cost of pipe replacement using HDD technique is not reduced up to a certain amount since it is often estimated based on the average value of renewal practices. If the size of the project goes over the average limit, then the pre-estimated unit cost is discounted up to a specific threshold of project size, reaching the maximum capacity of the machinery utilization. Hence, Eq. 4-8 is updated to accommodate the effect of economies of scale in the total replacement cost of a work-package.

$$WPC = \sum_{i=1}^{n} \left[\left(1-\alpha\right) UC_i \cdot d_i \cdot l_i \times (1 - D^{Qty}) + \frac{m}{2n} \cdot \alpha \cdot UC_i \cdot d_i \cdot l_i \right] \qquad \text{Eq. 4-9}$$

where D^{Qty} is the quantity discount proportional to the total length of the work-package (L^{wp}) (Nafi and Kleiner 2010); therefore,

$$D^{Qty} = \left\{ \begin{array}{ll} 0 & L^{wp} < L_{\min} \\ D^{Qty}_{\max} \times \dfrac{L^{wp} - L_{\min}}{L_{\max} - L_{\min}} & L_{\min} \le L^{wp} \le L_{\max} \\ D^{Qty}_{\max} & L^{wp} > L_{\max} \end{array} \right\} \qquad \text{Eq. 4-10}$$

where L_{min} and L_{max} are, respectively, the minimum and maximum range of pipe length that D^{Qty} is variable within, and $D^{Qty}_{\max}$ is the maximum possible quantity discount due to the economies of scale.

The revised total cost of work-package g (WPC_g) for replacing *n* segments using one replacement technique becomes,

$$WPC_g = UC_g \left(1 - \left(\frac{2n-m}{2n} \right) \alpha - \left(1-\alpha\right) D^{Qty} \right) \sum_{i=1}^{n} d_i \cdot l_i \qquad \text{Eq. 4-11}$$

where UC_g is the replacement cost of one meter of pipe per one mm of diameter ($/m/mm).

The new arrangement of work-package cost is Eq. 4-11 presents the two discounting terms due to contiguity and quantity effects, respectively. The first discounting term, defined as the Contiguity Coefficient ($C_{Contig.}$), implies the proximity and contiguousness of the work-package layout.

$$C_{Contig.} = \frac{2n-m}{2n} \qquad \text{Eq. 4-12}$$

The contiguity coefficient ranges from 0 for a group of segments in a disconnected layout, where no nodes connected to another node at all, towards 1 for the most contiguous segments with a fully-connected layout. Figure 4-1 exemplifies the calculation of C_{Contig} for a group of segments.

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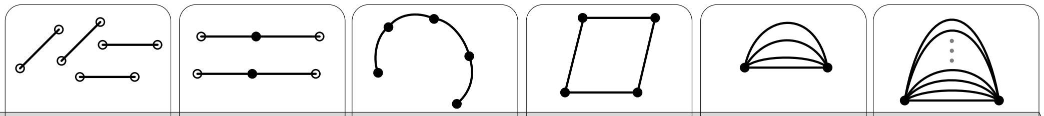


Number of Segments (n)	4	4	4	4	4	∞
Number of Nodes (m)	8	6	5	4	2	2
Contiguity Coefficient ($C_{Contig.}$)	$\frac{2\times4-8}{2\times4}=0$	$\frac{2\times4-6}{2\times4}=0.25$	$\frac{2\times4-5}{2\times4}=0.375$	$\frac{2\times4-4}{2\times4}=0.5$	$\frac{2\times4-2}{2\times4}=0.75$	$\frac{2\times\infty-2}{2\times\infty}=1$

Figure 4-1- Examples for the calculation of contiguity coefficient for a group of segments

4.2.3. Work-package definition

A Work Package (WP) refers to a group of segments in a water distribution network that is assumed (1) to be replaced together in the same planning year, and (2) to share the same replacement technique. Practically, there are other restrictions on the development of a work-package. All segments of a WP must be in reasonable proximity to other segments in the WP. In mathematical terms, the distance between all segments from the central point of the WP must be less than a pre-defined value, the Maximum Allowable Distance (*MAD*). The WP size must be within maximum and minimum values. The maximum size of a work-package (WPS_{max}) is levied to provide a fair environment for all potential contractors with various business capacities to tender competitively for pertinent contract of a work package. The minimum value (WPS_{min}) is also necessary to stimulate local contractors to tender for capital contracts. The work package upper and lower limits are subjective to several factors, such as replacement technique, number of bidders, economic conditions, and capital budget (Salman et al. 2013). Hence, all pipe segments in a WP_g must satisfy the following conditions.

(1) All segments of the WP_g must be replaced in the same year that the WP_g has been established for,

(2) All segments of the WP_g must be replaced with a common replacement technique,

(3) The distance between each segment of the WP_g and WP_g center point must be less than or equal to Maximum Allowable Distance (*MAD*),

(4) The total replacement costs of all segments in the WP_g must be less than or equal to maximum work package size (WPS_{max}), and greater than or equal to minimum work package size (WPS_{min}).

$$WPS_{\min} \leq WPC_g = \sum_{i=1}^{N} RC_i + \leq WPS_{\max} \qquad \text{Eq. 4-13}$$

4.3. Advanced AB-SD Model for Grouping Replacement Works

Chapter 3 Agent-Based and System Dynamics (AB-SD) simulation methods provides a platform to simulate complex interconnected water distribution networks at both network- and component-levels. The AB-SD model is equipped with a variety of analytical modules to determine the behaviour of contributing agents, and a Plan-Do-Check-Adjust (PDCA) iterative process to enable the feedback loop mechanism between the planning levels. Chapter 3 delineates all types of agents and describes there relevant processing modules in detail. The *Budget Allocation* module was designed based on the assumption of making renewal decisions for every deteriorated segment individually, and therefore, flags segments for replacement in order of priority, from the top to bottom of a candidate-list sorted according to risk measurements. The *Budget Allocation* module needs to be advanced to enable the model to create groups of candidate segments for replacement. Two new behavioural modules of Capital Work Clustering (CWC) and Capital Work-Package Selection (CWPS) are substituted for *Budget Allocation* module to develop and select most-efficient work packages for capital programs. Figure 4-2 presents the advanced AB-SD framework, including these two new behavioural modules.

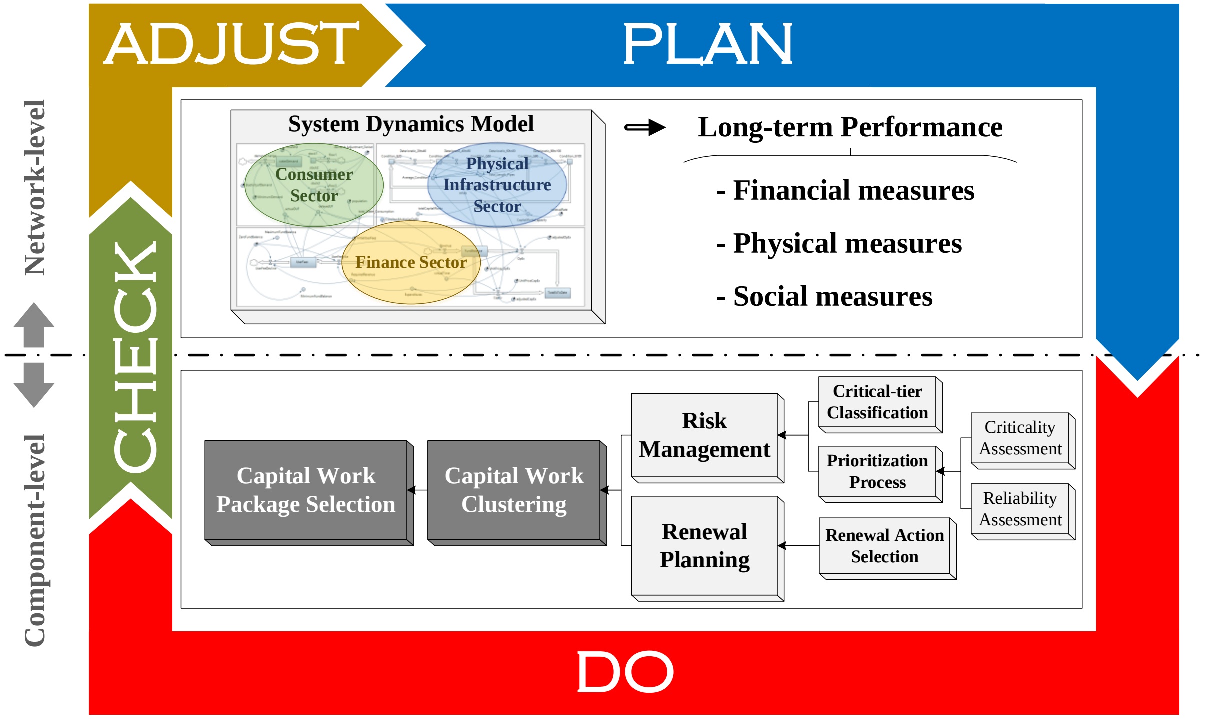


Figure 4-2- Advanced AB-SD modelling framework for building work packages

The Capital Work Clustering (CWC) module clusters all potential segments for replacement into groups in an effort to attain the most efficient combination in the network. Hence, CWC utilizes an optimization engine to explore and exploit the solution space. The second module, Capital Work Package Selection (CWPS), selects a number of work packages out of optimal clusters in the most efficient way subject to limited annual renewal budgets. The essence of this selection process is a constrained optimization problem. The following sections elaborate on these two behavioural modules and the corresponding optimization algorithms.

4.3.1. Capital Work Clustering (CWC)

The CWC module aims to cluster candidate segments for replacement into different groups in the most efficient manner. The number of ways of partitioning a set of *n* segments into *k* clusters is calculated using Eq. 4-17, known as Stirling Numbers of second kind (Weisstein 2002).

$$S_2(n,k) = \begin{Bmatrix} n \\ k \end{Bmatrix} = \frac{1}{k!}\sum_{i=0}^{k}(-1)^i \binom{k}{i}(k-i)^n \qquad \text{Eq. 4-14}$$

Hence, the number of ways to partition *n* segments into a number of groups is given by,

$$\sum_{k=1}^{k=n}\begin{Bmatrix} n \\ k \end{Bmatrix} = \sum_{k=1}^{k=n}\left(\frac{1}{k!}\sum_{i=0}^{k}(-1)^i \binom{k}{i}(k-i)^n\right) \qquad \text{Eq. 4-15}$$

The number of solutions exponentially increases with the number of segments. For instance, the number of solutions for grouping four segments is 15. However, the number of solutions increases dramatically to 4.7×10^{115} as the number of segments increases to one hundred. Thus, using classical linear optimization algorithms to find the optimal combination is almost impossible since we encounter a vast heterogeneous solution space with a high-level non-linearity.

A successful optimization method is one that can reasonably search various regions in the solution space, i.e., exploration, while scrutinizing the neighbourhood of the visited points, i.e., exploitation (Črepinšek et al. 2013). An effective and efficient optimization process should provide a balance between exploration and exploitation capabilities as the two cornerstones of problem-solving by search (Eiben and Schippers 1998). Evolutionary optimization algorithms such as Genetic Algorithm (GA) are well-known for both their exploration and exploitation strengths (Sivanandam and Deepa 2008). The GA parameters (i.e., crossover and mutation rates) needs to be set in order to reach a balance between the exploitation and the exploration of the search problem on a case-by-case basis (Wong et al. 2003). However, the low-level of diversity among possible solutions increases the stagnation problem in the GA searching operation and causes trapping in local optima (Črepinšek et al. 2013). In a water distribution network, there is a chance to have analogous segments in the candidate-list for replacement, which weaken the exploration strength.

On the other hand, increasing the dimension of solutions undermines GA optimization's efficiency in both exploring and exploiting the solution space. The K-Mean method is an iterative clustering algorithm in finding local optima (i.e., exploitation). However, it is not such a proper method to explore a large solution space in an optimization problem (Islam et al. 2018).

In this study, a bi-level optimization algorithm is devised to enhance both the exploration and exploitation capabilities of the clustering process. The CWC module utilizes GA-based and K-Means clustering methods (Islam et al. 2018; Maulik and Bandyopadhyay 2000) to reinforce the exploration and exploitation of the optimization process, respectively. Each solution in the optimization process represents a combination of clustering deteriorated segments. At the first level, a population of solutions is generated using GA operators. The solutions are then improved through K-Means clustering at the second level.

In genetic algorithms, each solution is presented by a chromosome, also called a genotype. A chromosome encodes a solution for clustering N segments with *N* genes, each representing a candidate segment. A chromosome is represented by an integer string, where the value of each gene represents the cluster number. The maximum number of clusters that can be generated out of *N* segments is *N*. Hence, each gene contains an integer value from 1 to *N*. Figure 4-3 demonstrates a chromosome representing a clustering solution for *N* candidate segments.

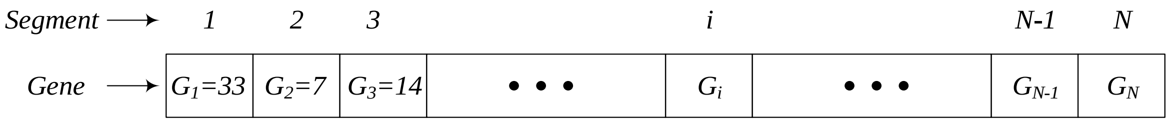


Figure 4-3- Representation of a chromosome in the clustering process

Figure 4-4 depicts the main six steps of the clustering process. The mainstream of the optimization process is GA-based (comprising the first five steps), and the K-Means method (grey block) contributes only to polish the best solutions to enhance searching for local optima.

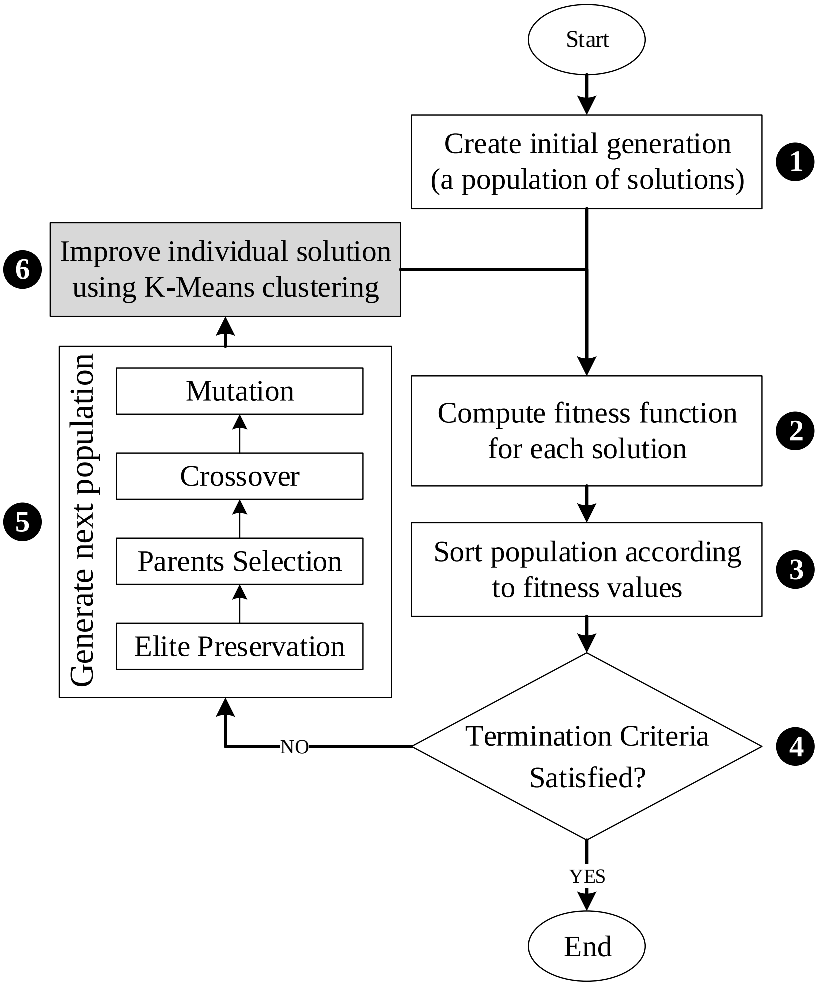


Figure 4-4- Methodology of clustering capital works

In the first step, an initial population of solutions is generated by assigning a random integer number to each gene. Although the value for each gene is randomly generated, it needs to conform to the work-packaging conditions explained in Section 4.2.3. Therefore, a random value generated for each gene is assigned if it does not violate work-packaging conditions.

In the second step, each chromosome (solution) is evaluated against the fitness function representing an optimization objective. The objective of the optimization problem of clustering candidate segments is to maximize the Benefit-Cost Ratio (BCR^{tot}) of total clusters, i.e., work-packages. The merit of pursuing this objective is to encompass all three aspects of the network (i.e., risk, cost, and levels of service) within a single objective function. The fitness function for evaluating each solution is as follows:

$$BCR^{tot} = \frac{\sum_{i=1}^{C} WPB_i}{\sum_{i=1}^{C} WPC_i} \qquad \text{Eq. 4-16}$$

In the third step, the generated chromosomes are sorted by descending BCR^{tot} values. The basis of GA optimization methods is the evolution process for natural selection of genetic systems. The next generation of solutions is generated through the repetitive application of GA operators, including selection, crossover, and mutation. Parent chromosomes (i.e., a set of solutions from the previous generation) are selected, proportional to their fitness values, to join the mating pool and generate the next generation of solutions. In accordance with elitist selection, the best solutions of each generation survive to the next generation without any change. In this study, five offspring are generated by an elitist selection. Other parent chromosomes are selected through the Rank Proportionate Selection (Jebari and Madiafi 2013), which contributes to generating other child chromosomes using crossover and mutation operators.

In a crossover operation, two parent-chromosomes exchange their information to produce two child-chromosomes for the next generation. Scattered crossover is used in this study to randomly generate a binary string with the length of a chromosome. Then, the value of gene i of the first child is gained from the first parent if the corresponding value in the binary string is 1, and from the second parent if the corresponding value in the binary string is 0. The second child is formed in the opposite way (Figure 4-5a). Crossover fraction (F_C) determines the number of child chromosomes generated by a crossover in a population other than elite children.

The rest of the child chromosomes are generated through the mutation. A gene value of a parent chromosome is likely to change with the probability of P_M. The mutation operator creates a random binary string of the same length as the chromosome where the gene value is changed if the corresponding value in the binary string is 1, and not changed if the corresponding value in the binary string is 0 (Figure 4-5b). The mutation probability (P_M) determines the likelihood of a value in a binary string is 1.

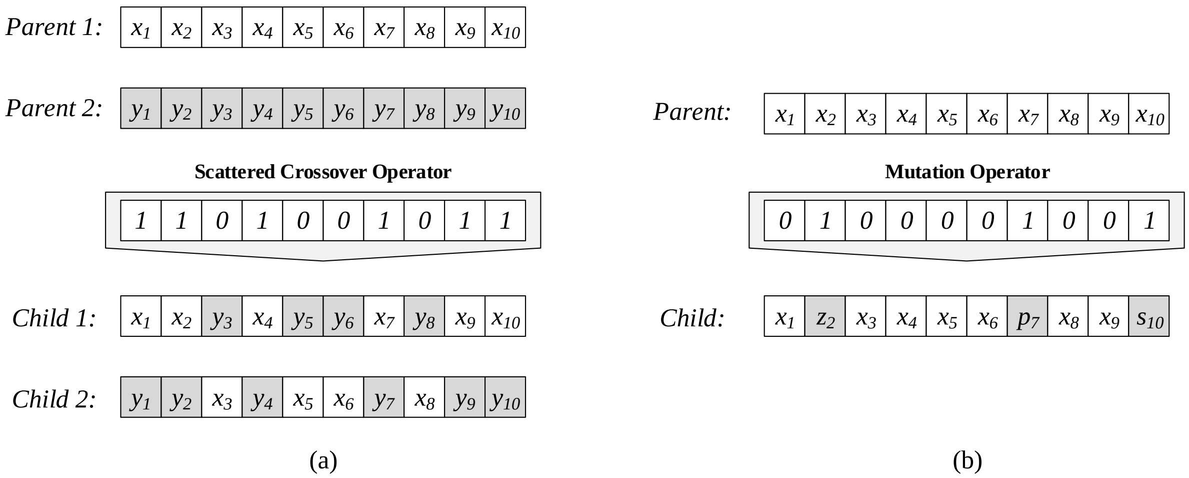


Figure 4-5- Crossover and mutation operators in GA-clustering process

After generating a new generation, the chromosomes, representing clustering solutions, are polished by the K-Means algorithm to enhance optimization performance. K-Means searches local optima by switching segments between clusters to improve the BCR^{tot} value. The procedure for this step is as follows:

(1) Randomly select segment *i* from cluster *k*,

(2) Calculate the improvement in BCR^{tot} by joining segment *i* to neighboring clusters if joining segment *i* to the neighbor cluster is feasible (i.e., can satisfy work-packaging conditions),

(3) Move segment *i* to the cluster that leads to the most improvement in BCR^{tot},

(4) Repeat steps 1 to 3 until no further improvement is possible. The process is terminated if no further segment switches between two clusters for a specified number of successive iterations.

The GA optimization method is generally faster than iterative searching engines such as the K-Means method. Furthermore, the searching time is exponentially increased by increasing the number of K-Means iterations. On the contrary, low K-Mean iterations would not be as effective in the enhancement of exploitation capability of the optimization process. Thus, the number of K-Means iterations should be set in a trade-off between the processing-time and effectiveness of the optimization progress. The sixth step utilized two types of K-Means searching engines: soft-searching (3 iterations) and hard-searching (100 iterations). Islam et al. (2018) found that a suitable K-Means intervention in GA optimization is every ten generations. They also demonstrate that modifying only high performing chromosomes enhances the overall clustering process. In this study, the hard-searching K-Means applied to the top one-tenth of the clustering solutions at every 10th generation, and the soft-searching K-Means method is applied to all other solutions at every generation.

Steps 2 to 4 are executed for the new generation of solutions (i.e., new chromosomes) and the outcomes are being used again to create the children of another generation in step 5. This iterative process is repeated until the termination criteria are triggered. The clustering algorithm uses the following criteria to determine when to stop; either one occurs first:

- Reach the maximum number of generations (G^{max}).
- Create NG^{max} successive generations with no improvement in the best solution.

The best chromosome of the last generation is the best solution for clustering segment candidates for replacement into WPs. Encoding the best chromosome reveals the characteristics of near-optimal WPs, including their segment-list, total cost, and total benefit. Appendix B delineates the optimization algorithm for grouping water segments in work-packages coupling Genetic algorithm (GA) and K-Means Clustering method.

4.3.2. Capital Work-Package Selection (CWPS)

The schedule of a WP execution depends on the WP's characteristics and annual capital budgets. Essentially, asset managers prefer to bring forward the execution of a WP with a higher benefit/cost ratio. However, the number of WPs scheduled for a year is restricted to the annual capital budget. The CWPS module is responsible for selecting WPs for year t so as to maximize the total benefit/cost ratio of all WPs scheduled to execute in the year t (BCR_t^{tot}). Thus, the optimization of WP selection for year t is formulated as follows:

$$\begin{cases} Maximize \quad BCR_t^{tot} = \dfrac{\sum_{i=1}^{C_t} WPB_i}{\sum_{i=1}^{C_t} WPC_i} \\ subject\ to: \quad \sum_{i=1}^{C_t} WPC_i \le B_t \end{cases} \qquad \text{Eq. 4-17}$$

where c_t is the number of WPs selected for year t, and B_t is the annual capital budget for year t.

The CWPS module utilizes a Single-Objective Genetic Algorithm (SOGA) to select WPs for each year efficiently. A binary chromosome represents the solution of the optimal WP selection for a given year. The size of a chromosome is equal to the number of available WPs in each year (P). The value of each position indicates whether the corresponding WP is selected for year t or not (Figure 4-6); WP_i is selected for execution in year t if the i^{th} gene's value is 1, and vice versa if it is 0. The principle steps of GA optimization in the CWPS module are the same as those in the clustering process (Figure 4-4), but with the K-Means step omitted.

The binary string for a random solution (i.e., a chromosome) is generated in an iterative process. Only one random WP is selected at each time, and turns the respective position into 1, to satisfy the budget constraint. This iterative random selection is repeated until the budget constraint prevents the addition of more WP.

Work-Package ⟶	*1*	*2*	*3*		*i*		*P-1*	*P*
Gene ⟶	$G_1=1$	$G_2=0$	$G_3=0$	• • •	G_i	• • •	G_{P-1}	G_P

Figure 4-6- Representation of a chromosome in the work-package selection process

4.4. Model Validation

Cities need to expand to accommodate more inhabitants over time. This expansion often occurs by cities pushing their boundaries outward to include adjacent land for development through the time. Thus, the inner areas are usually older than the outer ones. Urban infrastructure, such as water distribution networks, exhibit the same development pattern. In this study, three regular hypothetical networks (Networks A, B, and C) with the same development pattern are created to implement validation tests and study the impacts of grouping capital works on both long-term and short-term performance of their water distribution networks. Each network encompasses twelve zones numbered from oldest to youngest, with zone 1 the oldest and zone 12 the youngest. The total length of each network is 30km and consists of 1200 pipes. Age is the only variable in Network A, while age and pipe size are varying for Network B. Network C has the same characteristics as Network B with variation in land use.

The aim of the work-packaging optimization methodology is to develop capital work-packages that maximize the network's performances, in terms of risk and levels of service subject to an annual capital budget. Therefore, each network is investigated by running the model for two different renewal strategies: (Strategy 1) Optimal grouping strategy: develop most-efficient work-packages through grouping replacement works by maximizing total benefits gained by spending the annual capital budget; (Strategy 2) Non-optimal grouping strategy: develop work-packages through grouping replacement works by giving priority to the segments with higher PI values.

Three performance indicators are defined to evaluate the network's performance in terms of risk, physical condition, and cost. Eq. 4-18, Eq. 4-19, and Eq. 4-20 are defined risk, physical condition, and cost indicators of a network with *N* segments, respectively.

$$Network\ Risk\ Indicator\left(NRI\right)=\frac{\sum_{i=0}^{N}PI_i\times l_i\times d_i}{\sum_{i=0}^{N}l_i\times d_i} \qquad \text{Eq. 4-18}$$

$$Network\ Condition\ Indicator\left(NCI\right)=Network\ Average\ Age=\frac{\sum_{i=0}^{N}age_i\times l_i}{\sum_{i=0}^{N}l_i} \qquad \text{Eq. 4-19}$$

$$Network\ Accumulated\ Capital\ Expenses\left(NACapEx\right)\ =\sum_{yr=0}^{T}ACapEx_{yr} \qquad \text{Eq. 4-20}$$

where PI_i is priority index, l_i is the length, d_i is the diameter, and age_i is the current age of segment i, N is the total number of segments, T is the total years the implementation of capital plans, and $ACapEx_i$ is the annual capital expenditure in the year i.

4.4.1. Simulation assumptions

Table 4-2 summarizes the main simulation parameters for all three networks.

Table 4-2- Simulation parameters for water distribution networks

Description	amount	unit
Long-term strategic planning		
Long-term period	100	years
Annual Renewal Rate of total network length	1	%
Capital unit cost (1)	1000 (A), 1120 (B&C)	\$/m
Population	7500	persons
Initial Water demand (1)	300	litre/capita/day
Minimum Water demand (1)	200	litre/capita/day
Initial water fee	2.55	$\$/m^3$
Short-term capital programing		
Short-term period	5	years
Average service life (failure threshold)	120	years
Replacement unit cost (2)	4	\$/mm diameter/m
Minimum work-package size (WPS_{min})	100k	\$
Maximum work-package size (WPS_{max})	350k	\$
Maximum allowable distance (MAD)	150	m
Logistical cost fraction (α) (3)	10	%
Maximum discount for Economies of scale ($D_{\max}^{Qty}$) (4)	10	%
Minimum WP length for quantity discount (L_{min})	100	m
Maximum WP length for quantity discount (L_{max})	500	m

(1) Rehan et al. (2011), (2) Zhao and Rajani (2002), (3) Quiroga et al. (2007), (4) Nafi and Kleiner(2010)

The system pursues the renewal policy of replacing 1% of the network's total length annually. As discussed in Section 2.7, the most efficient cycle for the PDCA process is a 5-year period. Thus, capital programs are developed at 5-year intervals. The acceptable range of a work-package size (i.e., WPS^{min} and WPS^{max}) depends on the total length of the network and the renewal rate. In this study, the acceptable size range for work-package development is assumed \$100k to \$300k, regarding the networks' characteristics and the model assumptions. A segment becomes eligible to join a work-package if the geographical distance between the segment and WP center coordinates is less than the Maximum Allowable Distance (*MAD*) value. In this simulation, the *MAD* value is assumed 150m.

The GA parameters are problem-based settings (Rylander and Gotshall 2002). The parameters such as population size, the number of elite selections, the crossover fraction, and mutation probability are basically set with respect to the solution space. Although experts suggest recommendations for estimating these parameters (Rylander and Gotshall 2002; Stanhope and Daida 1998), they are actually set through trial-and-error attempts. Table 4-3 tabulates the GA parameters for the development of work-packages. All GA parameters are constant values.

Table 4-3- GA setting for clustering of capital works

Parameter	**Amount**
Population	50
Maximum generations (G^{max})	500
Maximum successive generations without any improvement (NG^{max})	100
Elite chromosomes	5
Crossover fraction (F_C)	0.6
Mutation probability (P_M)	0.05

The CWPS module executes another GA optimization for each planning year to find the optimal selection of work-packages. Table 4-4 summarizes the GA parameters' values for the CWPS module. The dimension of solution space for each year varies with the number of existing work-packages (N_{WP}). Therefore, the GA population size varies according to the number of existing work-packages from which the optimal selection of WP is found.

Table 4-4- GA setting for work-package selection

Parameter	**Amount**
Population	min (N_{WP}×10, 100)
Maximum generations (G^{max})	100
Maximum successive generations without any improvement (NG^{max})	30
Elite chromosomes	5
Crossover fraction (F_C)	0.7
Mutation probability (P_M)	0.05

4.4.2. Simulation results of *Network A*

All pipes of *Network A* have the same characteristics, except for age. However, it is assumed that all pipes in a zone have been installed in the same year. Therefore, the age of pipes is the determinant of the development of renewal work-packages. Figure 4-7 shows the configuration of *Network A* along with its inventory profile and associated critical-tier map.

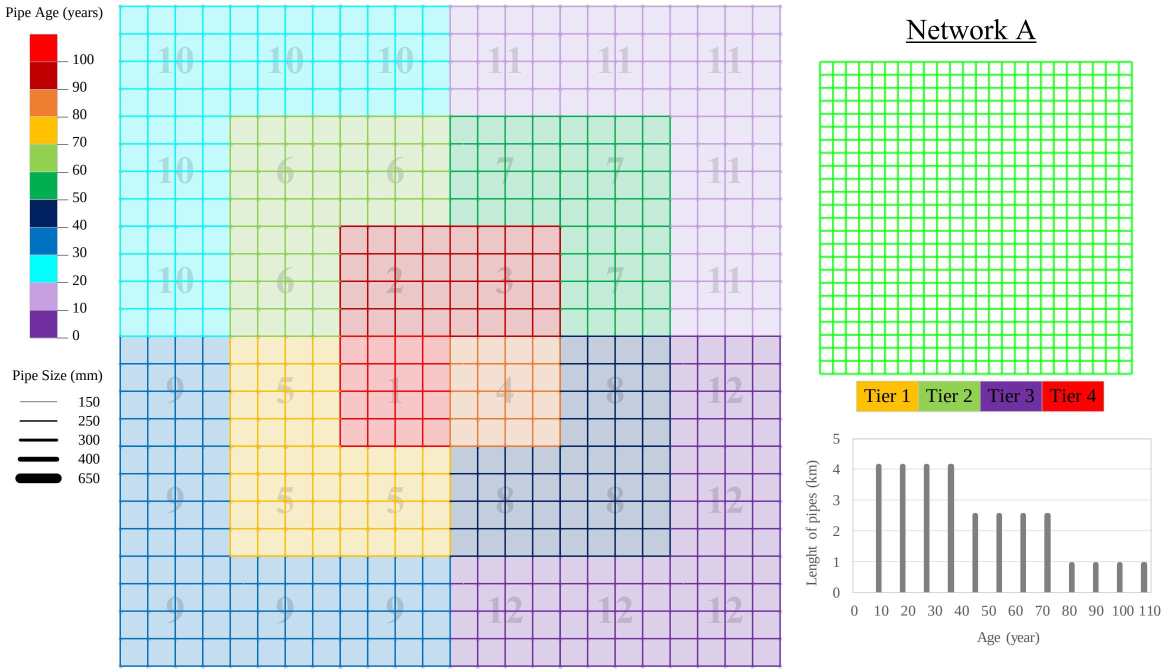


Figure 4-7- The configuration of Network A

According to Section 3.3.3a, all pipes in *Network A*, which are 25m long with 250mm diameter, are classified as a tier-two pipe.

Figure 4-8 presents the six snapshots of simulation results for *Network A* based on near-optimal grouping renewal (Strategy 1). The results confirm that the progress of WP development aligns with the network's age-map. It implies that the initial WPs select pipe segments with the priority of zone 1, 2, 3 and 4, respectively. Full details of simulation results of capital planning for every 5-year interval are provided in Appendix C.1.

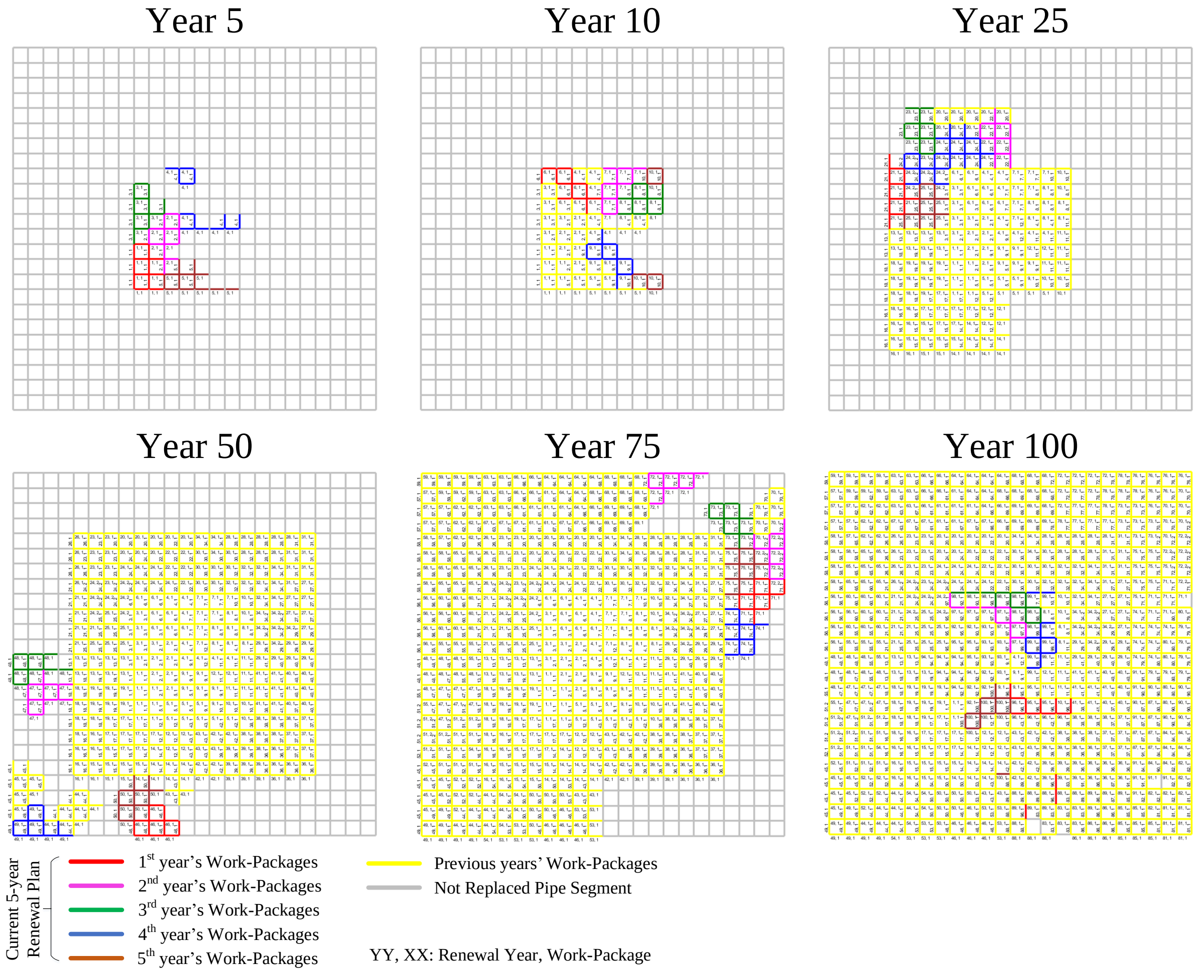
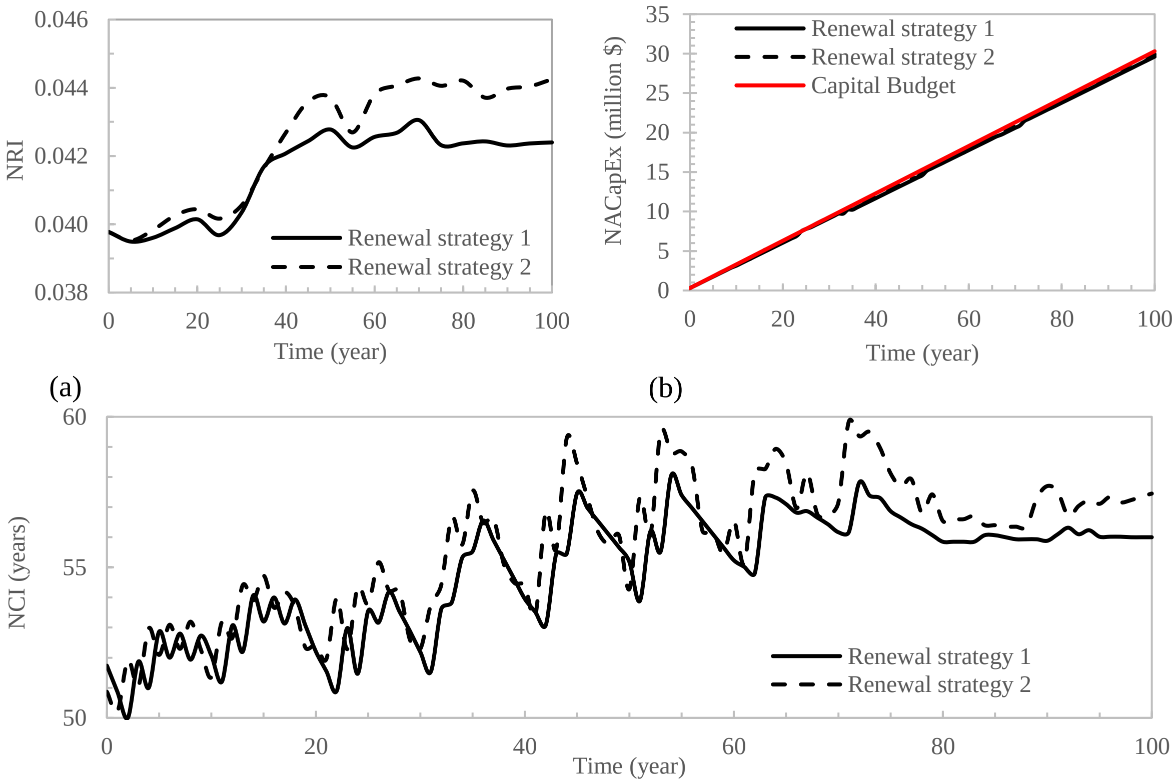


Figure 4-8- Simulation results of *Network A*

Figure 4-9 provides the variation of three performance indicators. A quick glance through these figures shows that with almost the same amount of financial resources (Figure 4-9b), better performance can be achieved by implementing the near-optimal work-packaging model. Figure 4-9a compares the network risk indicators of both renewal grouping strategies over a 100-year planning period. It shows that the network benefits from 4.37% risk reduction by implementing the optimal grouping strategy (Strategy 1). Furthermore, the physical condition of the network is enhanced by 2.59% by the end of the 100-year planning period (Figure 4-9c).



(a)

(b)

(c)

Figure 4-9- Performance of Network A under various renewal grouping strategies

4.4.3. Simulation results of *Network B*

Network B's water mains have the same characteristics, except for age and size. Four pipe diameters are installed in *Network B,* where the pipe sizes of 650 mm, 400 mm, 300 mm and 150 mm represent transmission, primary feeder, secondary feeder, and distribution mains, respectively. Figure 4-10 demonstrates the layout of *Network B* along with the associated inventory profile and critical-tier map.

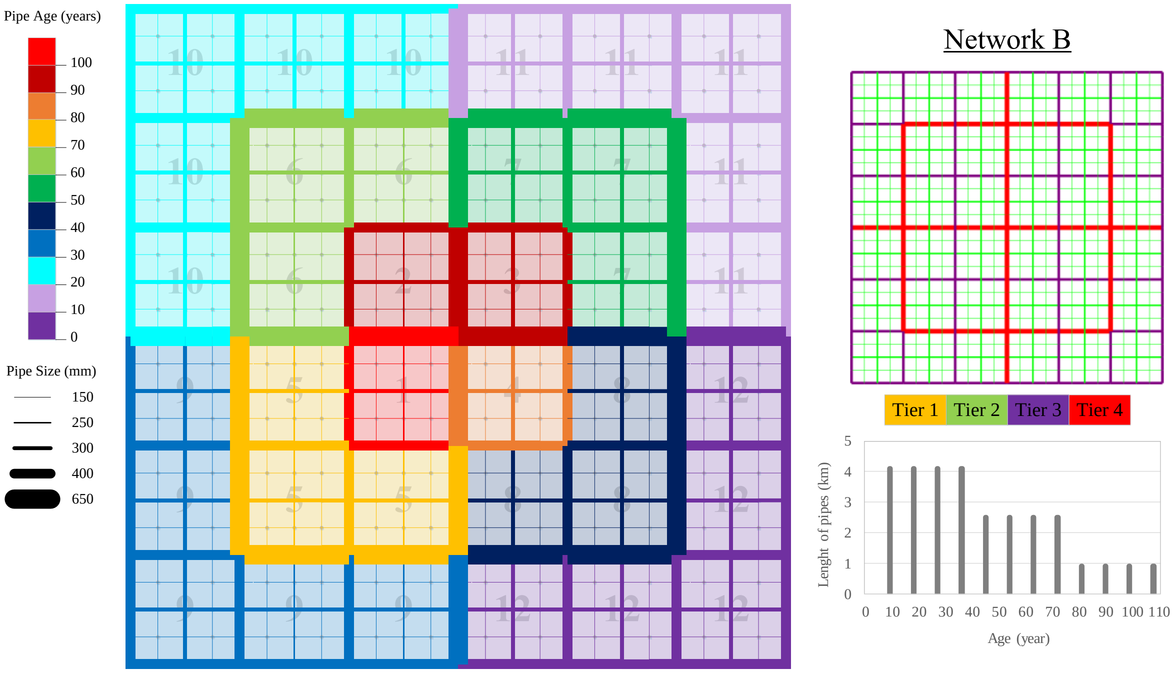


Figure 4-10- The configuration of Network B

Figure 4-11 presents the six snapshots of simulation results for *Network B*. The review of the first three consecutive 5-year renewal plans reveals that the priority of selecting segments for replacement is given to those segments with the highest risk, i.e., those are categorized in tier 4. Therefore, optimal work-packages have tried to include tire-four segments in their to-do lists. The overall progress of work-package development shows that segments have been joining together by the priority given to older zone as well as higher risk pipes. Full details of simulation results, including capital plans for every 5-year interval, are provided in Appendix C.2.

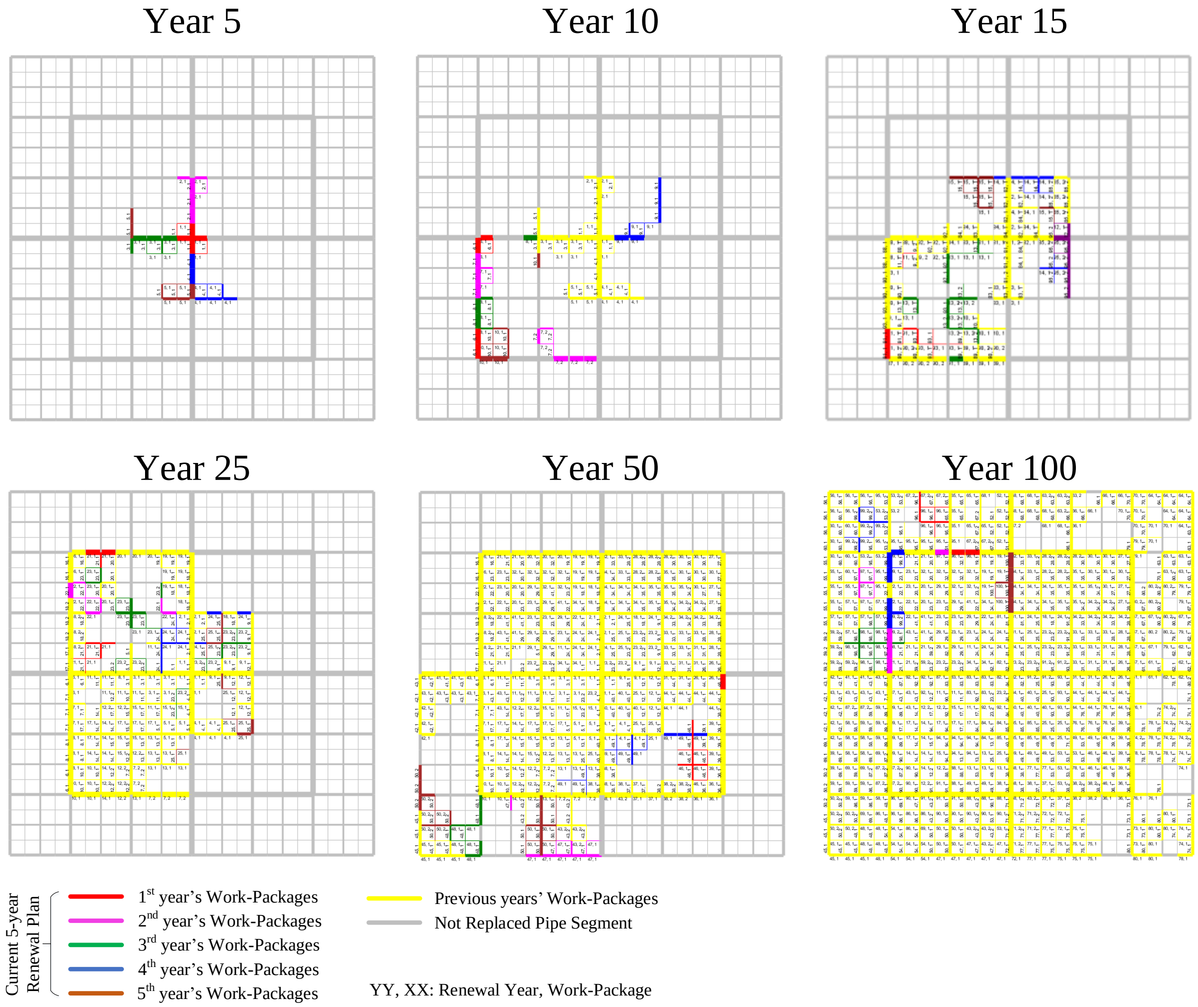


Figure 4-11- Simulation results of *Network B*

The variation of performance indicators is presented in Figure 4-12. The main takeaway of all three figures is that the most efficient utilization of the limited financial resources is achieved by implementing the optimal grouping strategy. Figure 4-12a identifies 2.62% reduction in risk indicator by optimizing renewal work-packages. The average age of the network, representing the network condition, also shows that renewal strategy 1 forecasts a better condition by 4.69% with the same amount of investment at year 100 (Figure 4-12c).

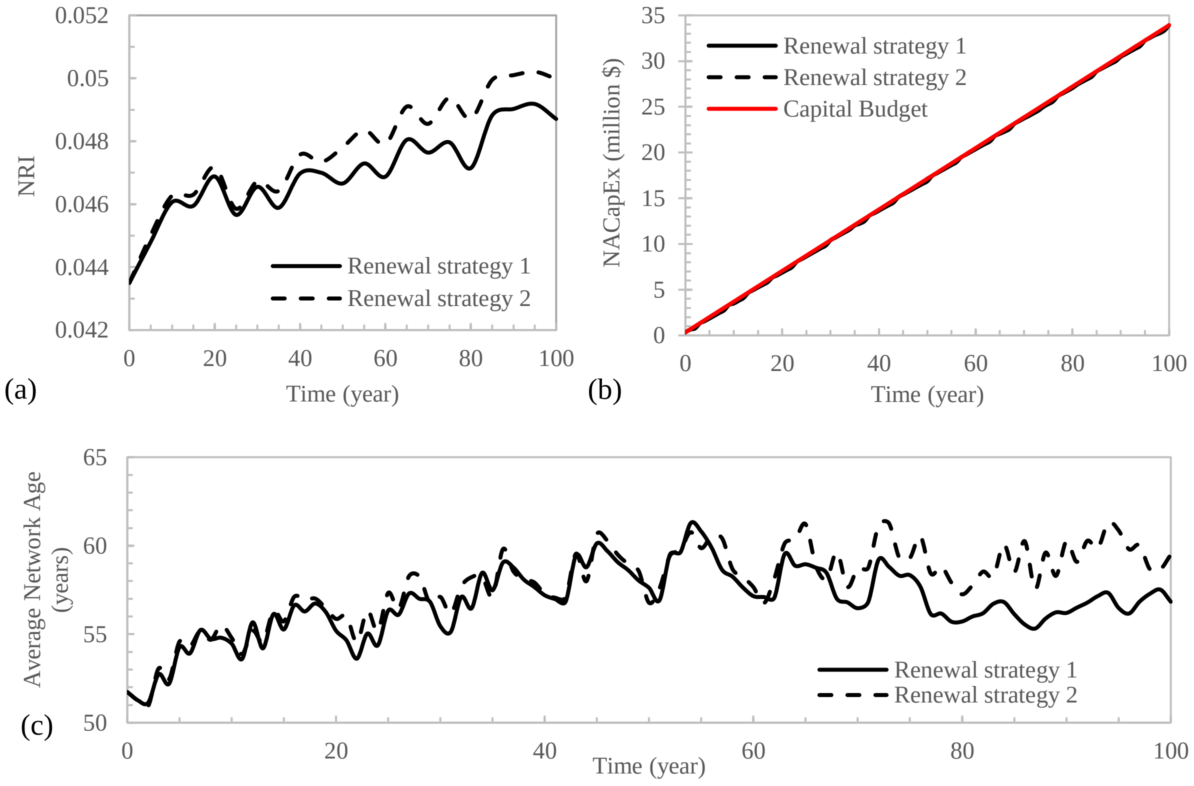


Figure 4-12- Performance of Network B under various renewal grouping strategies

4.4.4. Simulation results of *Network C*

Network C's water mains have the same characteristics as *Network B*. In the previous networks, it is assumed that all segments are located in the residential area without any technical restriction allowing them to be replaced by an open-cut method. *Network C* is designed to explore the effects of renewal technique selection in the development of most-efficient work-packages.

Network C provides water services to two types of areas: residential and high-density development. It is also assumed there are only two broad options for replacing a pipe: Open-Cut (OC) and Trenchless Technique (TT). The following simple rules are applied to select the appropriate replacement technique:

i. The preference is given to TT in high-density areas

ii. The preference is given to OC in residential areas

iii. If the accessibility of a segment is restricted by a natural or artificial obstacle, such as rivers and highways, TT will be the sole option for replacement.

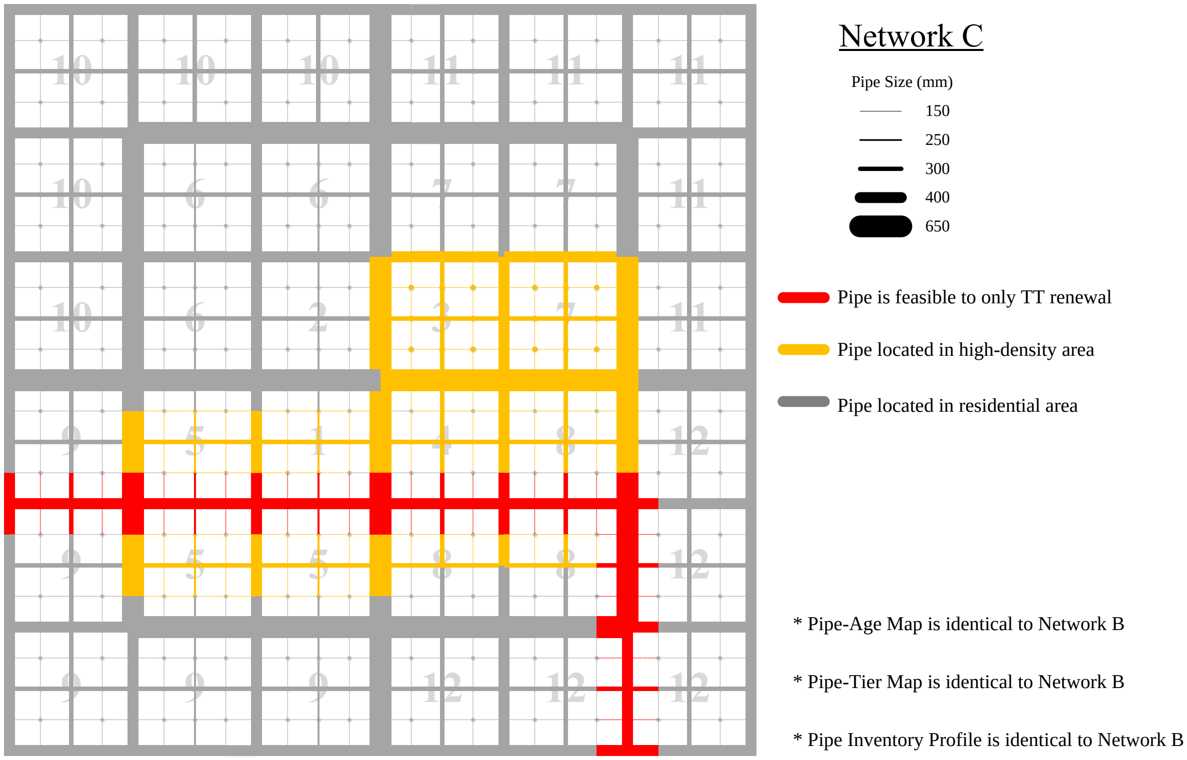
iv. OC is the sole option for the replacement of distribution mains unless it is not feasible (e.g., when rule iii is effective).

There are too many factors involve in the calculation of the replacement unit cost, including material, size, depth, location, and accessibility. Trenchless technologies can be executed with minimal disruption to the surface facilities. Therefore, they have significantly lower social and environmental costs during the construction period compared to the open-cut method. In contrast, open-cut is usually cheaper than trenchless construction using professional machinery and skilled labour in more open areas, such as residential locations. Table 4-5 provides the unit costs used in this study, for the replacement of a water main using OC and TT methods in both residential and high-dense locations.

Table 4-5- Replacement unit costs in residential and high-dense locations

	Open-Cut (OC)	**Trenchless Technology (TT)**
Residential area	3 $/mm/m	3.5 $/mm/m
High-density area	5 $/mm/m	4.5 $/mm/m

Figure 4-13 presents the layout of *Network C*. The age-maps and tier-maps of *Networks B* and *C* are identical. The grey and orange pipes are buried in residential and high-dense areas, respectively. The red pipes are presumed to be installed beneath a highway. Therefore, their accessibility is restricted by the highway and, consequently, the TT is the only method to be employed.



* Pipe-Age Map is identical to Network B

* Pipe-Tier Map is identical to Network B

* Pipe Inventory Profile is identical to Network B

Figure 4-13- The configuration of Network C

The progress of work-package development in *Network C* is similar to *Network B*, as both of their age-maps and criticality-maps are the same (Figure 4-14). Full details of simulation results, including capital plans for every 5-year interval, are provided in Appendix C.3. Figure 4-15 exhibits that, as expected, all segments crossing over by the highway and most of the segments buried in the high-dense area are replaced by the TT method. In contrast, most of the segments located in the residential area are replaced by the OC method. Similar results to other networks are achieved in respect of the long-term performance indicators. Following the similar capital investment for the network renewal in the long-term (Figure 4-16b), the optimal grouping strategy improves the performance indicators in comparison to the non-optimal grouping strategy. The results show a 1.93% and 3.78% improvement in the network's risk and average age indicators, respectively.

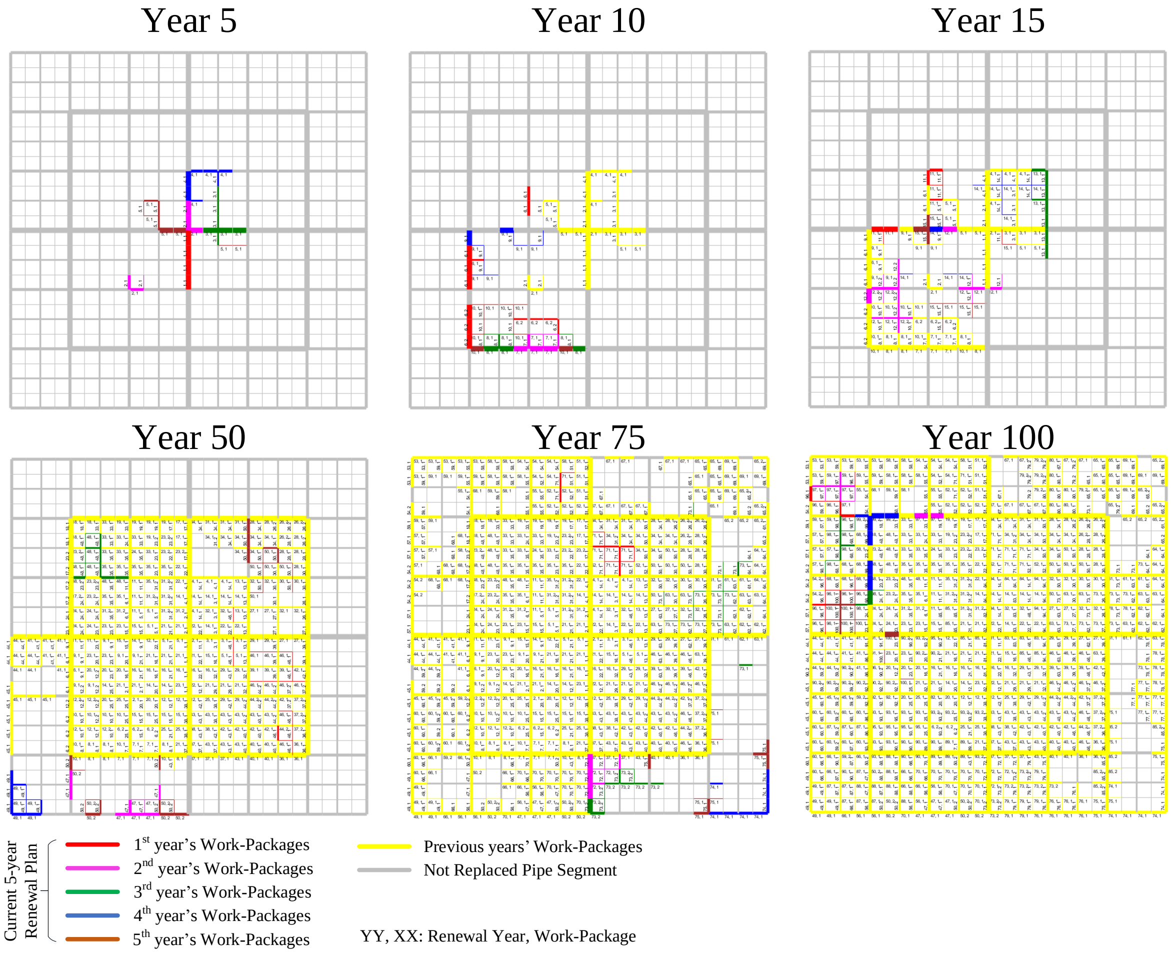


Figure 4-14- Simulation results of *Network C*

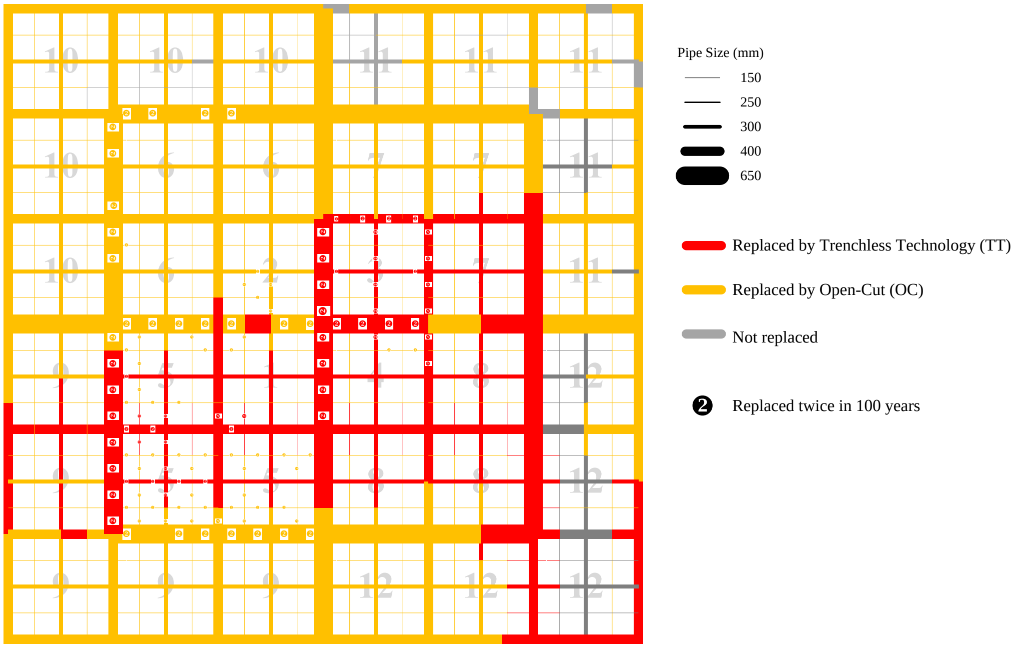


Figure 4-15- Replacement technique for water mains of Network C

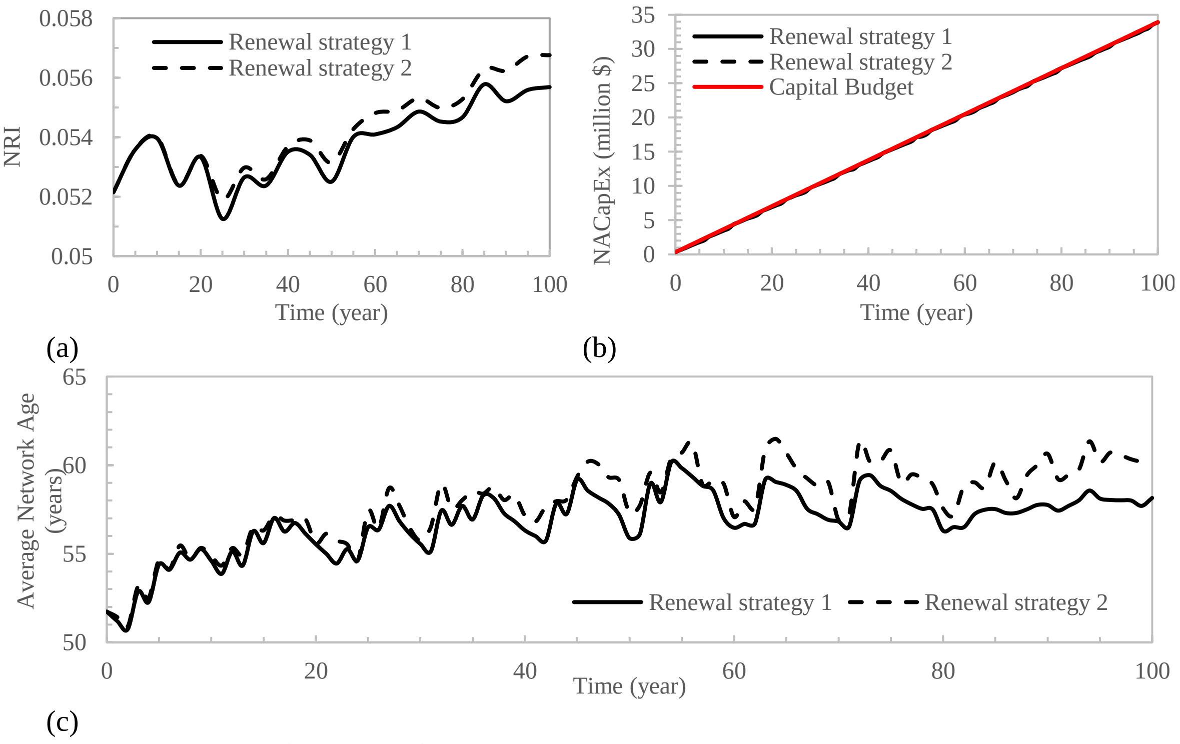


Figure 4-16- Performance of Network C under various renewal grouping strategies

4.5. Impact of Contiguity and Quantity Discounts on the Development of Optimal Work-Packages

In all the hypothetical networks, all 144 segments located in zones 1 to 4 are flagged as candidates for replacement at the starting points. The CWC module runs an optimization process to cluster these 144 segments into work-packages (or clusters) such that the overall benefit/cost ratio is maximized. As discussed earlier, the contiguity and size of a work-package are the main drivers of candidate segments congregating to form the near-optimal work-packages. The contiguity discount promotes adjacent and connected segments to join together in a group. On the other hand, work-packages try to adopt as many segments as possible to take advantage of quantity discounts. To explore the effects of contiguity discount and quantity discount, *Network A* has been simulated under three simulation scenarios (Table 4-6).

Table 4-6- Summary of simulation scenarios for clustering capital works

Scenario	Contiguity discount C_{Contig} (%)	Quantity discount D^{Qty} (%)
1	10	0
2	0	15
3	10	15

The results of clustering in the first round of capital planning (i.e., years 0 to 5) for simulation scenario 1 are provided in Figure 4-17. The optimal configuration of 14 work-packages, or clusters, shows that the CWC module is trying to group connected segments together as much as possible because the contiguity discount is the only driver for developing optimal work-packages. However, the other constraints, such as acceptable work-package size and maximum allowable distance (*MAD*), are involved in the formation of work-packages.

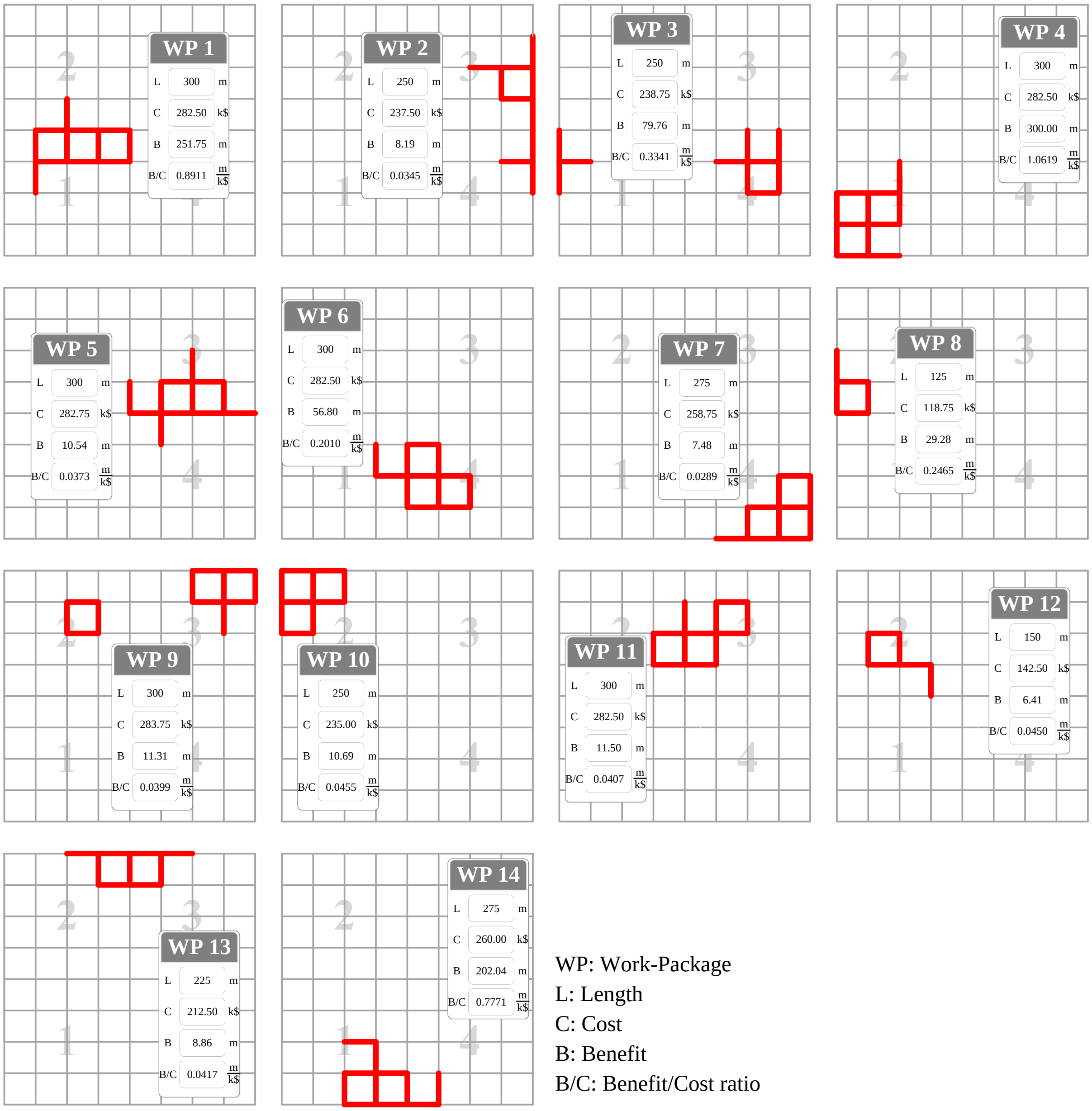


Figure 4-17- Clustering simulation results for scenario 1 of *Network A*

If the quantity discount is the only driver in the development of optimal work-packages, each work-package tries to incorporate as many segments as possible to its to-do list. A cap of $300k is assumed as the maximum work-package size (Table 4-2). The size of work-packages in scenario 2 shows that all work-packages are developed with the largest possible sizes. Every work-package consists of thirteen segments with the total length of 325 m and the nearest cost to the maximum work-package size, which is $300k. However, the clustering process has no interest in grouping contiguous segments as the contiguity discount set to be zero in scenario 2.

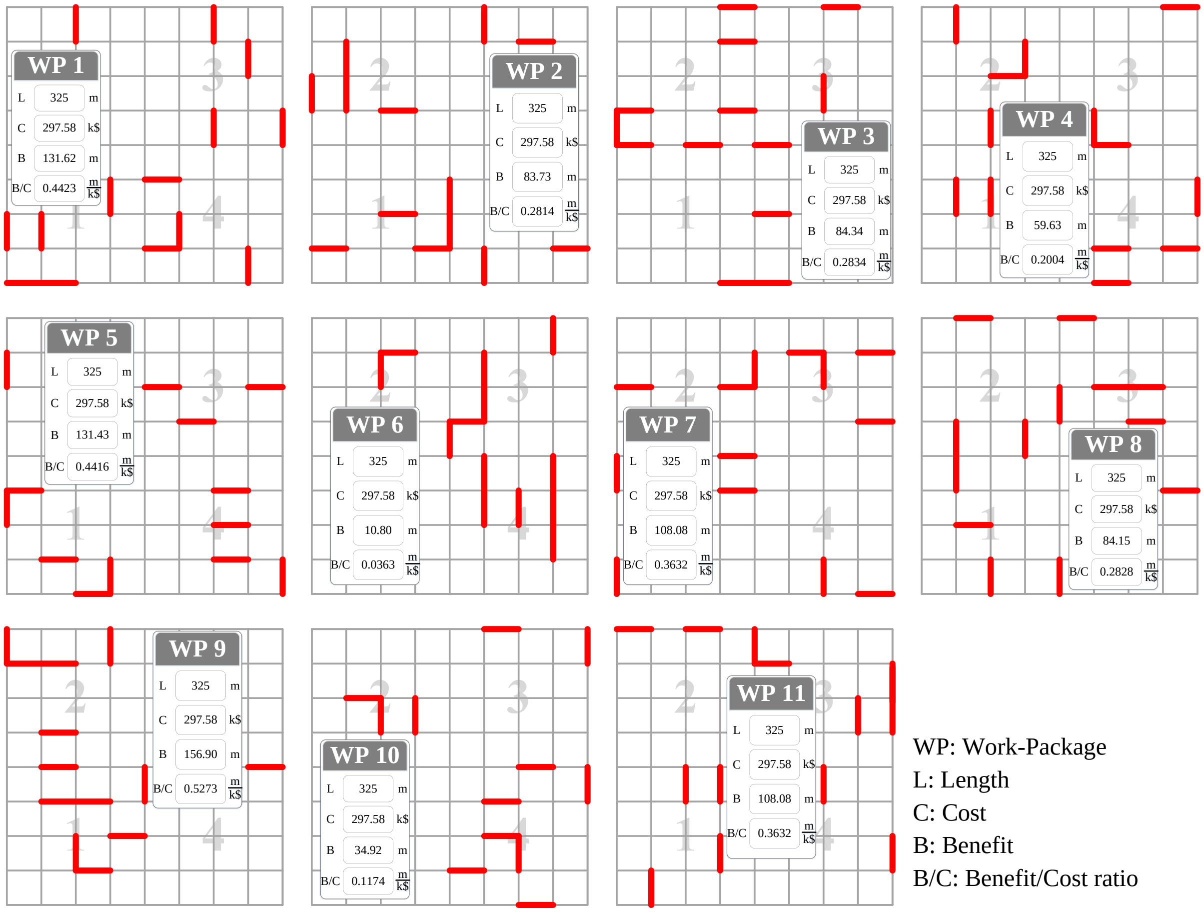
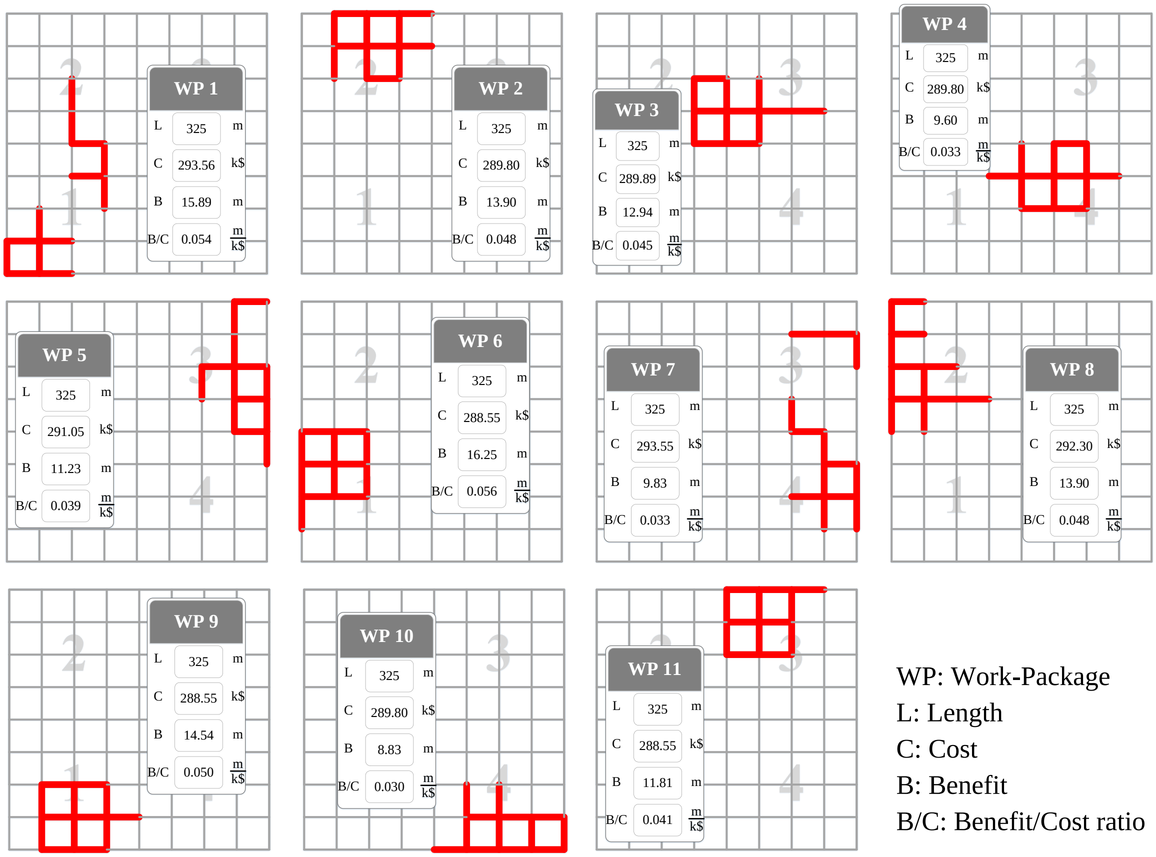


Figure 4-18- Clustering simulation results for scenario 2 of *Network A*

As expected and verified in scenario 3, the most contiguous and largest possible work-packages were obtained by incorporating both contiguity and quantity factors in the optimization process (Figure 4-19). The clustering process results in eleven work-packages, which are in the near-optimal configuration in the presence of both contiguity and quantity discounts. A review of the work-packages' attributes reveals that all have been developed in an effort to maximize their sizes, up to the maximum allowable size, as well as their contiguity.



WP: Work-Package
L: Length
C: Cost
B: Benefit
B/C: Benefit/Cost ratio

Figure 4-19- Clustering simulation results for scenario 3 of *Network A*

4.6. Conclusions

This study set out to develop an integrated capital planning model to produce the most efficient renewal plans to maximize the utilization of limited capital budgets. The presented methodology for the development of optimal work-packages is more compatible with current renewal practices in which the capital works are joined together to be more efficient economically and practically. It is shown that optimal group replacement scheduling improves the performance of a water distribution network in the long-term in terms of risk and physical condition. The risk index of water distribution networks is reduced by 1.93% to 4.37%, implementing the optimal group replacement strategy. This strategy also has a similar beneficial effect on the physical condition of the network. The physical condition of the networks improved from 2.59% to 4.69% compared to the non-optimal strategy by the end of 100 years.

This chapter demonstrates three simple regular networks to conduct verification tests and to make the results more understandable. However, the model can be applied to any heterogeneous water distribution network with more complexity. Using the agent-based modelling approach provides a platform to build interactions between the different components of a water system and various planning levels. Furthermore, interactions between segments agents enable the optimization process to search the large solution space more effectively and efficiently.

Chapter 5.

Conclusions, Contributions and Future Recommendations

5.1. General Summary and Conclusions

The aim of the present research is to propose and develop a modelling methodology to integrate levels of planning to align strategic, tactical, and operational objectives in water distribution systems. To this end, it is essential to combine two top-down (network-level) and bottom-up (component-level) planning approaches to simulate a dynamic and complex infrastructure system, such as urban water distribution networks, over their life-cycles. Conducting an extensive literature review reveals that there is no Decision Support System (DSS) to provide managerial and technical solutions for water distribution systems from an integrated planning perspective. This research applies an innovative modelling solution using a hybrid Agent-based and System Dynamics (AB-SD) simulation model to analyze the life cycle performance of urban water distribution networks under different management strategies.

Specific conclusions for various aspects of this research are listed in each of Chapters 2 to 4 under section conclusions. A general summary of the conclusions for the research is presented below.

Comparing the results of social, physical, and financial performance indicators reveals that an integrated planning approach using the AB-SD model and SD model output similar trends in spite of the fact that the AB-SD model is slightly more conservative than the SD model. The case-studies demonstrate the applicability of the AB-SD model in addressing component-centric decisions, such as *Which* water main need to be replaced, *When* and *How*, aligned with long-term policy levers and strategies. The proposed agent-based modelling framework provides an adaptive platform to accommodate various decision-making processes running in the system by defining agents' behaviours or even introducing new agent-type. Users can elaborate on an agent's behaviour without requiring to understand the complexity of the system interactions. For instance, *Budget Allocation* module has been advanced and substituted for two other processing modules (Capital Work Clustering – CWC – and Capital Work Package Selection – CWPS) to enable the AB-SD model to establish optimal work packages. The simulation results of optimal group scheduling show that the water distribution networks can take advantage of risk reduction up to 4.37% and physical condition enhancement up to 4.69% by grouping replacement works with limited financial budgets.

5.2. Contributions

This research makes the following original contributions to the state of knowledge:

- Identified the knowledge gap in current asset management models and decision support systems to incorporate all contributing levels of planning in water distribution systems;
- Introduced a novel modelling methodology and developed a framework to integrate strategic, tactical, and operational planning levels into a Decision Support System (DSS) for water distribution networks;
- The Rehan et al.'s (2011, 2013) water distribution system dynamics (SD) model is advanced by adding the agent-based model to identify water mains as simulation entities and capture their associated interactions;
- Developed a hybrid Agent-Based and System Dynamics (AB-SD) simulation model to accommodate top-down and bottom-up planning paradigm to align network-centric and component-centric decision-making processes;
- Developed a feedback loop mechanism between network-level model (strategic plans), component-level model (tactical and operational plans) and neutral water infrastructure database to share and exchange their information, systematically;
- Different long-term financial and renewal strategies are explored and compared for asset management of water distribution networks.
- Developed a heuristic optimization algorithm to find optimal solutions for grouping capital works (establish optimal work packages) to enhance the long-term performance of the water distribution network in terms of risk and physical condition. Three hypothetical networks are simulated to validate the advanced AB-SD simulation model.

5.3. Recommendations and Directions for Future Research

This research presents the first-known application of the hybrid of agent-based and system dynamics modelling approach in the development of an integrated Decision Support System (DSS) for water distribution networks. This DSS can align the strategic, tactical, and operational policy levers to coordinate their objectives by combining top-down and bottom-up planning approaches. The application of the AB-SD model can be extended to other types of municipal infrastructure systems. Moreover, the adaptive agent-based modelling environment provides a platform to extend the scope of the model to perform more advanced analyses in infrastructure asset management. Specific recommendations for future research work are listed as follows:

1. The present AB-SD model assumes pipe replacement as the sole capital work in the development of capital programs for water distribution networks. Multi-proactive renewal strategies, including replacement, rehabilitation, or repair, can be explored by advancing simulation modules as future research.
2. This research uses the SD model developed by Rehan et al. (2011). Further research can be conducted by utilizing a more advanced SD model developed by Rehan et al. (2013) and Ganjidoost (2016) to study the long-term performance of water distribution networks by implementing various managerial strategies, such as pay-as-you-go with inflation, borrowing, and capital reserving.
3. Develop a holistic, integrated decision-support-system for water infrastructure systems, including water distribution and wastewater collection networks incorporating water and wastewater treatment plants to explore other areas, such as Infiltration and Inflow (I&I) analysis, system energy efficiency, climate change effects, sustainability.
4. This study assumes that all water mains selected for replacement are executed in a given year. In practice, renewal projects may be scheduled for longer or shorter than a year. Further research can be undertaken to develop operational decision-making processes for optimal scheduling of capital works. Construction constraints such as the number of construction crews and contractor capacity could be taking into account for future research.

5. Develop behavioural models for water users and their interactions with other components of the system at the tactical and operational levels (i.e., develop the associated attributes and behaviour with user agents).
6. Perform an optimization between capital budget allocation among different renewal actions (active or proactive replacement, rehabilitation, renovation, and repair) to enhance the long-term performance of water supply systems.
7. Implement the AB-SD model to a real case-study to explore other parameters and decision-making processes associated with water distribution networks and investigate further renewal strategies.

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Appendix A

Reviewed Infrastructure Asset Management Models for Water Distribution Networks

Author/s	Main Features
Grigg and Bryson (1975)	First to utilize system-dynamics simulation to study the interaction of water supply, customers, and utility's finances to investigate an appropriate rate policy. The model parameters are: consumers, storage, available water funds, debt, occupied land area, water infrastructure value, and water rights owned.
Shamir and Howard (1979)	Calculate optimal replacement time for a pipe by comparing the present value of pipe replacement with that of repairing breaks.
Walski (1987)	Compares the present value of pipe replacement with its maintenance costs, including break repairs, water loss cost, and pipe accessory replacement.
Luong and Nagarur (2001)	Present a mathematical model and semi-Markov process to support the process of choosing renewal alternatives, i.e. replace or repair, for a water main experiencing failure.
Kleiner et al. (2001)	Identify optimal rehabilitation or renewal strategy and its optimal time of replacement and implementation using a dynamic programming approach. They propose a heuristic method to discover the most cost-effective renewal strategy for each individual pipe, considering the performance of the whole system financially as well as hydraulically. However, this approach is limited to a small network with at most 15-20 pipe links due to the limitations of available heuristic methods.

Author/s	Main Features
Dandy and Engelhardt (2001)	Use genetic algorithm (GA) to find the optimal pipe replacement schedule to minimize the present value of capital, repair and damage costs according to the input factors: pipe identification, time of the replacement, the size of a new pipe.
Loganathan et al (2002)	Provide a mathematical approach for estimating optimal times to replace a pipe, based on breakage rate. First defining a threshold break rate for any pipe with respect to its diameter and length, they then determine which pipe should be replaced in excess of the rate.
Hong et al (2006)	Propose a mathematical approach to minimizing the expected annual average cost over the planning horizon instead of expected total cost to find optimal replacement time of a pipe.
Bagheri and Hjorth (2007)	Develop a causal-loop diagram for the simulation of sustainability development introducing a new type of loop named Viability Loops. They applied their proposed SD modelling approach to the water supply system of Tehran, the capital of Iran.
Dridi et al (2008)	Develop an optimization model, using three GA-based technique, to locate any pipes need to be replaced and when in a planning period. The model is combined with a hydraulic simulator, i.e. Epanet2.0 and a probabilistic break model to simulate structural deterioration of pipes.
Nafi and Kleiner (2010)	Propose a GA optimization methodology to efficiently schedule water mains replacement activities with limited financial resources in a determined planning period. It considers the impact of economies of scale and roadwork coordination on total capital cost.

Author/s	Main Features
Qi and Chang (2011)	Use system dynamics simulation to develop an urban water demand estimation model for both long- and short-term periods. System dynamics method enables them to take into account the complexity of interactions among effective variables in socio-economics, macro-economics, population and water demand to forecast the domestic water demand in both economic boom and downturn environment scenarios. Finally, the model is validated by implementation in Manatee Country, Florida.
Rehan et al. (2011)	Demonstrate the application of a system dynamic modelling approach in the development of integrated water and wastewater infrastructure network asset management. The simplicity of defining causal loop diagrams in an SD model helps asset managers and modelers to define the interconnections and feedback loops among the physical inventory, financial and user sectors. This is the first known application of an SD simulation tool in water and sewer pipeline infrastructure asset management. The model developed in this study can be employed as a dynamic framework for urban water network life-cycle management.
Zarghami and Akbariyeh (2012)	Model an urban water supply system, including water supply resources, potential sources of demand for water resources, and management tools (wastewater reuse and recycling, inter-basin water transfer, water price and conservation tools), using a system dynamics approach. The water system of the city of Tabriz, Iran, is considered as the case study.
Salman et al. (2013)	An optimized scheduling and decision-making model is developed for rehabilitation activities performed within available budgets and planning time. Unsupervised Neural Networks (UNNs) and Mixed-Integer Nonlinear Programming (MINLP) are using to build a two-stage model. Several sub-models for selecting rehabilitation methods, network performance assessment

Author/s	Main Features
	(reliability and criticality analysis), and rehabilitation-work grouping are also utilized. Uses of the proposed model are limited to water distribution network with series and parallel pipe connections.
Rehan et al. (2013)	Develop detailed causal loop diagrams and a decision-support-system tool based on system dynamics method, to perform self-financially sustainable asset management of an urban watermain network. The inter-relationships among the water infrastructure network components are taken into account to trace the network performance along its service life. A series of financial strategies are analyzed, including pay-as-you-go, capital reserving, and borrowing.
Roshani and Filion (2014)	Develop an event-based approach to optimally schedule watermain capital works (rehabilitation and replacement) in water distribution networks. The optimization problem is defined as a multi-objective problem of minimizing both capital and operational costs by seeking the best scheduling to rehabilitate pipes. The Non-Dominated Sorting Genetic Algorithm (NSGA-II) is employed for the optimization process. The model is implemented in Fairfield water network.
Scholten et al. (2014)	Multiple criteria, comprised of system reliability, cost, and intergenerational equity, are taken into consideration to select a robust rehabilitation long-term strategy for a water distribution network. Multi-criteria decision analysis and scenario planning are used to evaluate strategic rehabilitation alternatives under four different socio-economic circumstances: no change (Status Quo), massive growth (Boom), qualitative growth (Quality of life), and decline (Doom). The highest performance of the network is shown to occur under all four future scenarios, with annual pipe replacement of 1.5-2%. The water network data of four utilities in Switzerland is utilized for model implementation.

Author/s	Main Features
Shadpour et al. (2015)	Re-model the complex dynamic behaviour of a financially sustainable water and wastewater network model presented by Rehan et al. (2012), using nonlinear algebraic differential equations (DAEs). They found that the spurious oscillations in the system dynamics model developed in STELLA occur due to numerical aberrations, and were thus able to eradicate them.
Rehan et al. (2015)	The model proposed in Rehan et al. (2013) is verified in this study using data from several medium-sized cities located in Ontario, Canada.
Li et al. (2015)	Demonstrate that utilizing a replacement decision optimization method for group scheduling (RDOM-GS) can improve replacement planning significantly and reduce costs and service interruptions. The Pareto optimality analysis, performed on a medium-sized water network in Australia with regard to four different scenarios, verifies the statement, with an approximate reduction of 10% and 25% in capital expenditure and service interruption time, respectively.
Ganjidoost (2016)	Study the integration of water distribution and wastewater collection networks using a system dynamics modelling approach to simulate interaction between the system infrastructure, socio-political sector, and financial analysis.

Appendix B

Heuristic Optimization Algorithm for Grouping Water Segments Coupling of Genetic Algorithm (GA) and K-Means Clustering Method

Objective: cluster *n* pipe segments into *k* work-packages to maximize the total benefit/cost ratio

Define

$P = \{P_1, \ldots, P_{nP}\}$: set of solutions for clustering *n* segments (GA population)

nP: Population size

$S = \{s_1, s_2, \ldots, s_N\}$, set of segments, s_i: *segment i*

$P_i = \{l(s) \mid s = 1, 2, \ldots, N\}$: set of cluster labels of S (Chromosome)

nG: number of generations

nSG: number of successive generations without any improvement in solution

nG^{max}: maximum number of generations

nSG^{max}: maximum number of successive generations without any improvement in solution

F_C: crossover fraction

P_M: mutation probability

nE: number of elite selections

WPB_i: benefit of work-package *i*

WPC_i: cost of work-package *i*

BCR^{tot}: total benefit/cost ratio of work-packages

```
/* CREATE INITIAL GENERATION OF SOLUTIONS */
for i=1 to nP
    for j=1 to N
        stop = 0
        while stop is 0
            m ← random integer number from [1, N]
            if adding segment j to work-package k satisfies work-packaging constraints
                $P_i[j] = l_j$ ← k (assign segment j to work-package k)
                stop ← 1
            end
        end
    end
    $\sum_{i=1}^{C} WPB_i$ ← Calculate the total benefit of generated work-packages using equation (4-2)
    $\sum_{i=1}^{C} WPC_i$ ← Calculate the total cost of generated work-packages using equation (4-11)
    $BCR^{tot}$ ← Evaluate $P_i$ according to fitness function (equation 4-16)
    Sort P in descending order of $BCR^{tot}$
end

While $nG \le nG^{max}$ AND $nSG \le nSG^{max}$ (termination condition not met)

    /* CREATE NEXT GENERATION OF SOLUTIONS */
    copy nE best solutions into the next generation (elite preservation)
    select random solutions as parents via Rank Proportionate Selection (Parent selection)
    stop = 0
    while stop is 0
        Form offspring's solution via scattered crossover (Crossover operation)
        if offspring solution satisfies work-packaging constraints
            Add offspring solution to the new generation
```

```
        stop ← 1
    end
end

stop = 0
while stop is 0
    if (rand (0.0, 1.0) < $P_M$)
        Mutate the offspring's solutions (Mutation operation)
    end
    if offspring solution satisfies work-packaging constraints
        add offspring solution to the new generation
        stop ← 1
    end
end
$\sum_{i=1}^{C} WPB_i$ ← Calculate the total benefit of generated work-packages using equation (4-2)
$\sum_{i=1}^{C} WPC_i$ ← Calculate the total cost of generated work-packages using equation (4-11)
$BCR^{tot}$ ← Evaluate $P_i$ according to fitness function (equation 4-16)
Sort P in descending order of $BCR^{tot}$

/* K-MEAN CLUSTERING TO IMPROVE SOLUTION Pi */
for i=1 to nP
    K-Means ($P_i$, $k_i$)
        Input:
            $S = \{s_1, s_2, \ldots, s_N\}$ (set of segments initially clustered into $k_i$ clusters)
            $k_i$: number of clusters in solution $P_i$
            $P_i = \{l(s) \mid s = 1, 2, \ldots, N\}$ (set of cluster labels of S, $l(s_i) \in \{1, \ldots, k_i\}$ )
            $C_i = \{c_1, c_2, \ldots, c_{k_i}\}$          (set of clusters in solution $P_i$)
```

```
            Output: re-organize N segments into $k_i$ work-packages to improve $BCR^{tot}$
                $P_i' = \{l'(s) \mid s = 1, 2, \ldots, N\}$ (improved set of cluster labels of S, $l'(s_i) \in \{1, \ldots, k_i\}$ )
                $C_i' = \{c_1', c_2', \ldots, c_{k_i}'\}$            (improved set of clusters in solution $P_i$)

        if (i % INT(nP/10) == 0  AND  Number of generations%10==0)
            iteration ← 100 (Hard searching)
        else
            iteration ← 3 (Soft searching)
        end

        while (number of iterations without improvement > iteration)
            Random selection of $s_j \in c_m$
            $BCR^{tot}_{updated} = 0$
            for $\forall c_k \in C_i, c_k \neq c_m$
                $BCR^{tot}_{New} \leftarrow$ calculate $BCR^{tot}$ if $s_j$ join $c_k$
                $\Delta BCR^{tot} \leftarrow BCR^{tot}_{New} - BCR^{tot}$
                if $\Delta BCR^{tot} > BCR^{tot}_{updated}$
                    $f \leftarrow k$
                    $BCR^{tot}_{updated} \leftarrow \Delta BCR^{tot}$
                end
            end
            move $s_j$ from $c_m$ to $c_f$
            $C_i' = \{c_1', c_2', \ldots, c_{k_i}'\} \leftarrow C_i = \{c_1, c_2, \ldots, c_{k_i}\}$ (update clusters)
            $\sum_{i=1}^{C} WPB_i \leftarrow$ Calculate total benefit of generated work-packages using equation (4-2)
```

```
            $\sum_{i=1}^{C} WPC_i$ ← Calculate the total cost of generated work-packages using equation (4-11)
            $BCR^{tot}$ ← Evaluate $P_i$ according to fitness function (equation 4-16)
        end
    end
end
Sort P in descending order of $BCR^{tot}$
Output $P_1$ as the best solution for clustering $n$ segments into work-packages (i.e., clusters)
```

Appendix C
Optimal 5-years Capital plans for Grouping Renewal Strategy

C.1. Network A

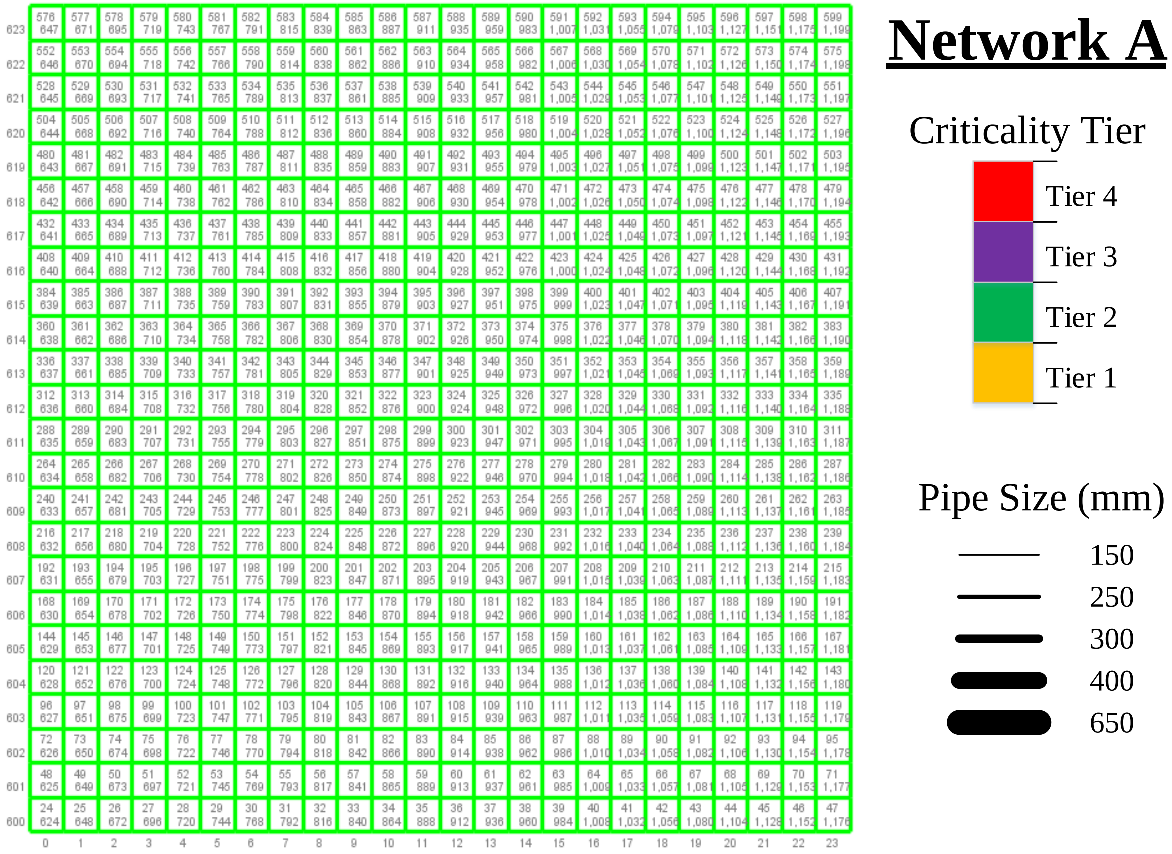

Figure C-1- Criticality-Tier map for Network A

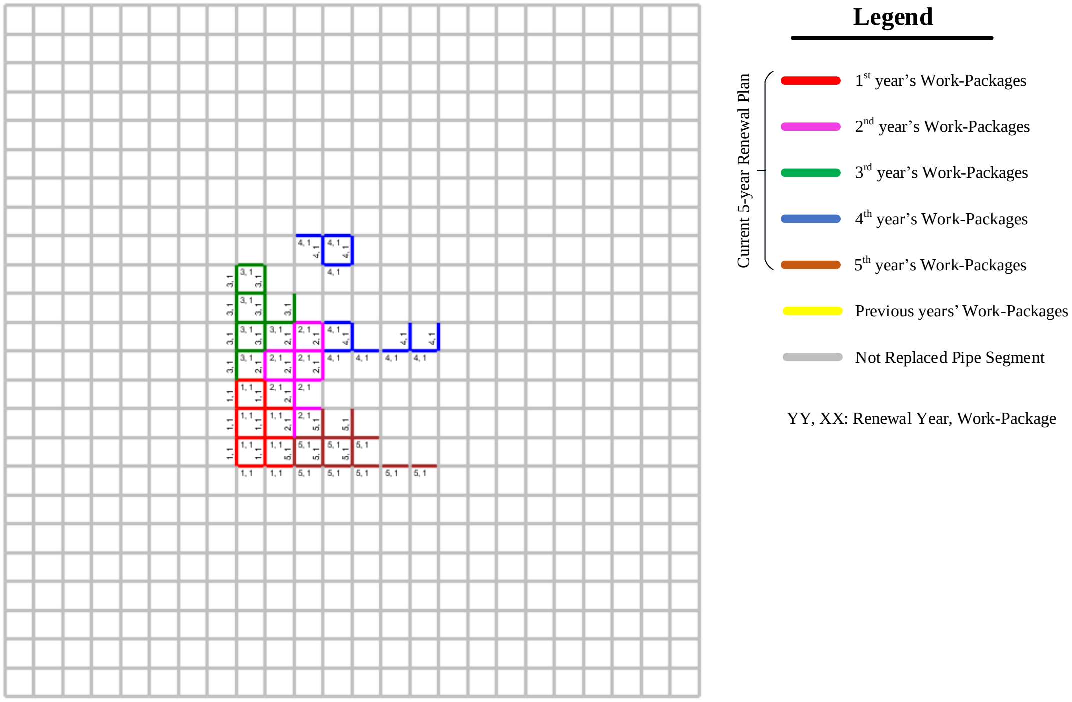

Figure C-2- Optimal grouping renewal plan for years 1-5 of Network A

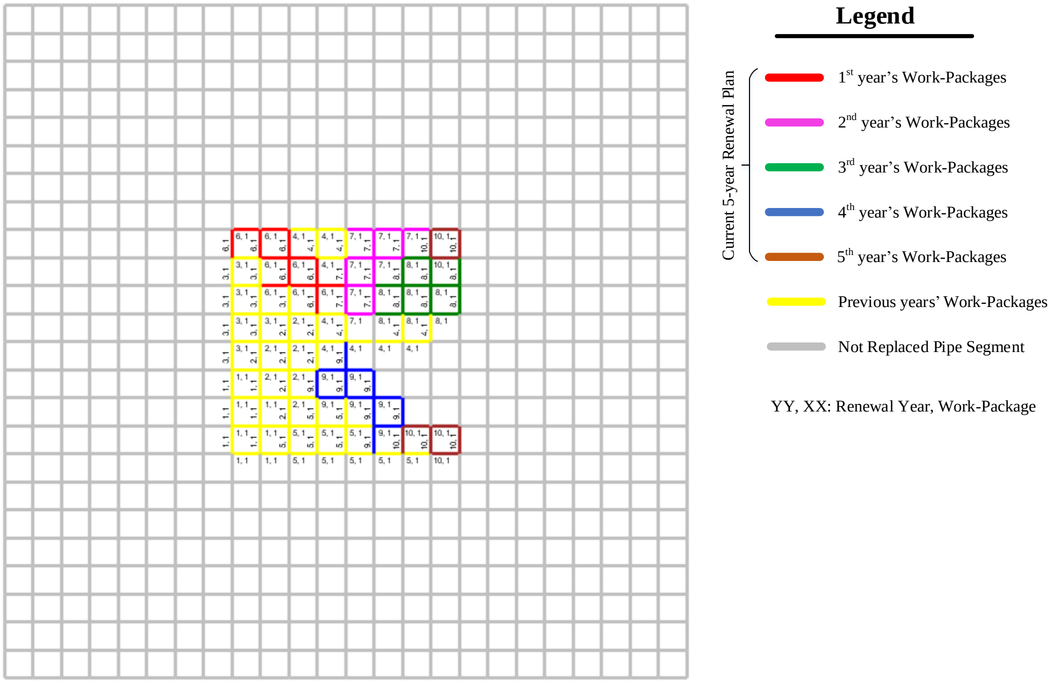

Figure C-3- Optimal grouping renewal plan for years 5-10 of Network A

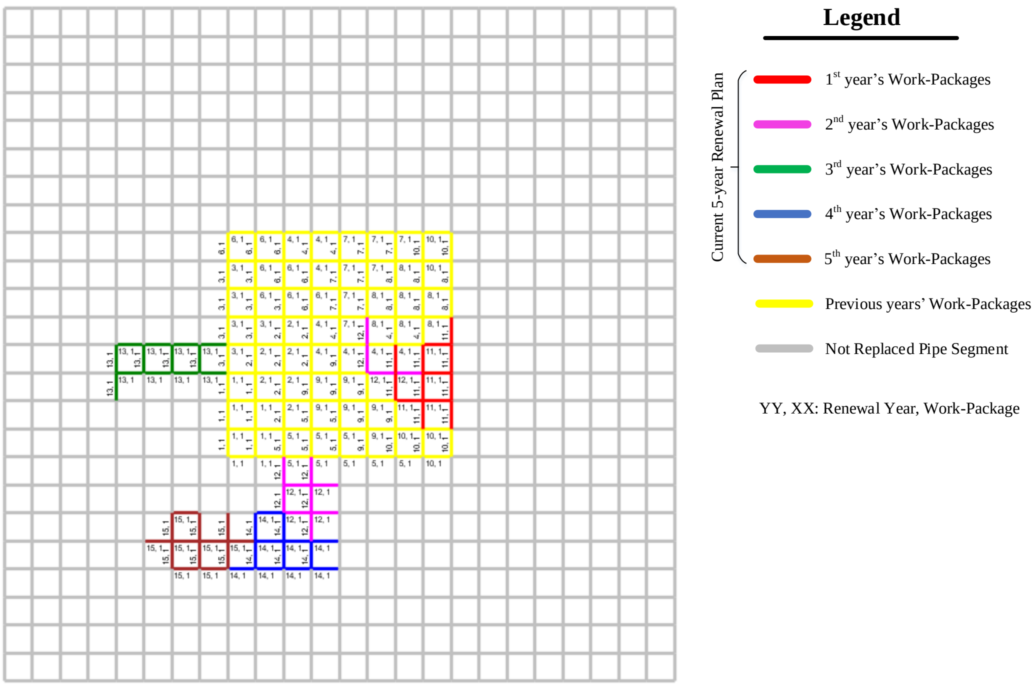

Figure C-4- Optimal grouping renewal plan for years 11-15 of Network A

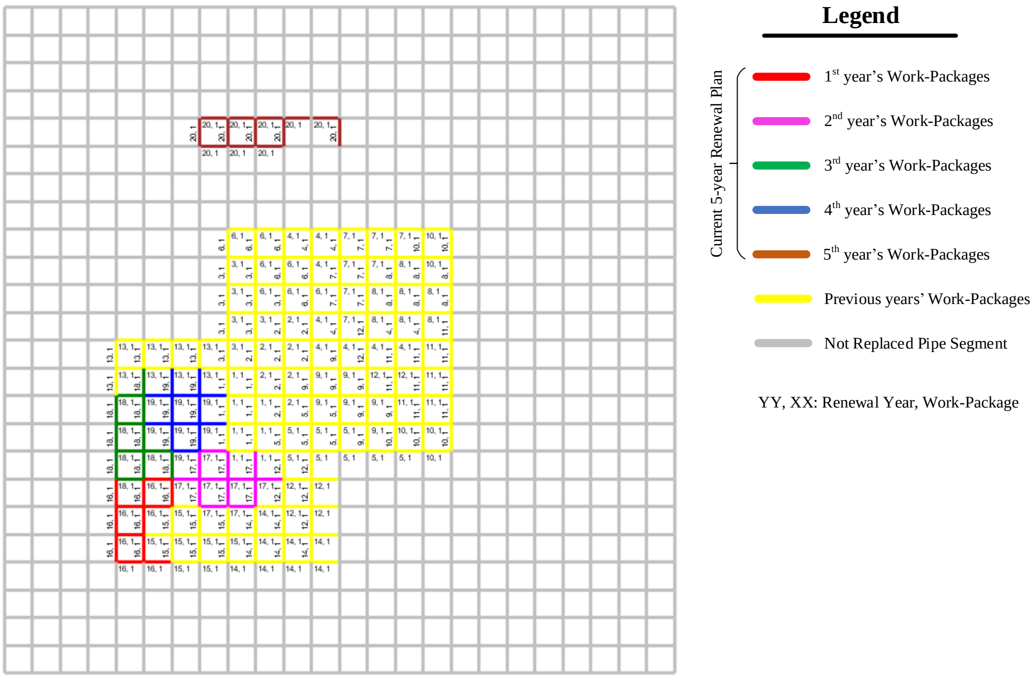

Figure C-5- Optimal grouping renewal plan for years 16-20 of Network A

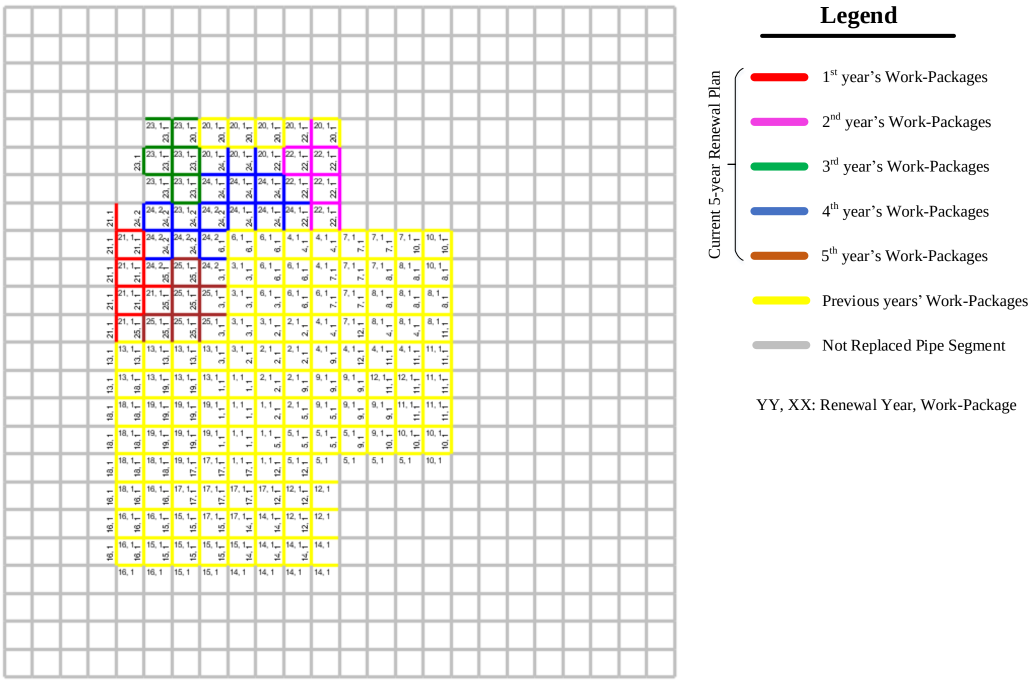

Figure C-6- Optimal grouping renewal plan for years 21-25 of Network A

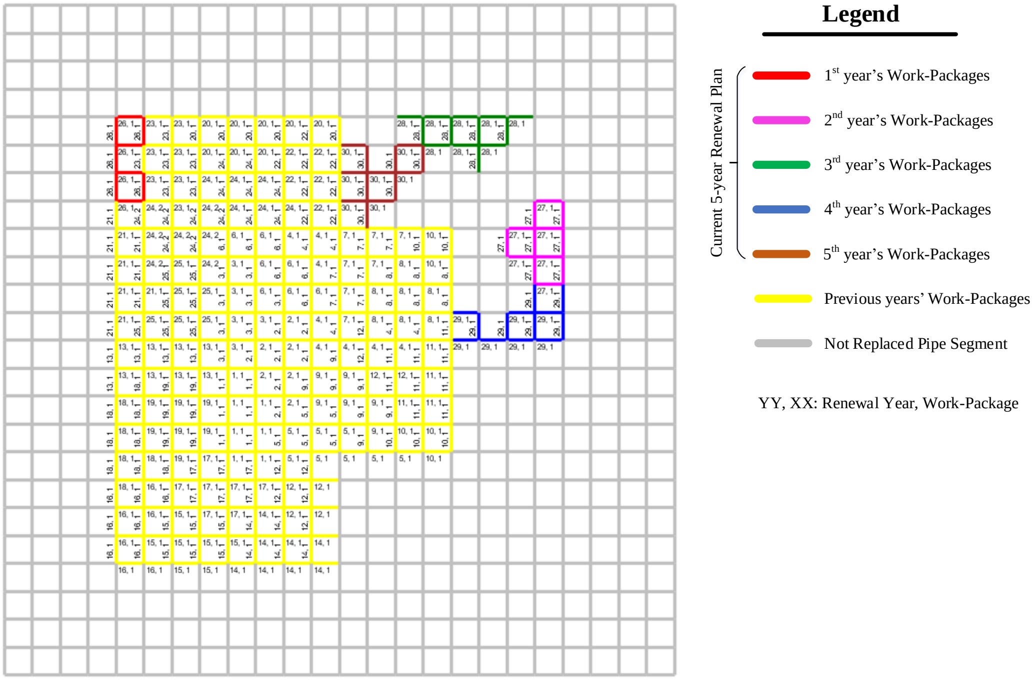

Figure C-7- Optimal grouping renewal plan for years 26-30 of Network A

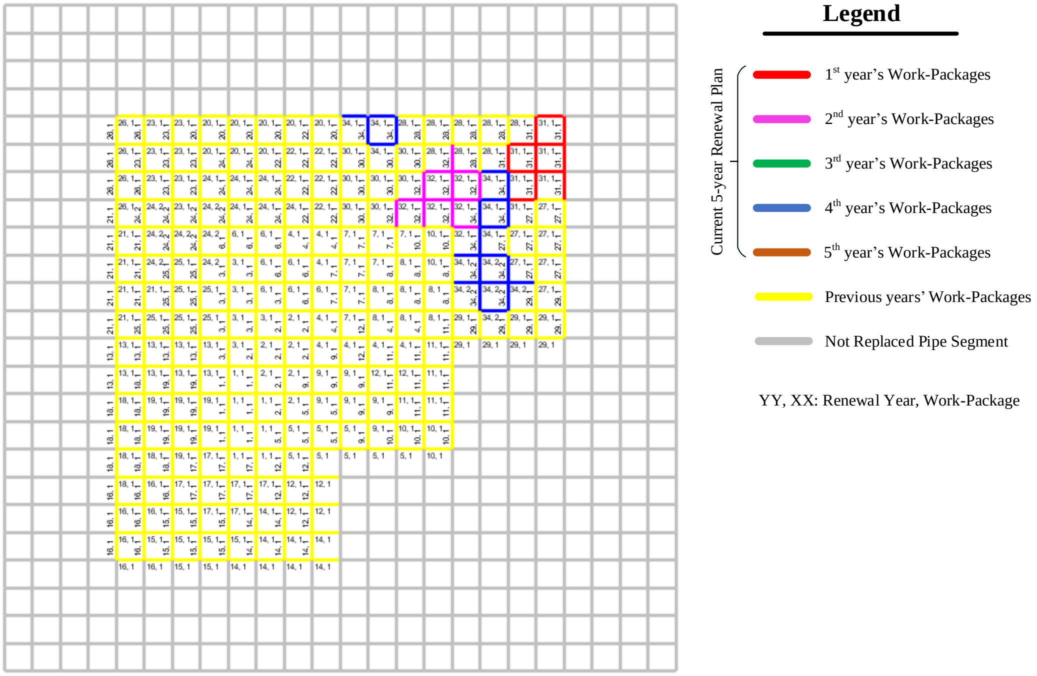

Figure C-8- Optimal grouping renewal plan for years 31-35 of Network A

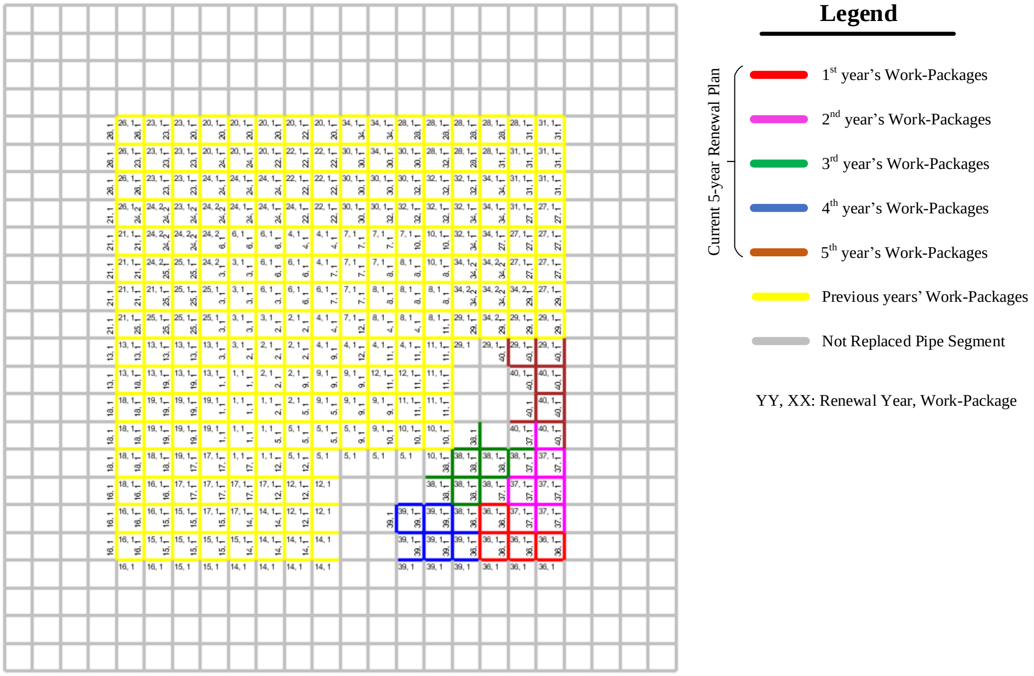

Figure C-9- Optimal grouping renewal plan for years 36-40 of Network A

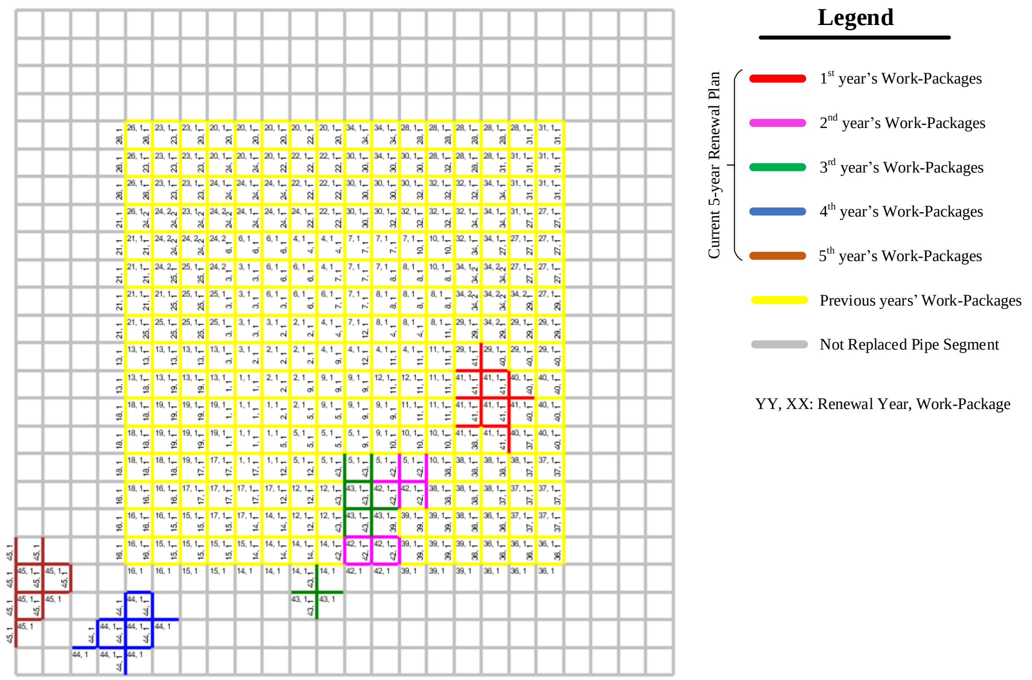

Figure C-10- Optimal grouping renewal plan for years 41-45 of Network A

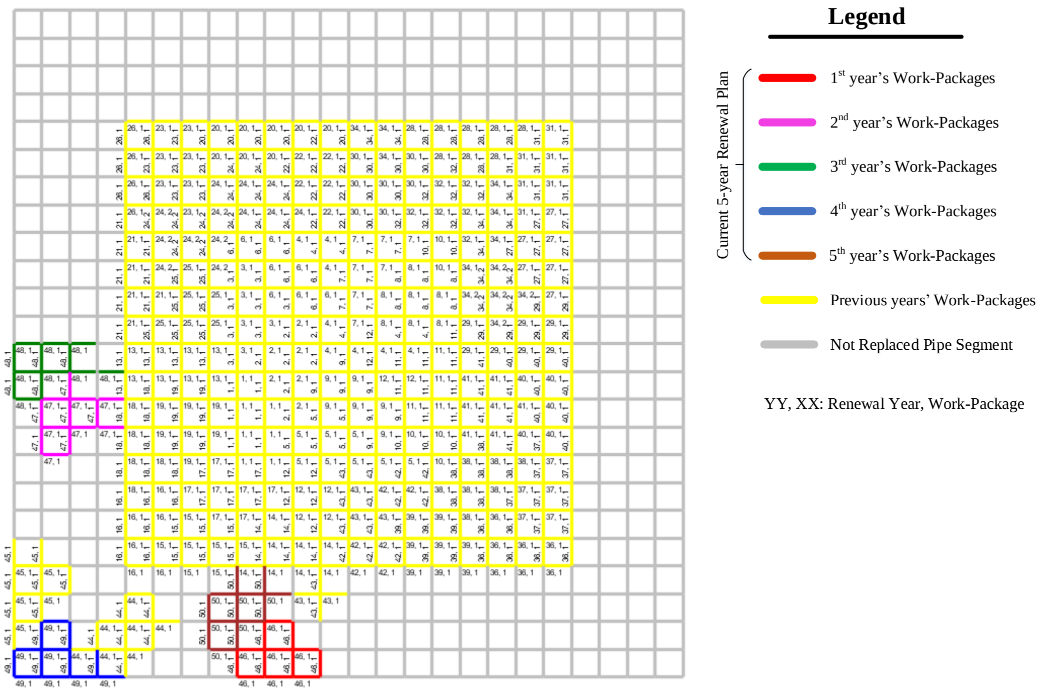

Figure C-11- Optimal grouping renewal plan for years 46-50 of Network A

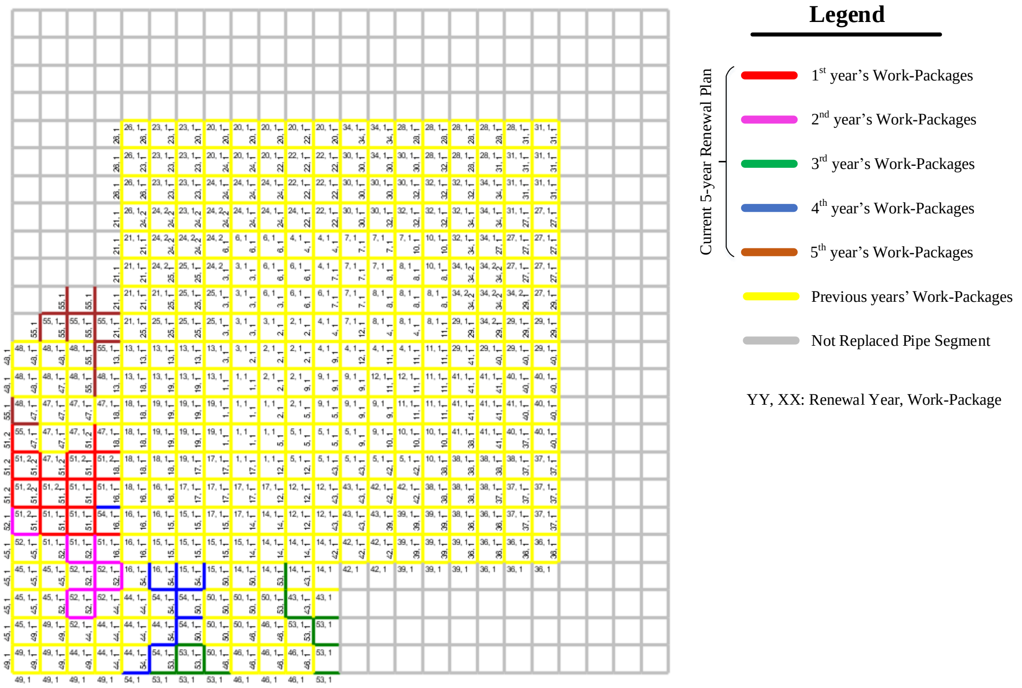

Figure C-12- Optimal grouping renewal plan for years 51-55 of Network A

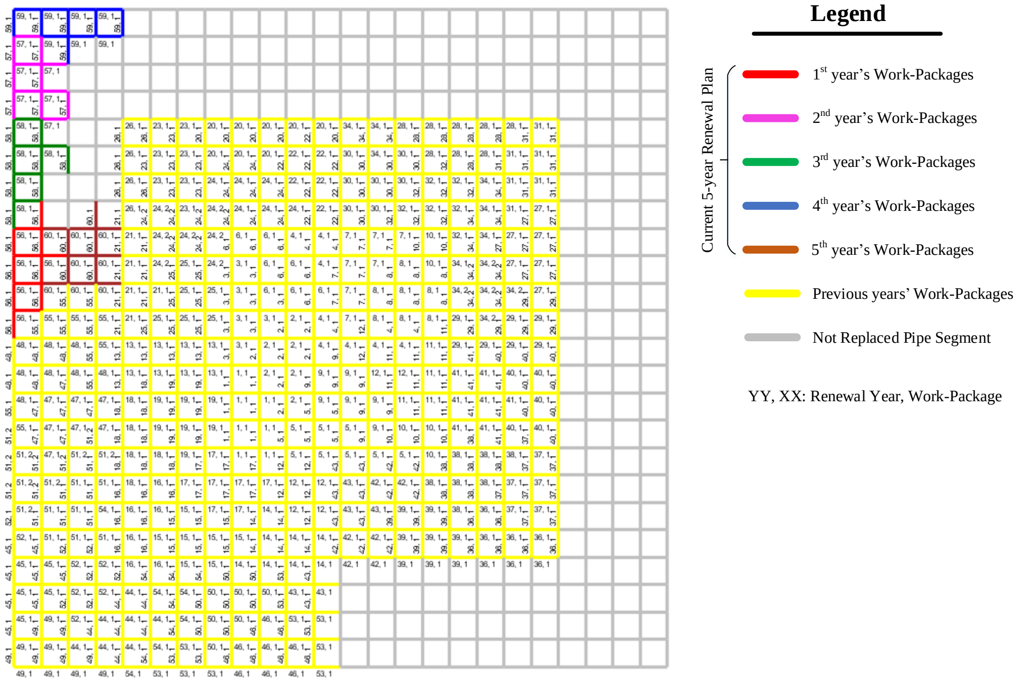

Figure C-13- Optimal grouping renewal plan for years 55-60 of Network A

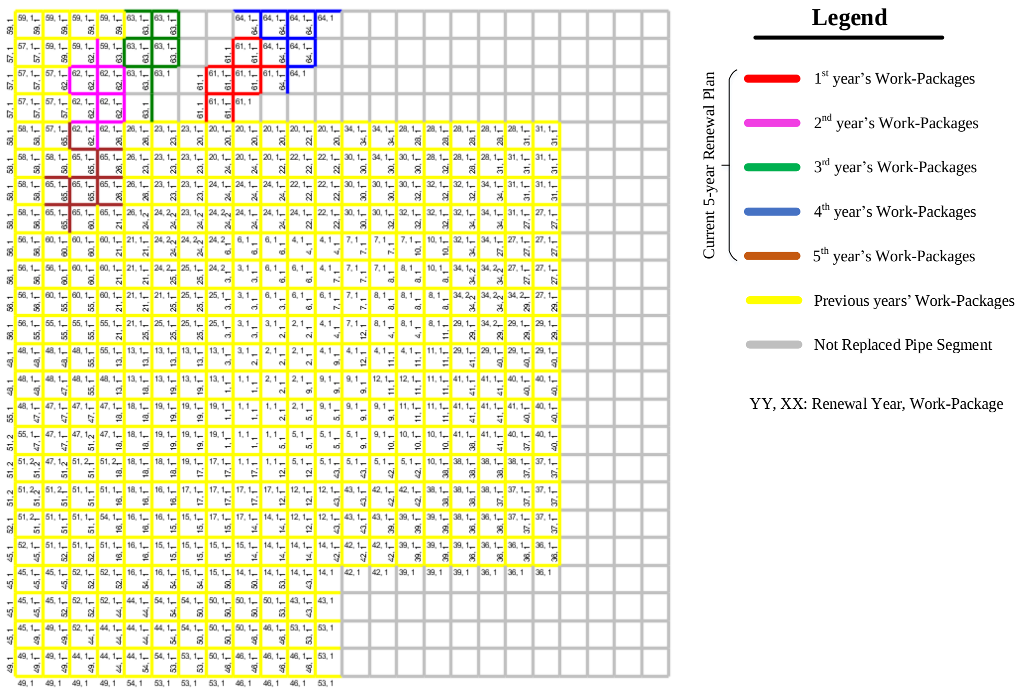

Figure C-14- Optimal grouping renewal plan for years 61-65 of Network A

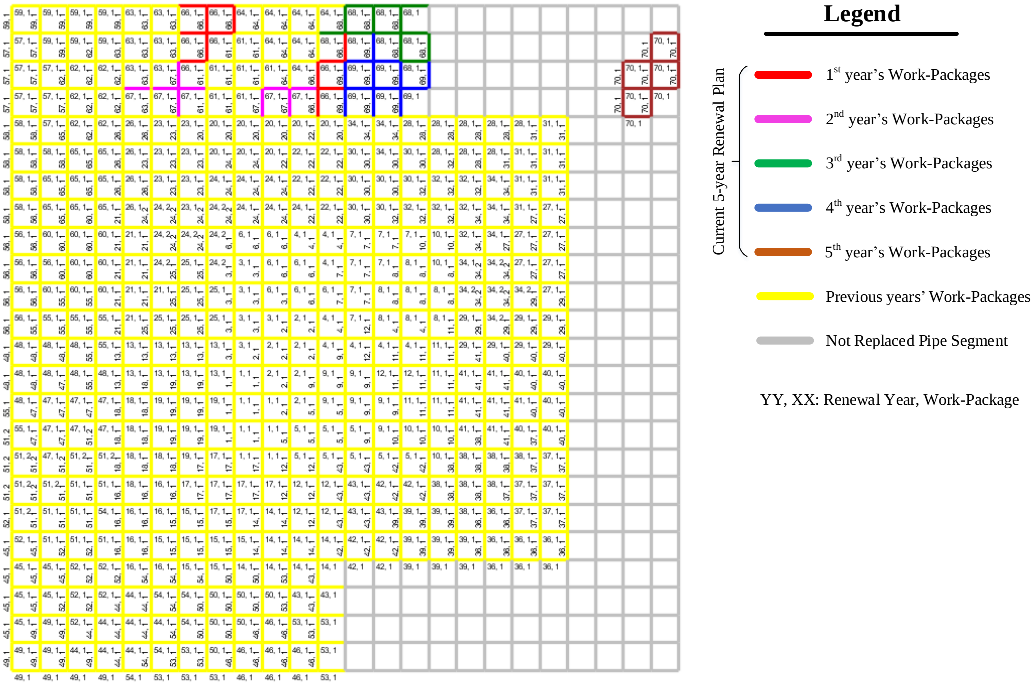

Figure C-15- Optimal grouping renewal plan for years 66-70 of Network A

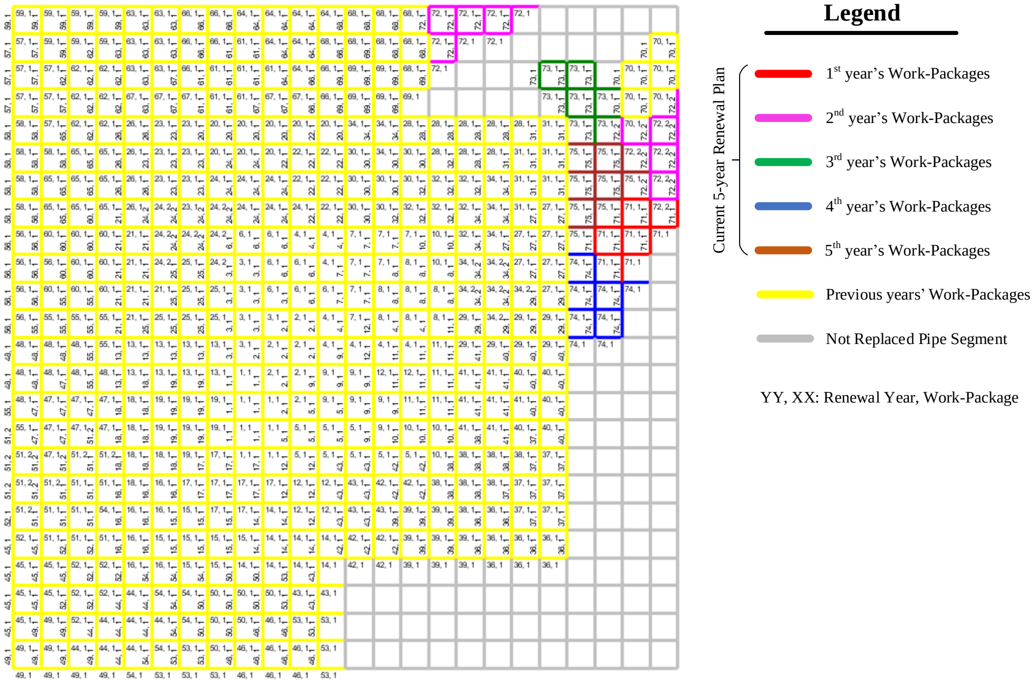

Figure C-16- Optimal grouping renewal plan for years 71-75 of Network A

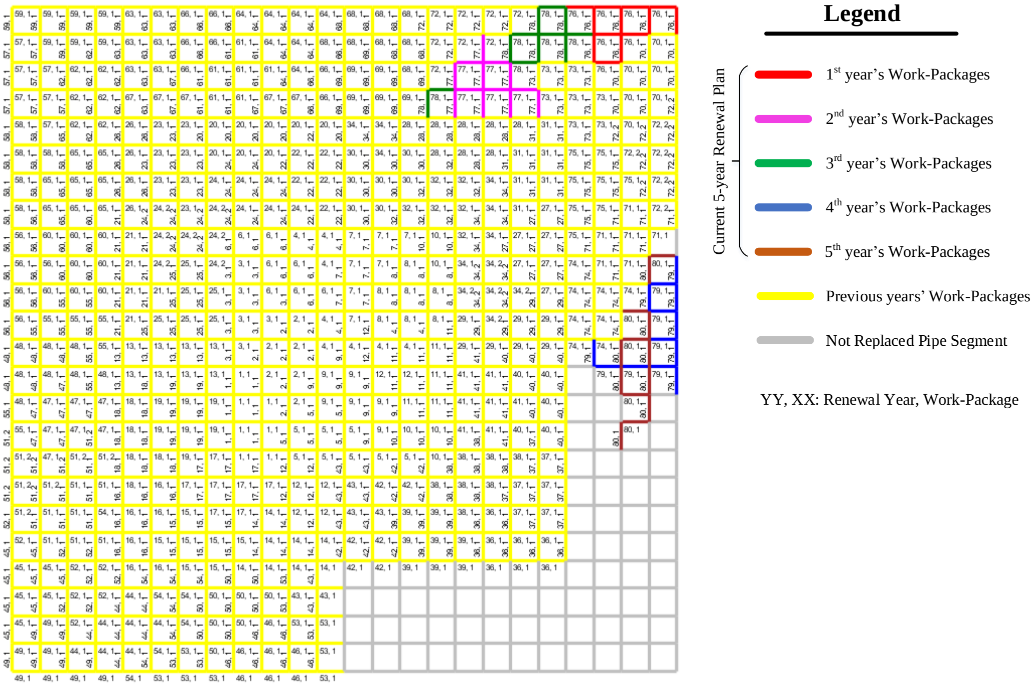

Figure C-17- Optimal grouping renewal plan for years 76-80 of Network A

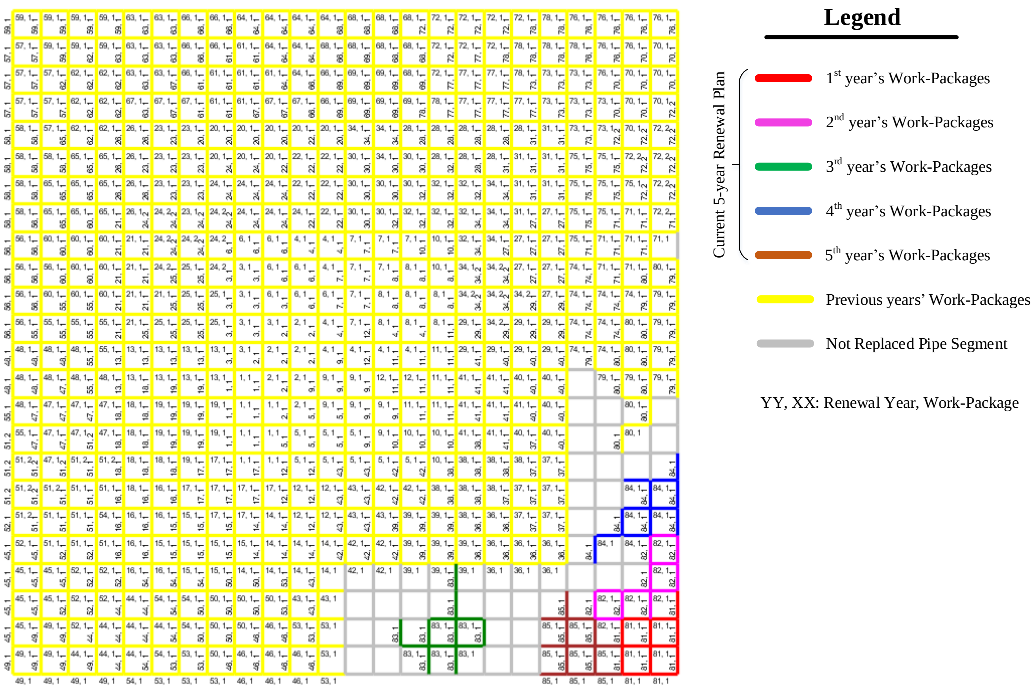

Figure C-18- Optimal grouping renewal plan for years 81-85 of Network A

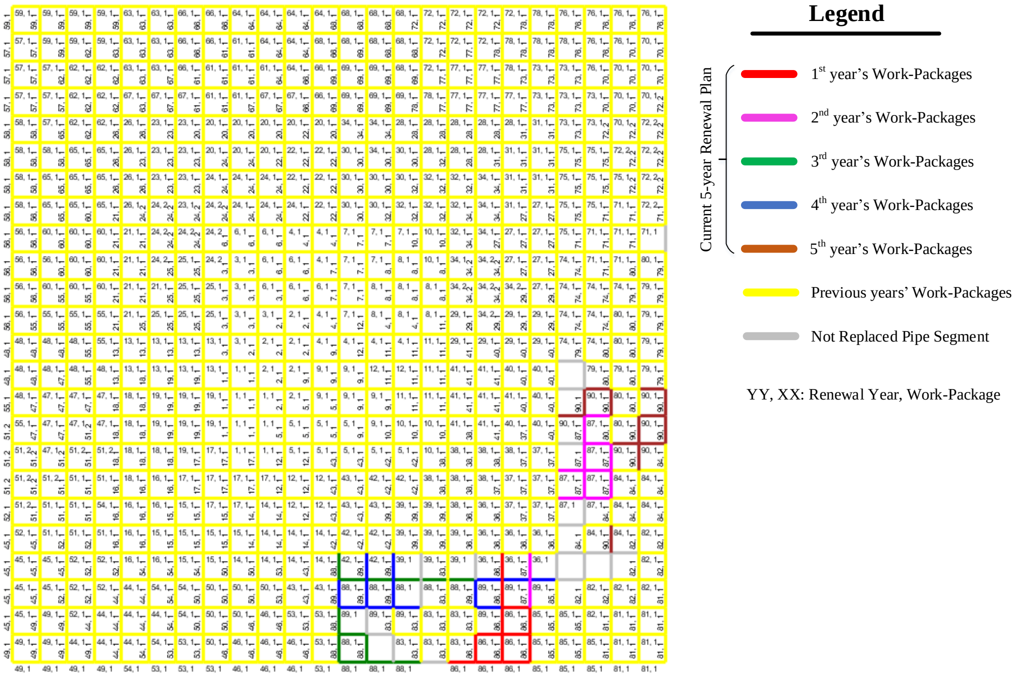

Figure C-19- Optimal grouping renewal plan for years 86-90 of Network A

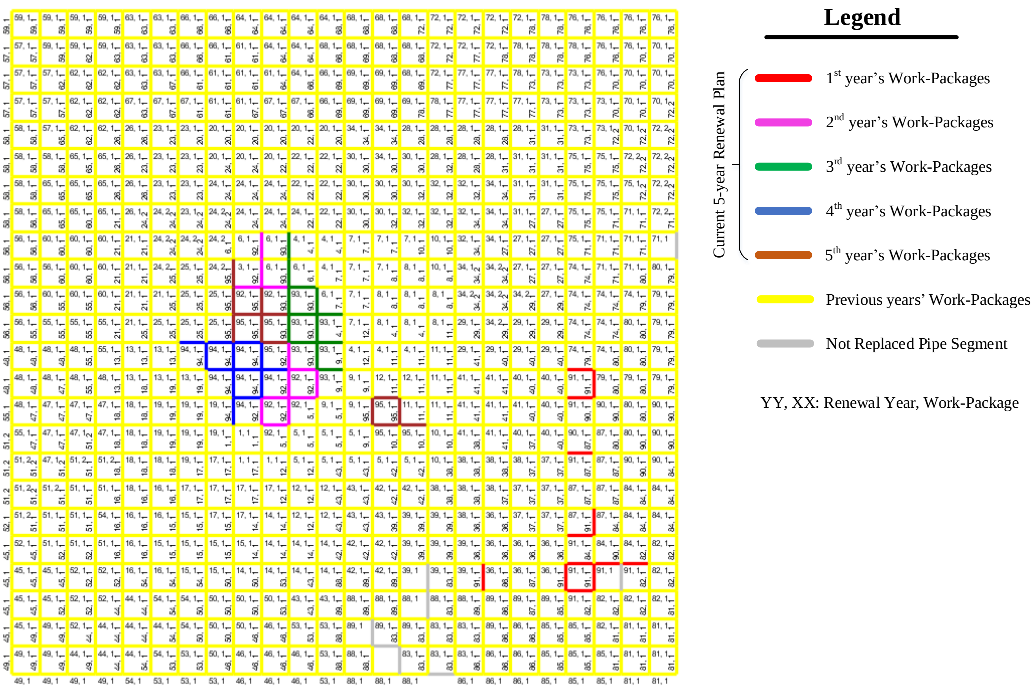

Figure C-20- Optimal grouping renewal plan for years 91-95 of Network A

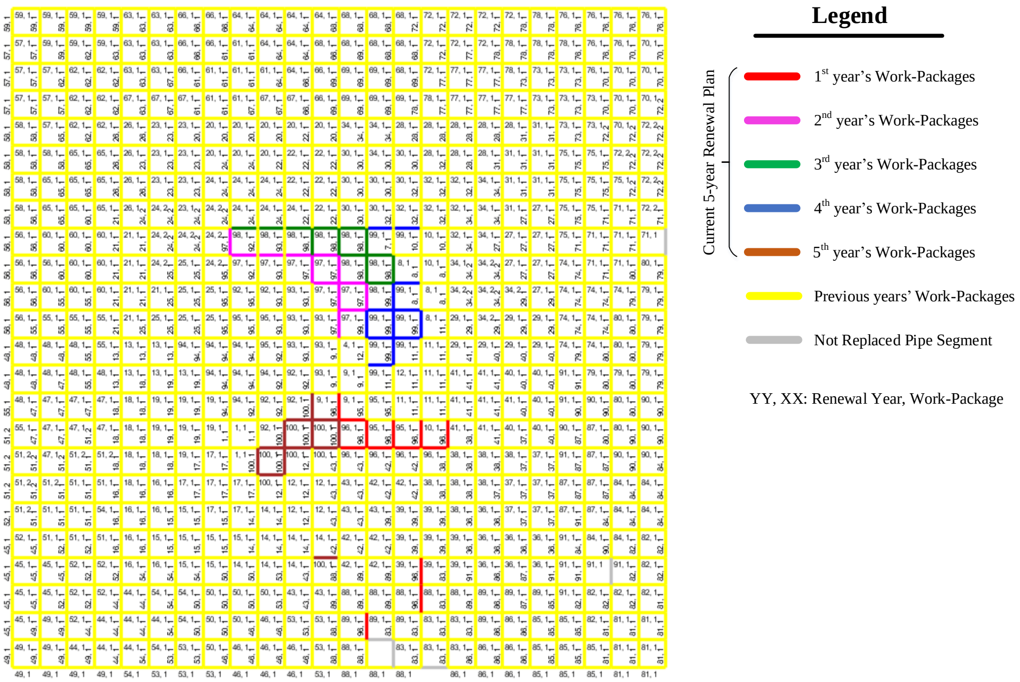

Figure C-21- Optimal grouping renewal plan for years 96-100 of Network A

C.2. Network B

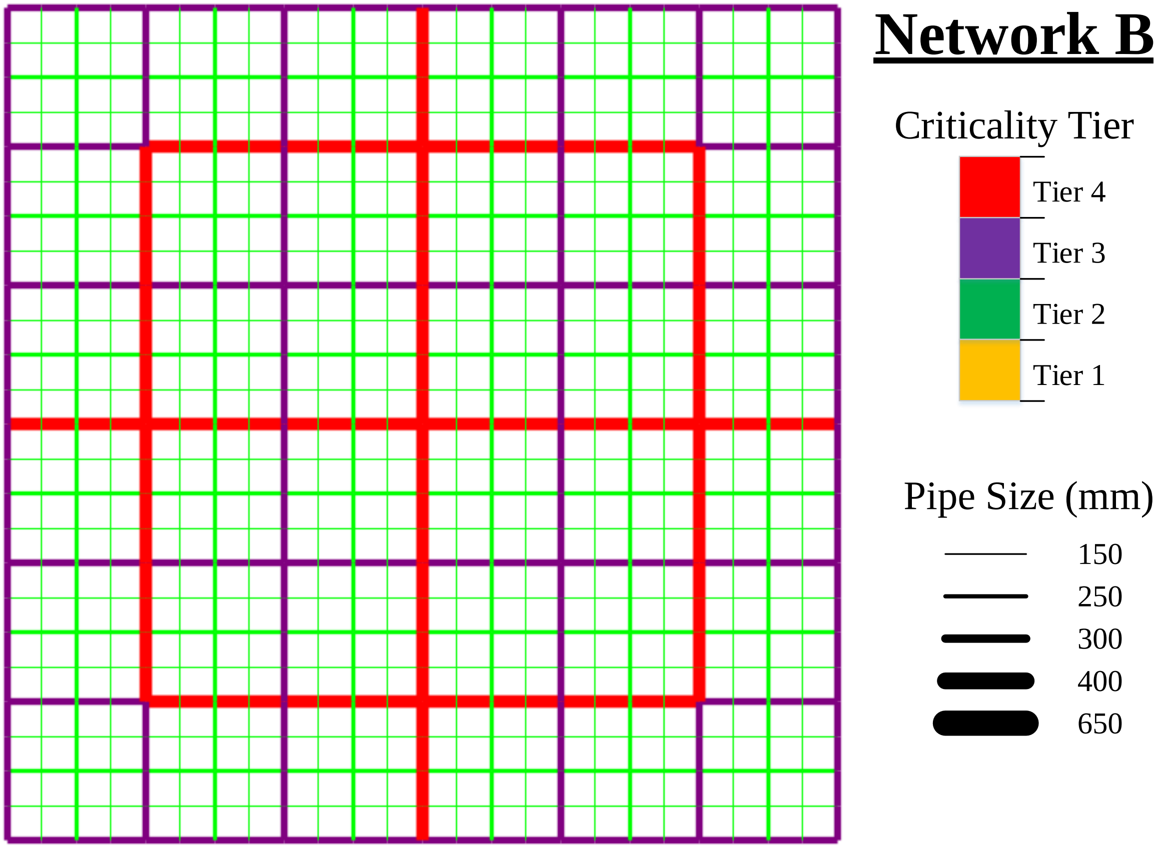

Figure C-22- Criticality-Tier map for Network B

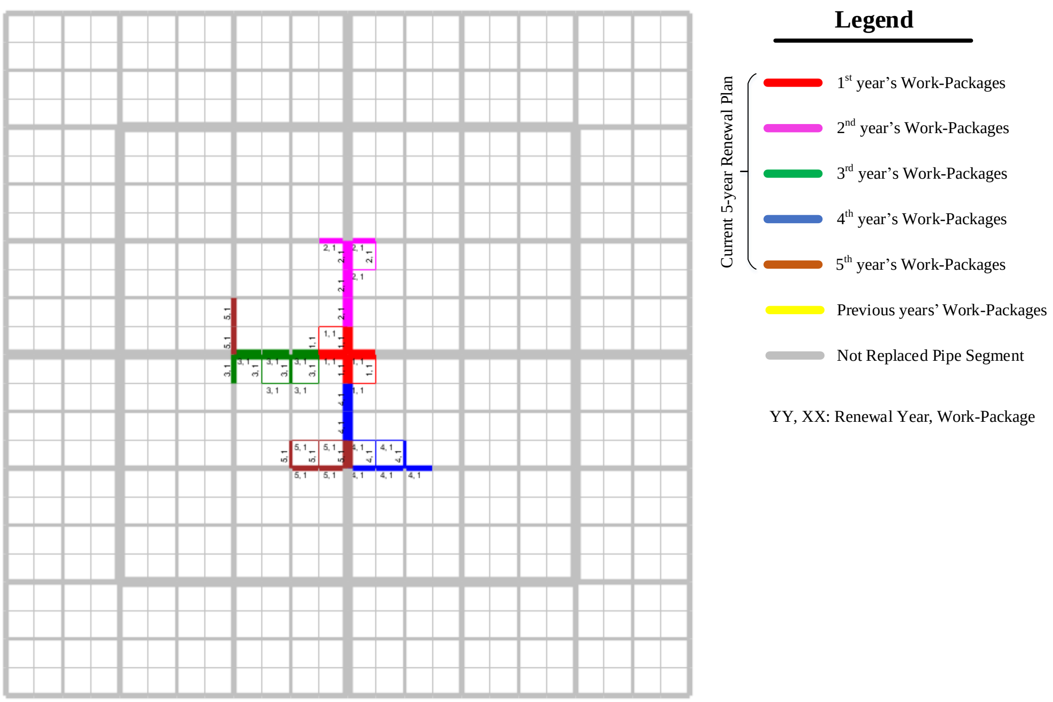

Figure C-23- Optimal grouping renewal plan for years 1-5 of Network B

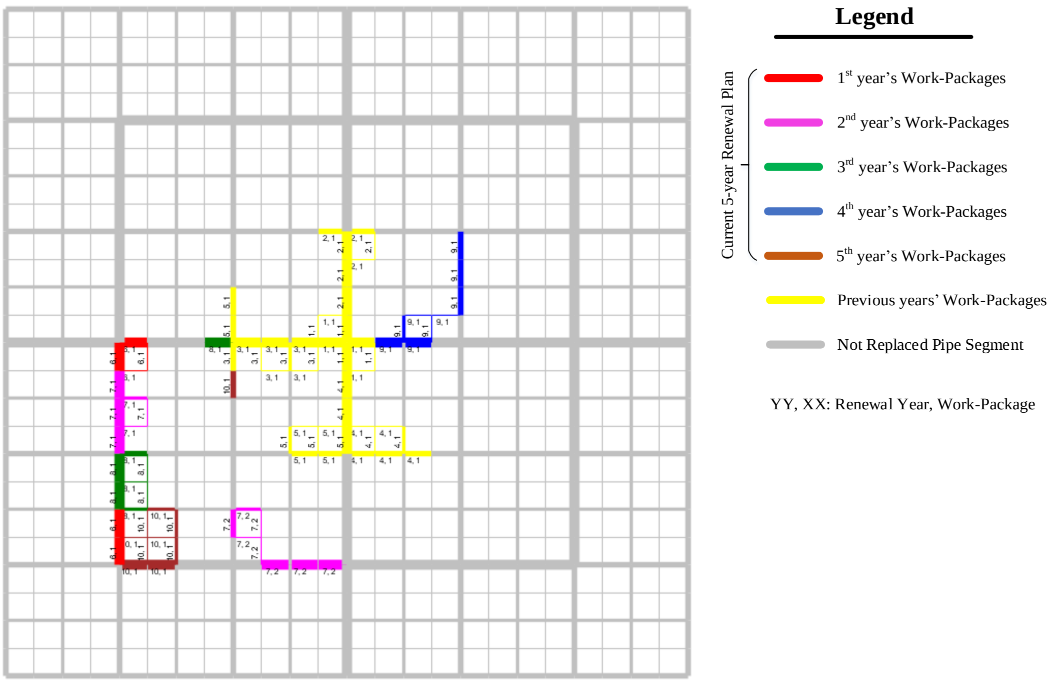

Figure C-24- Optimal grouping renewal plan for years 6-10 of Network B

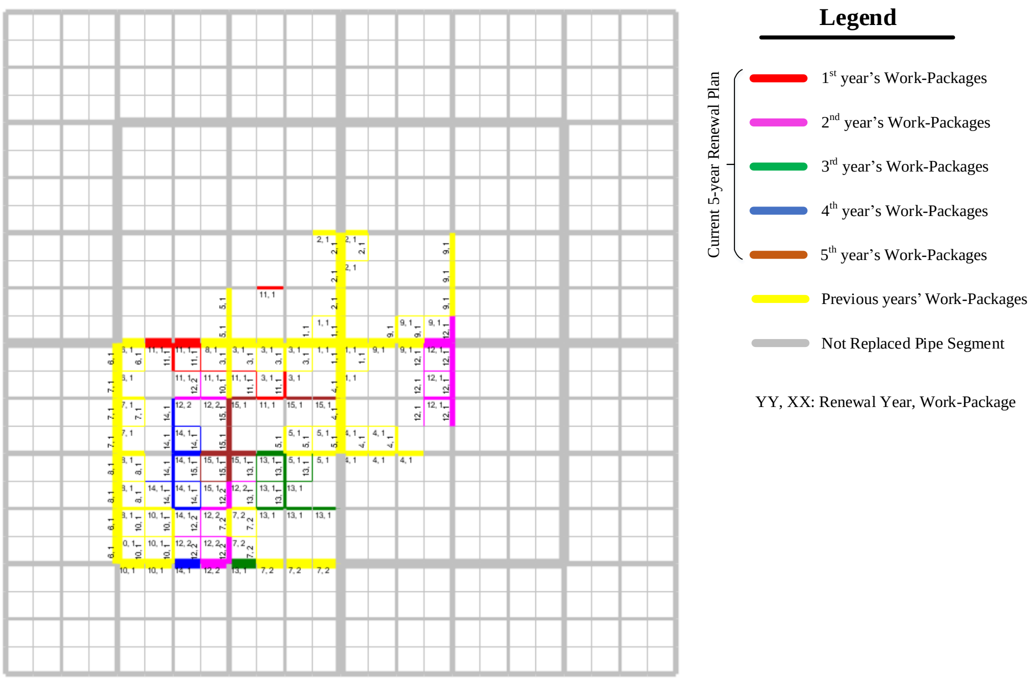

Figure C-25- Optimal grouping renewal plan for years 11-15 of Network B

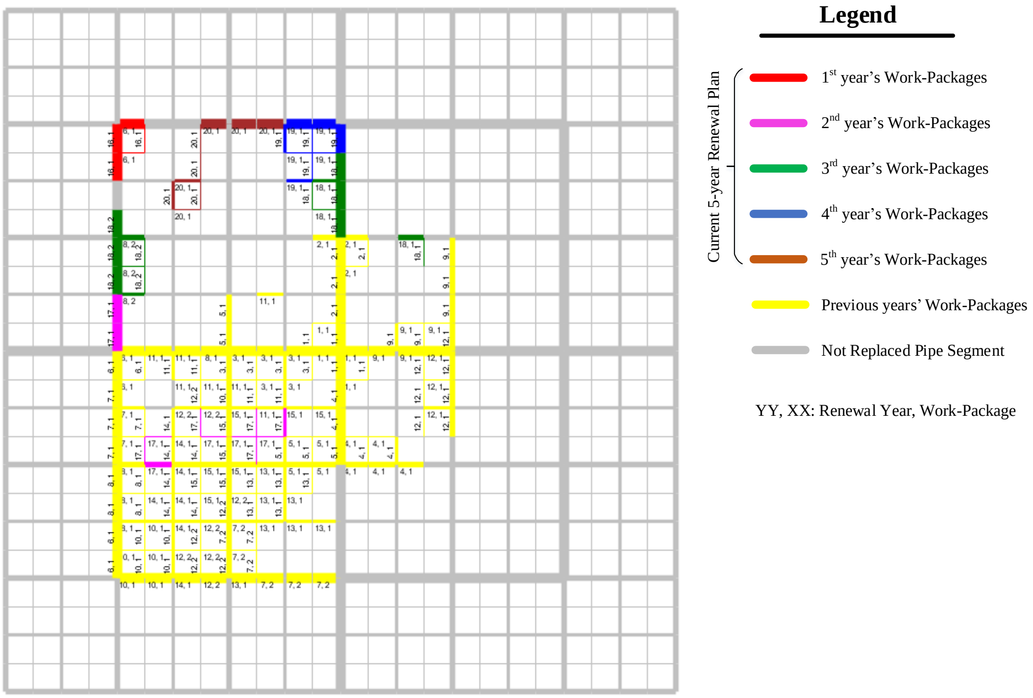

Figure C-26- Optimal grouping renewal plan for years 16-20 of Network B

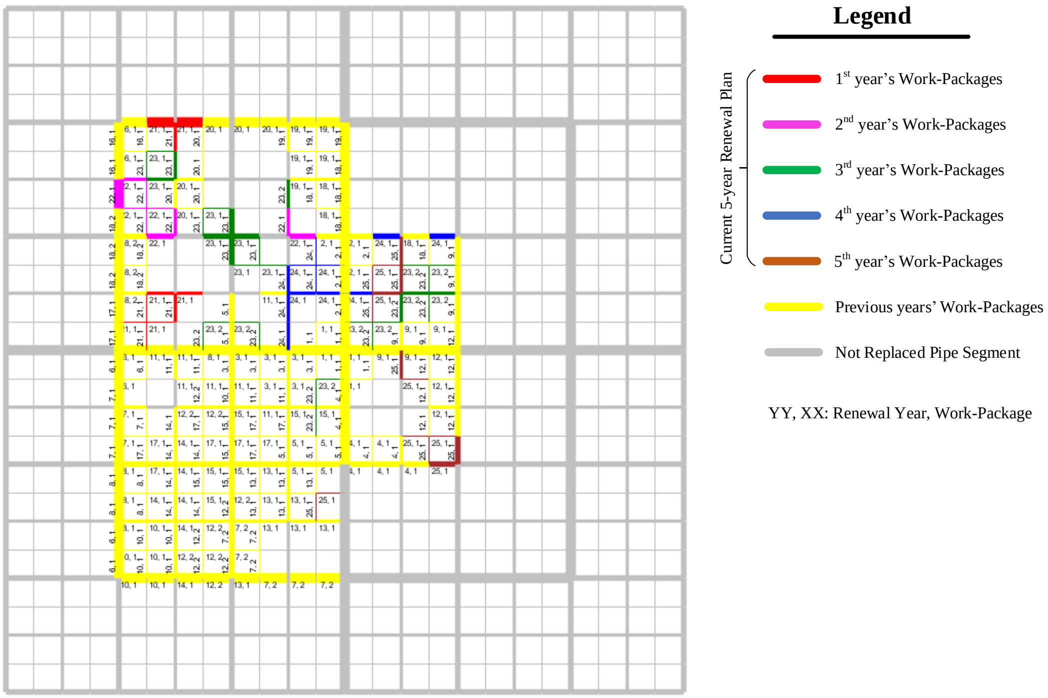

Figure C-27- Optimal grouping renewal plan for years 21-25 of Network B

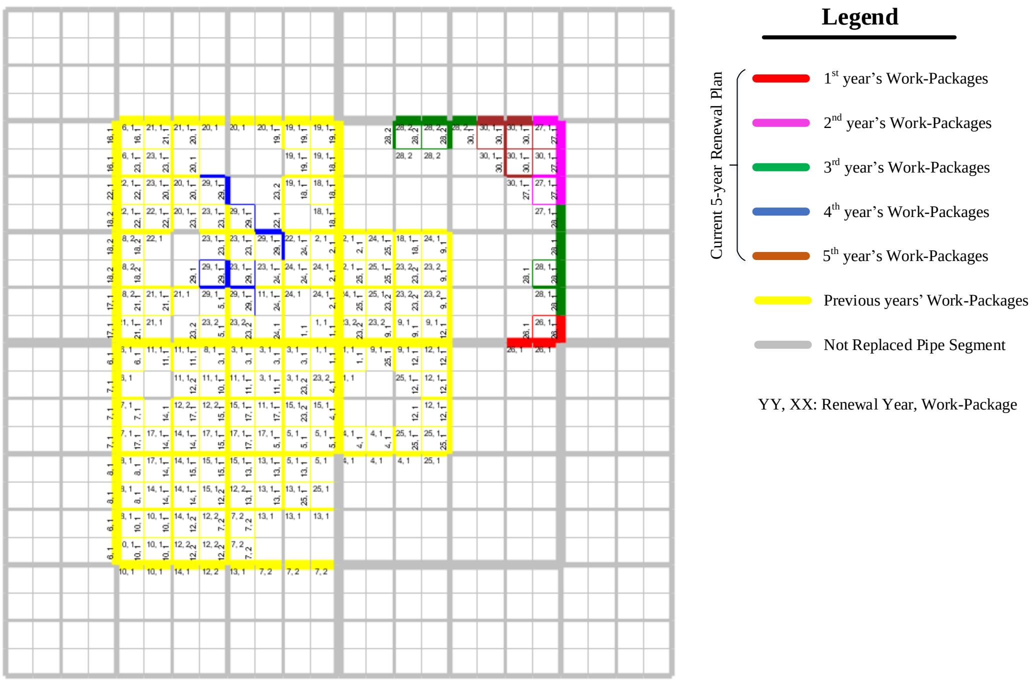

Figure C-28- Optimal grouping renewal plan for years 26-30 of Network B

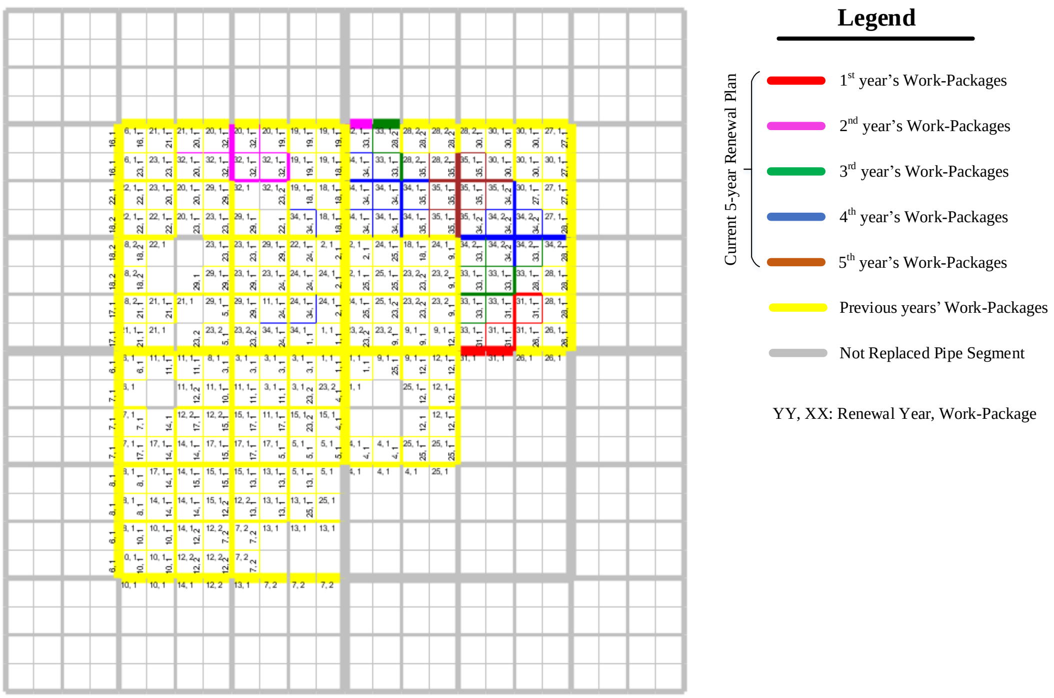

Figure C-29- Optimal grouping renewal plan for years 31-35 of Network B

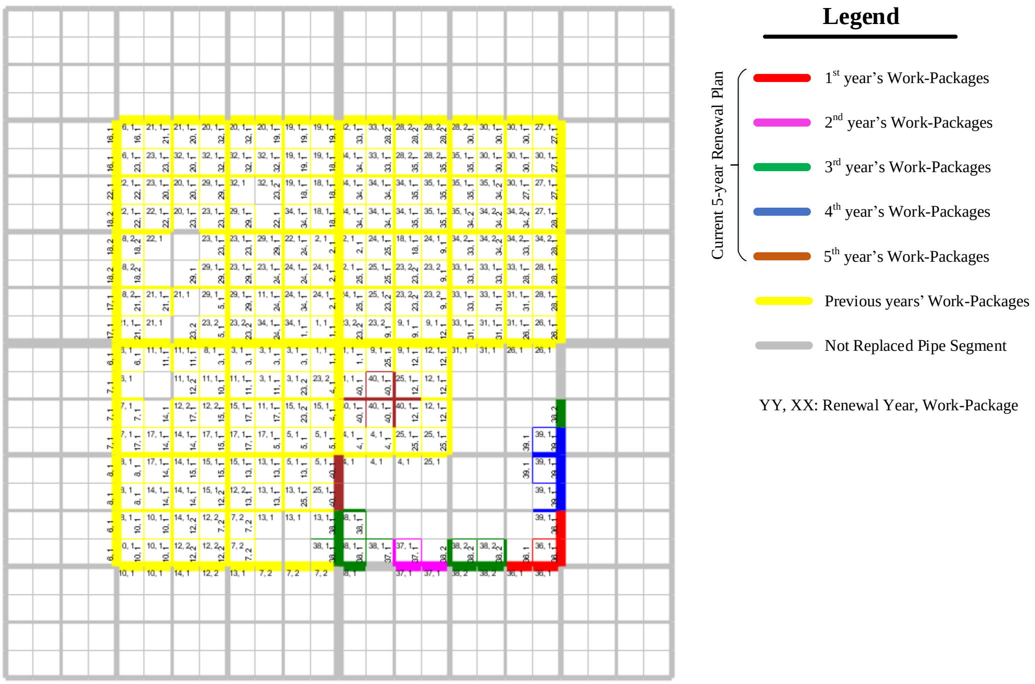

Figure C-30- Optimal grouping renewal plan for years 36-40 of Network B

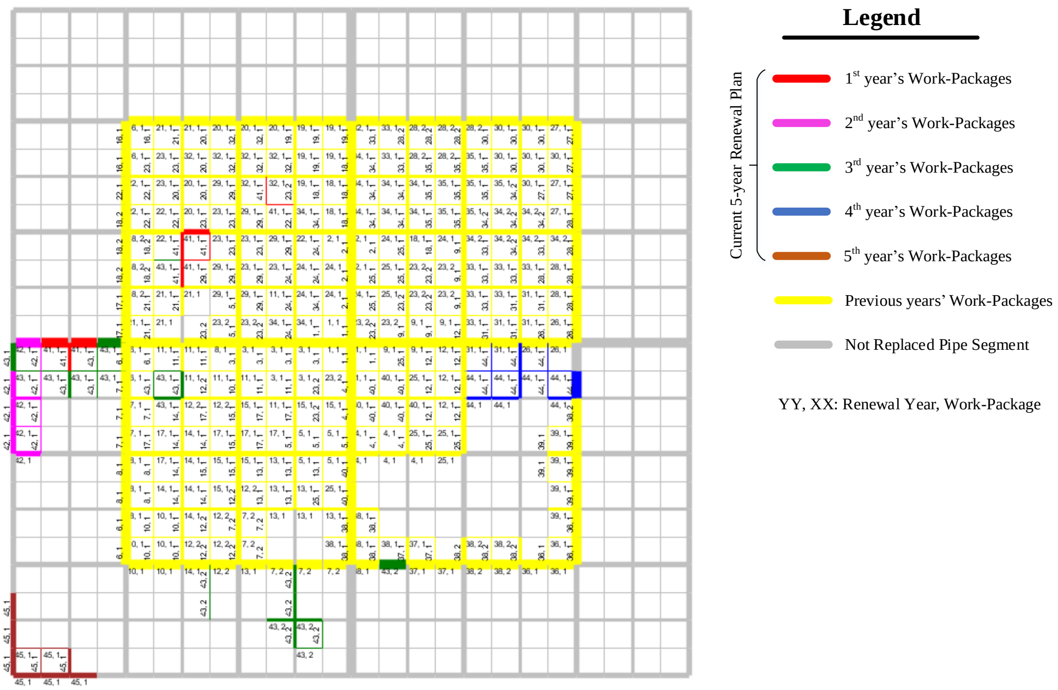

Figure C-31- Optimal grouping renewal plan for years 41-45 of Network B

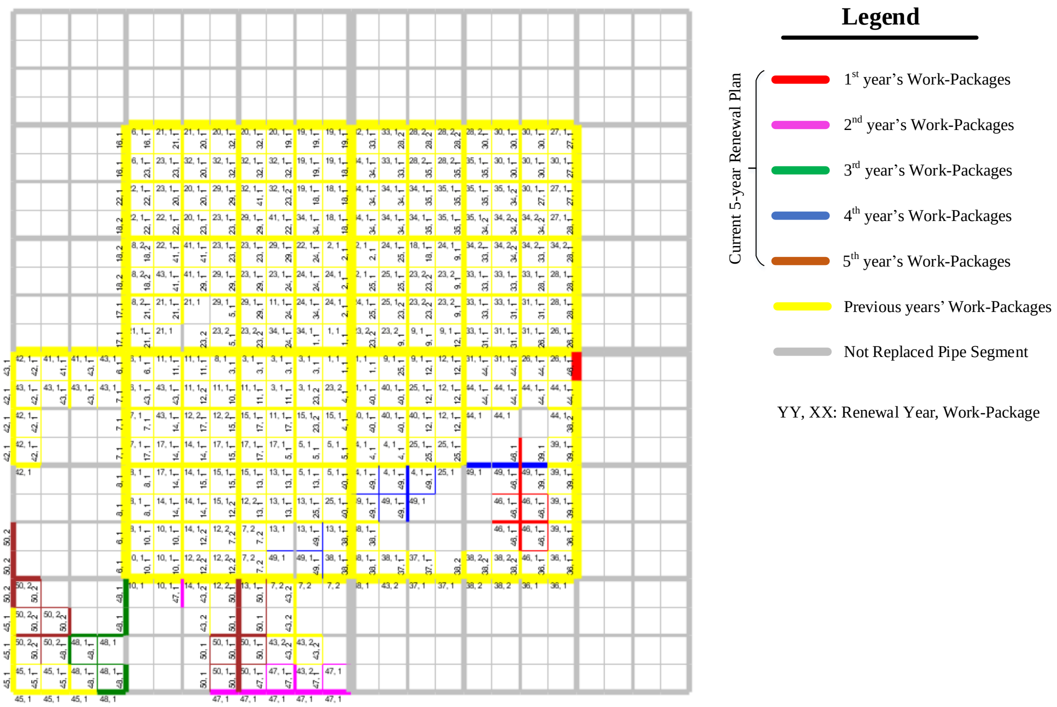

Figure C-32- Optimal grouping renewal plan for years 46-50 of Network B

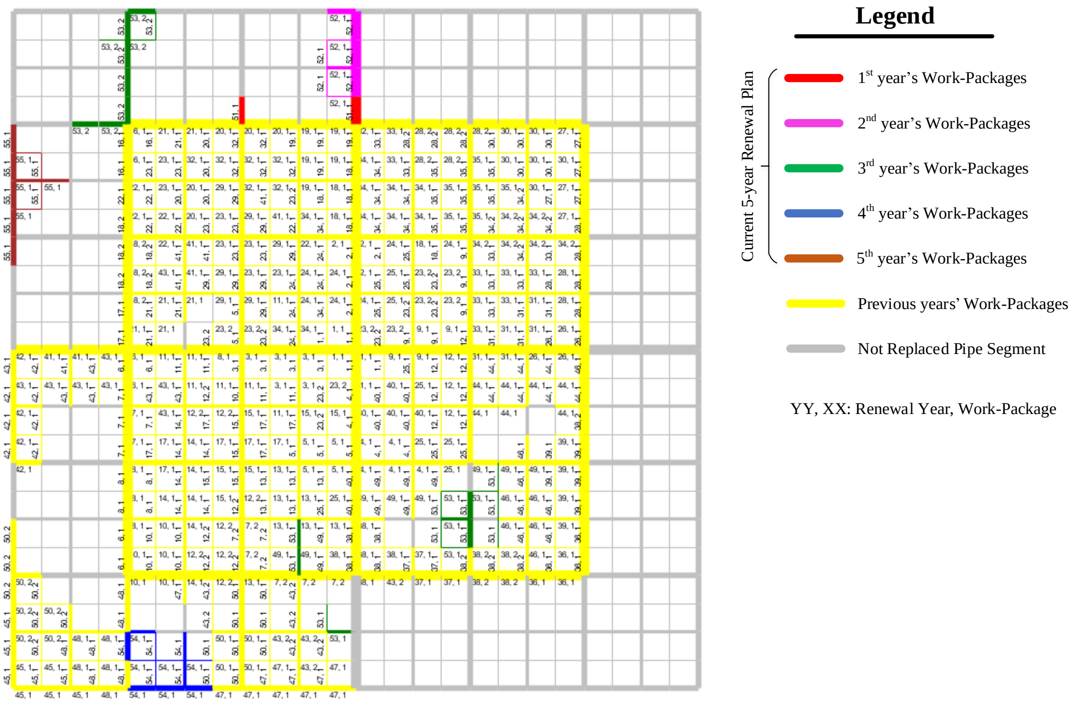

Figure C-33- Optimal grouping renewal plan for years 51-55 of Network B

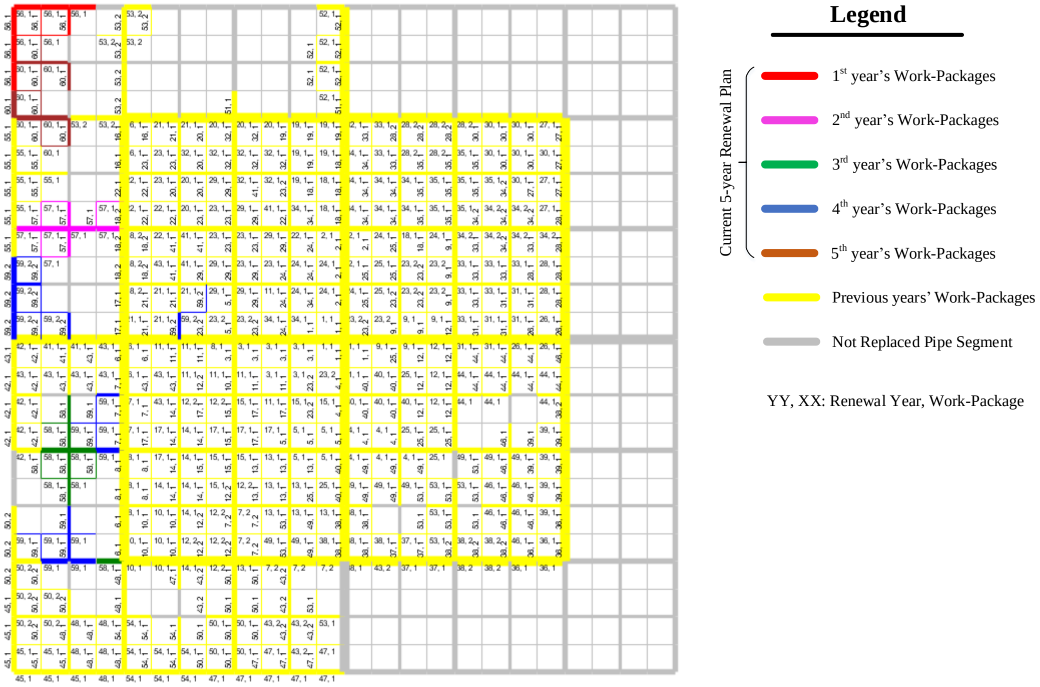

Figure C-34- Optimal grouping renewal plan for years 56-60 of Network B

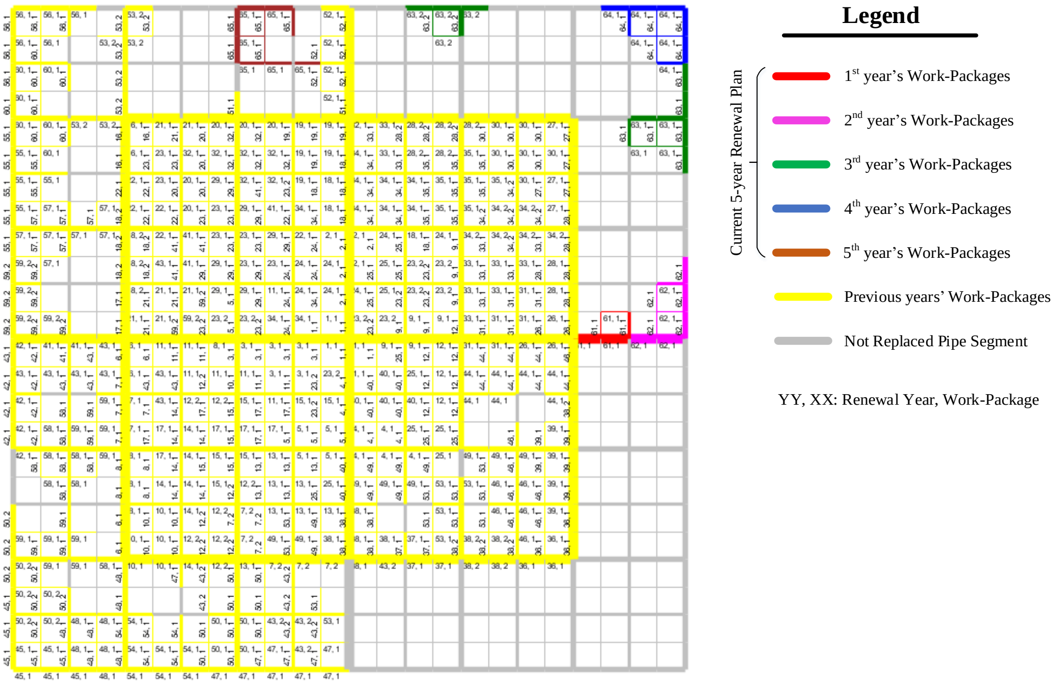

Figure C-35- Optimal grouping renewal plan for years 61-65 of Network B

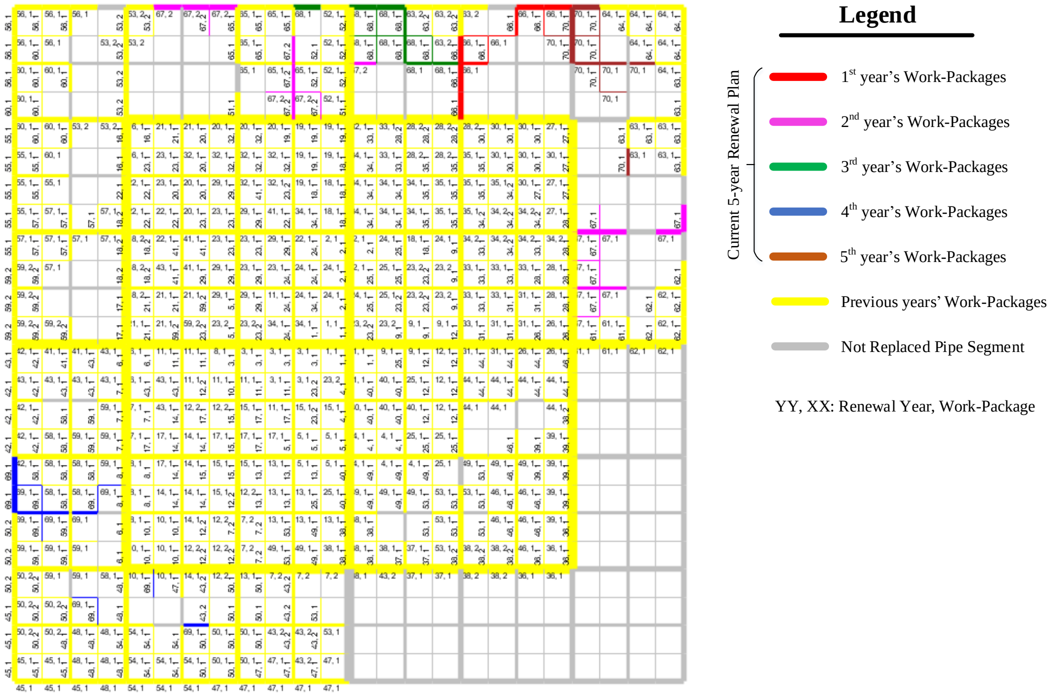

Figure C-36- Optimal grouping renewal plan for years 66-70 of Network B

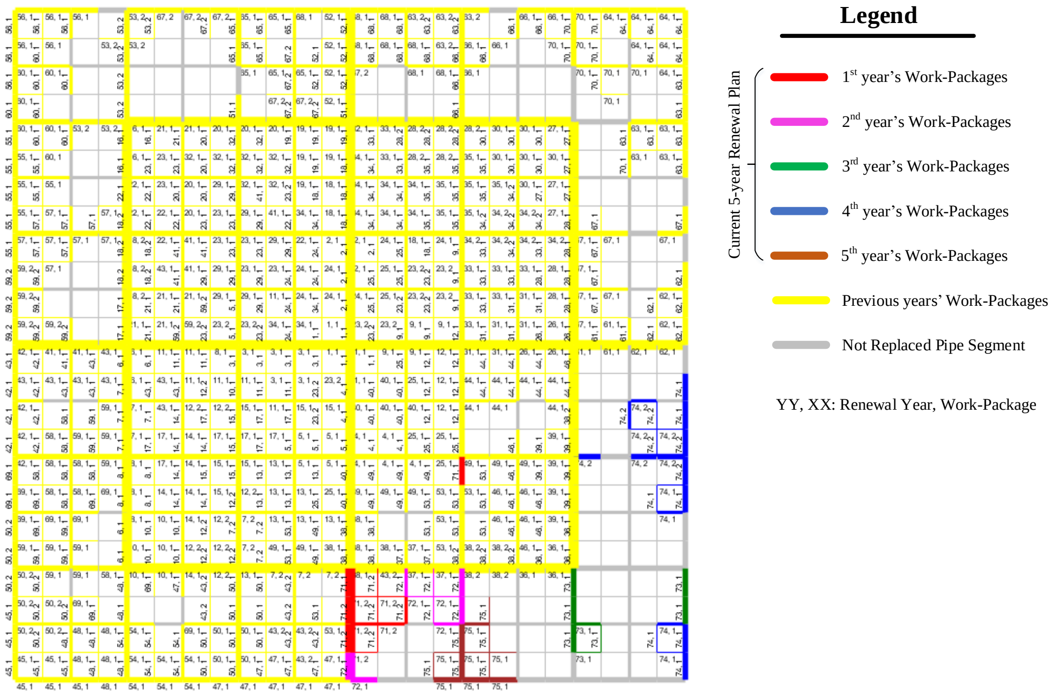

Figure C-37- Optimal grouping renewal plan for years 71-75 of Network B

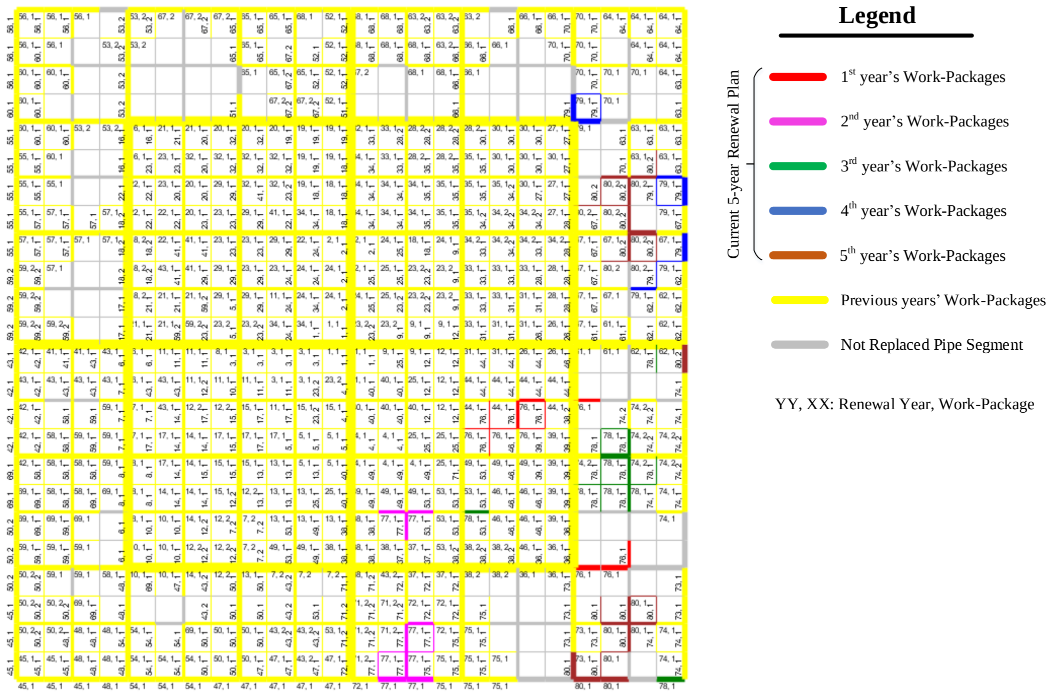

Figure C-38- Optimal grouping renewal plan for years 76-80 of Network B

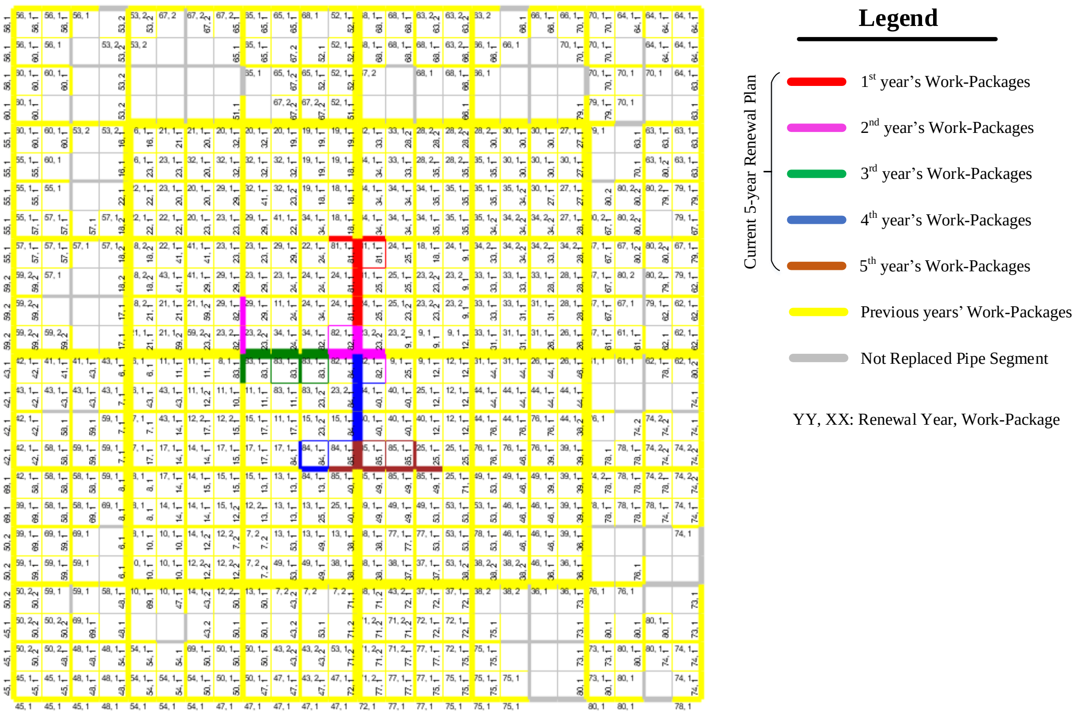

Figure C-39- Optimal grouping renewal plan for years 81-85 of Network B

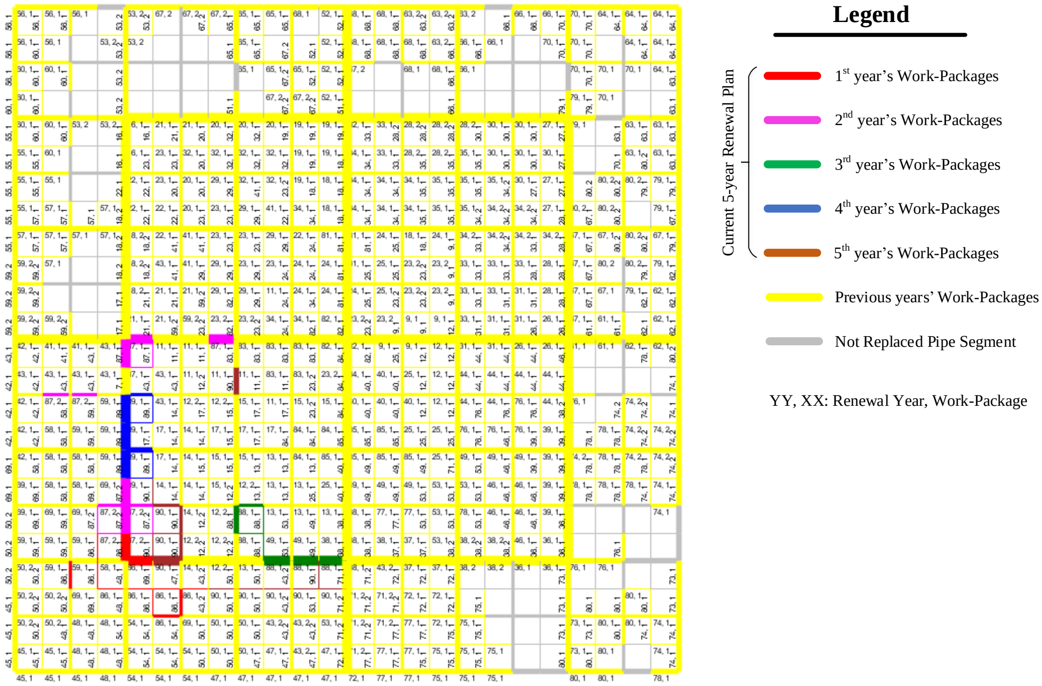

Figure C-40- Optimal grouping renewal plan for years 86-90 of Network B

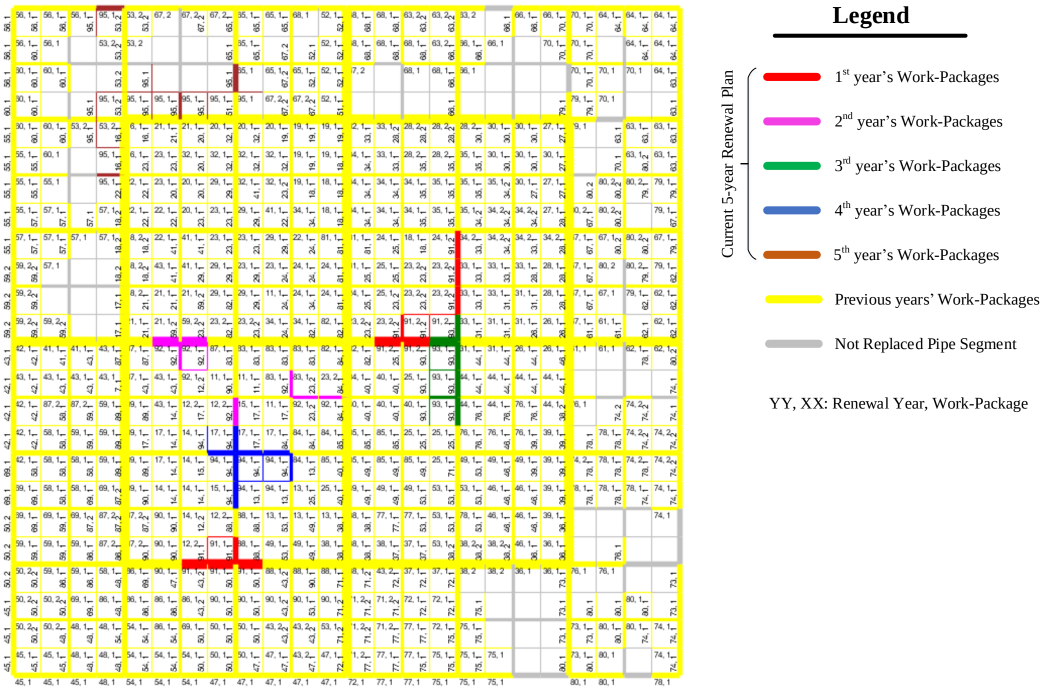

Figure C-41- Optimal grouping renewal plan for years 91-95 of Network B

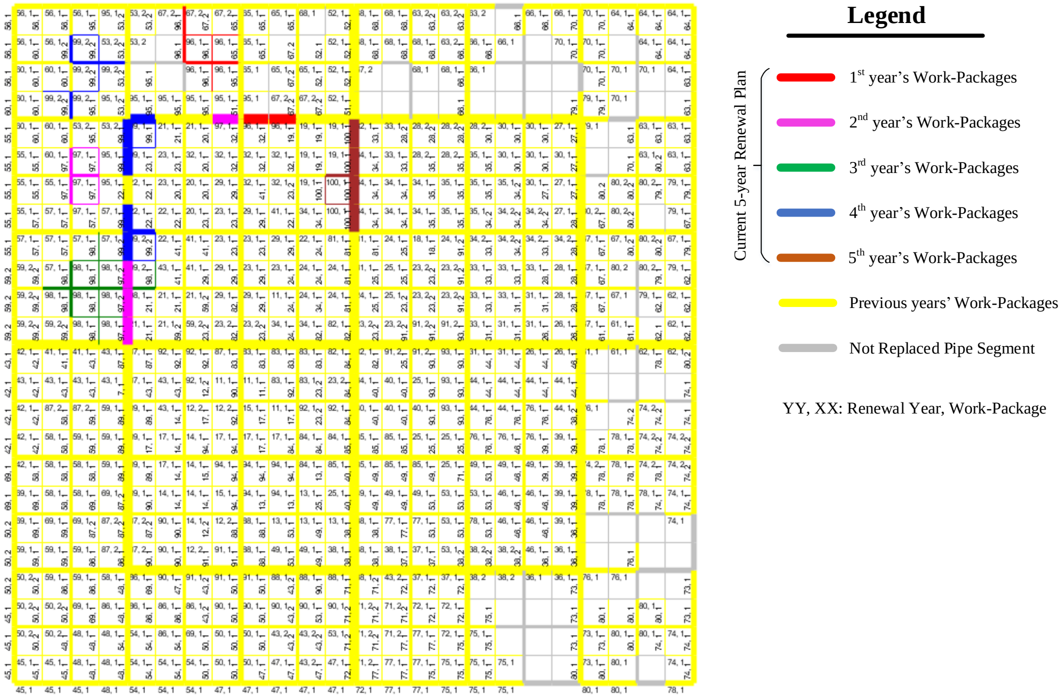

Figure C-42- Optimal grouping renewal plan for years 96-100 of Network B

C.3. Network C

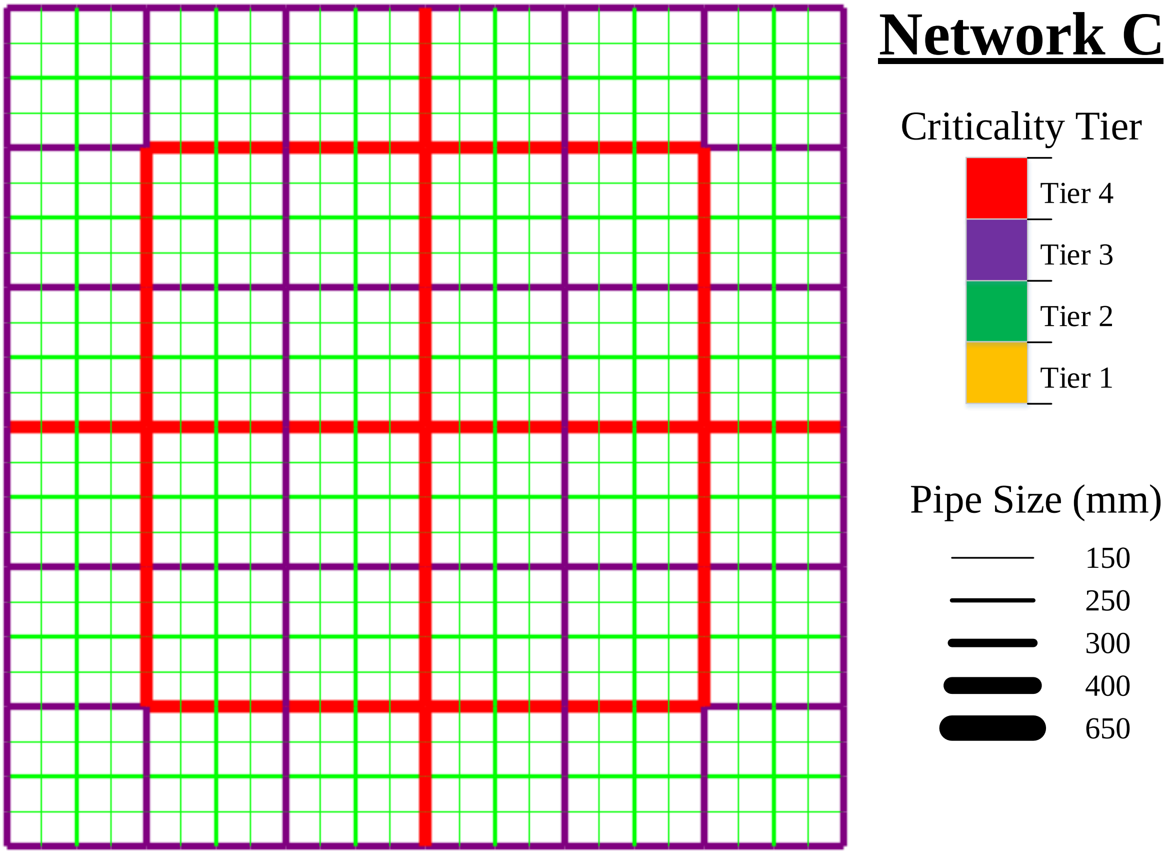

Figure C-43- Criticality-Tier map for Network C

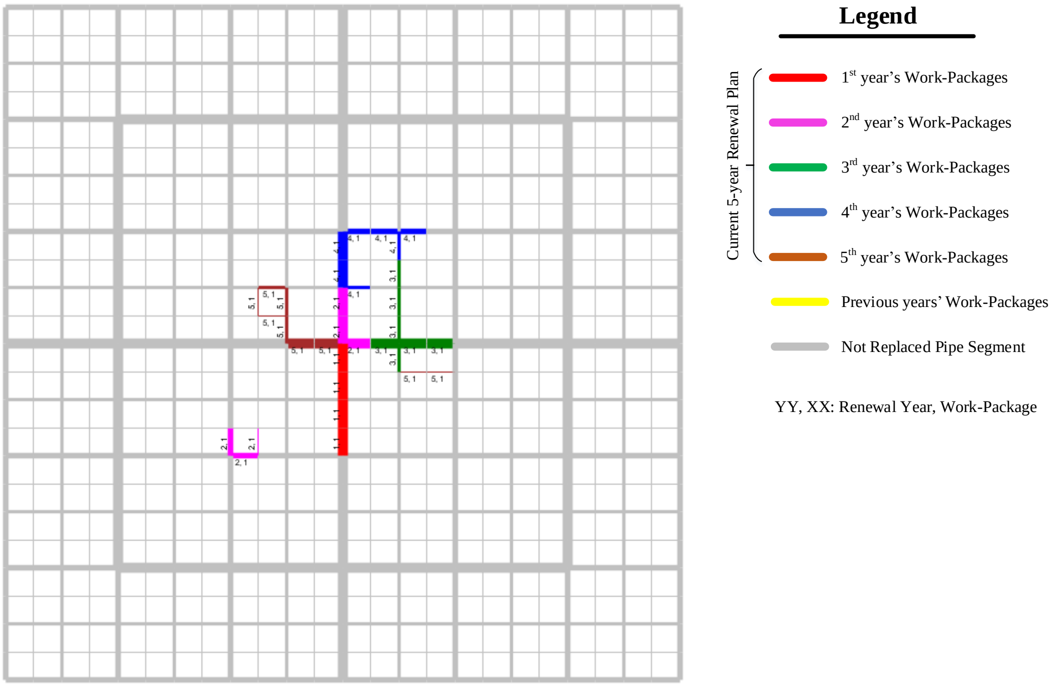

Figure C-44- Optimal grouping renewal plan for years 1-5 of Network C

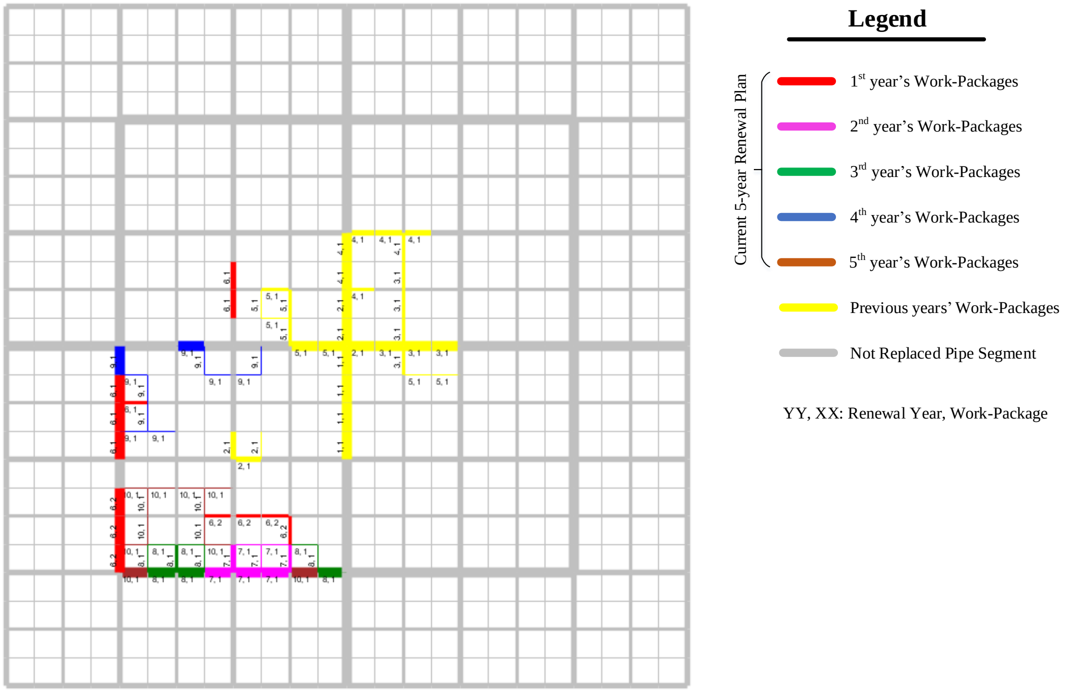

Figure C-45- Optimal grouping renewal plan for years 6-10 of Network C

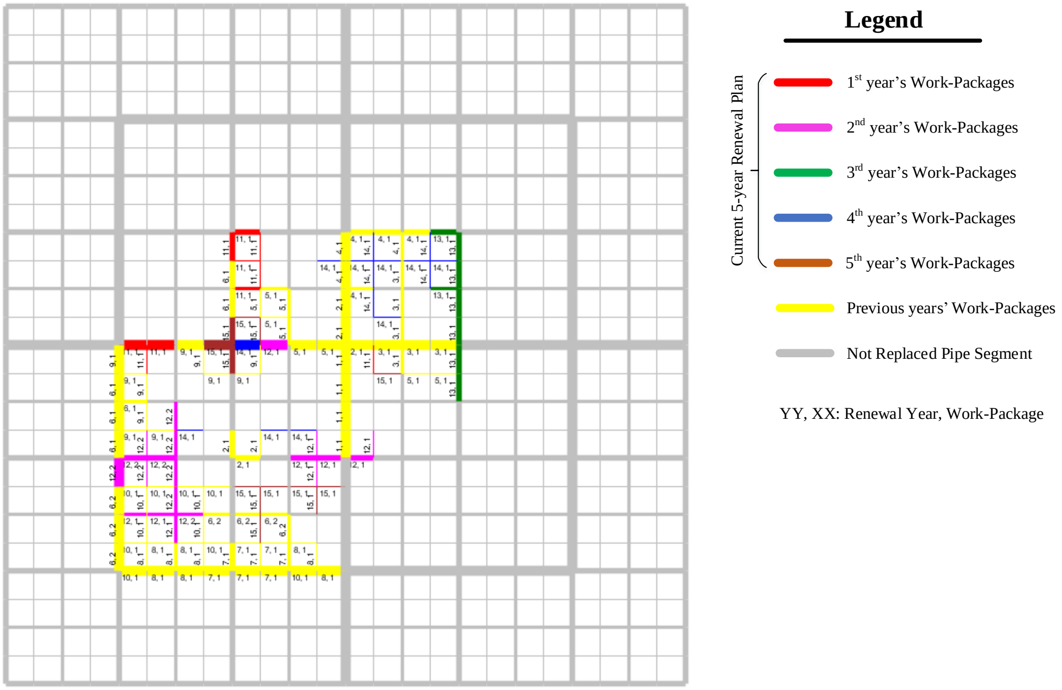

Figure C-46- Optimal grouping renewal plan for years 11-15 of Network C

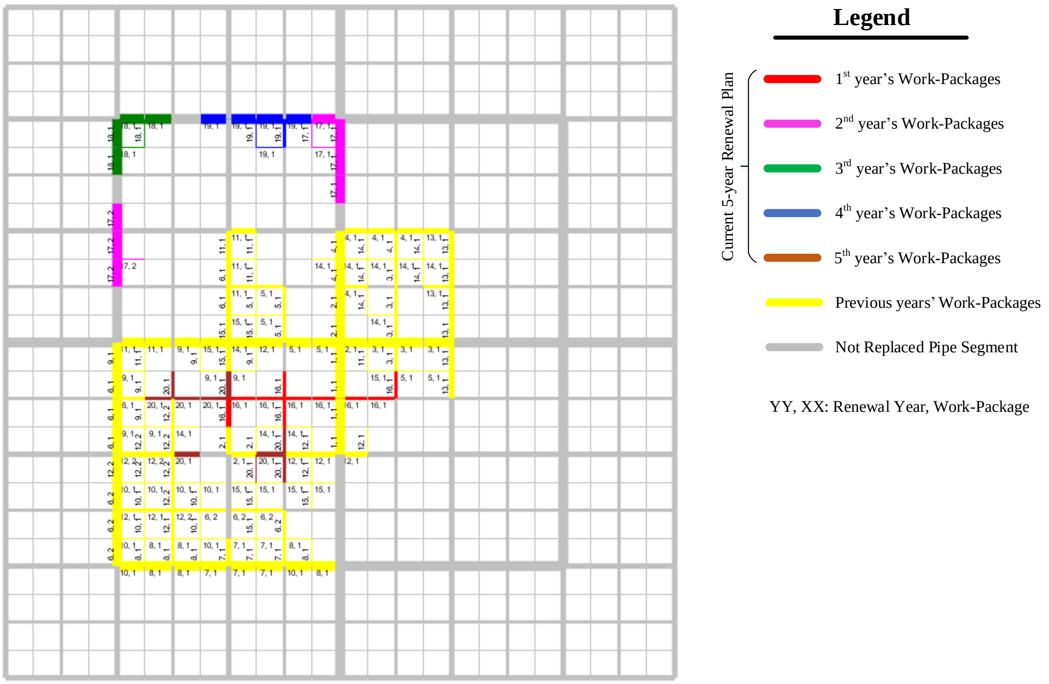

Figure C-47- Optimal grouping renewal plan for years 16-20 of Network C

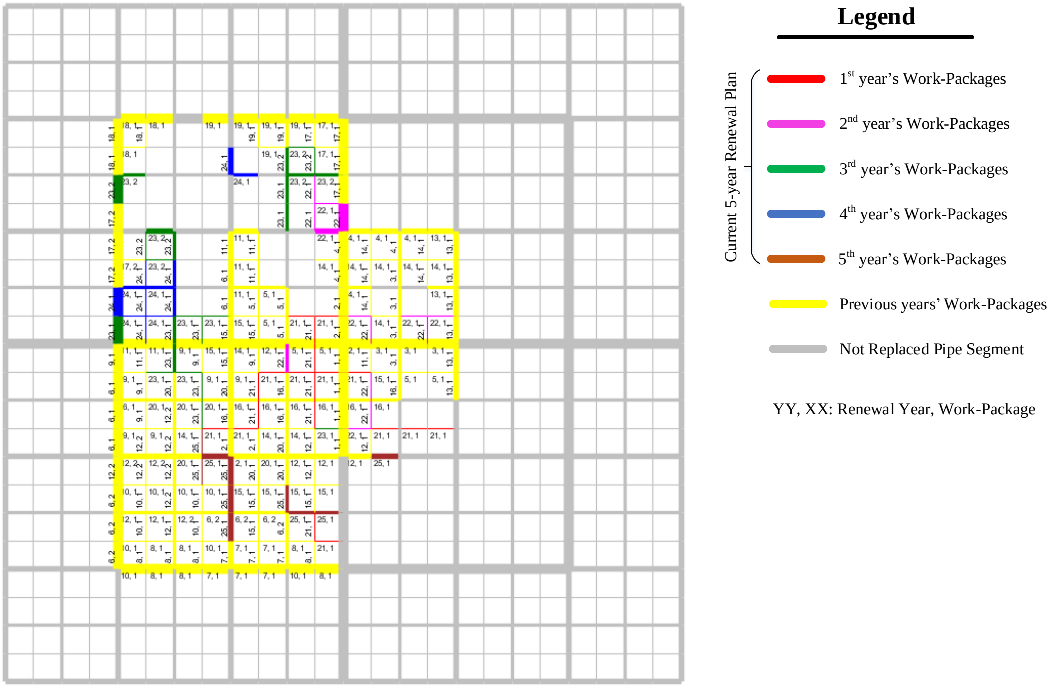

Figure C-48- Optimal grouping renewal plan for years 21-25 of Network C

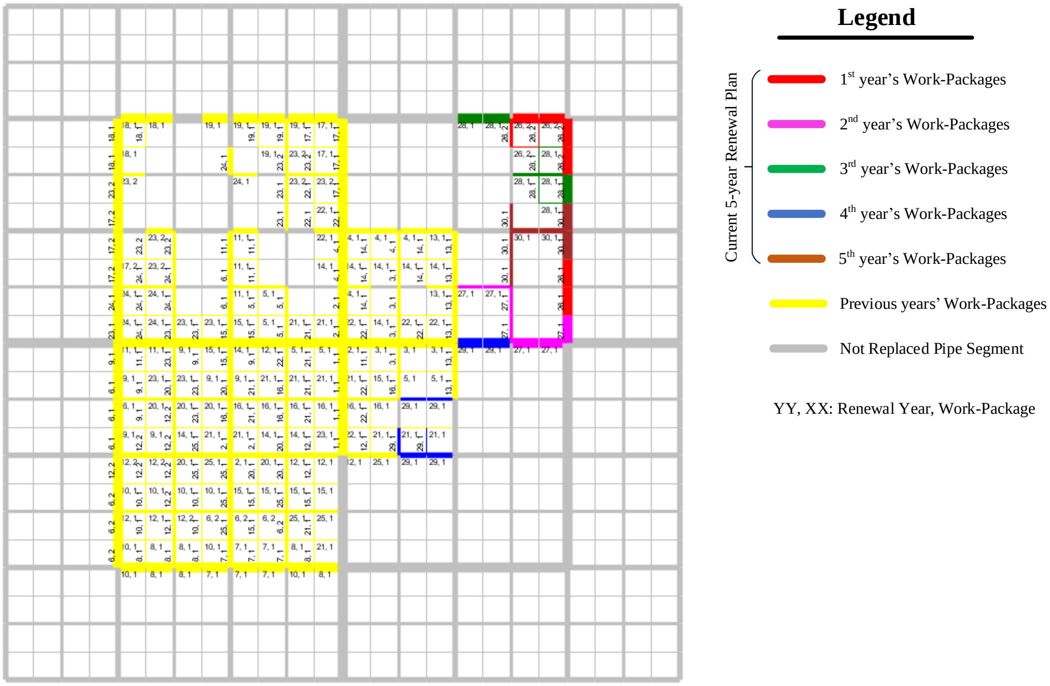

Figure C-49- Optimal grouping renewal plan for years 26-30 of Network C

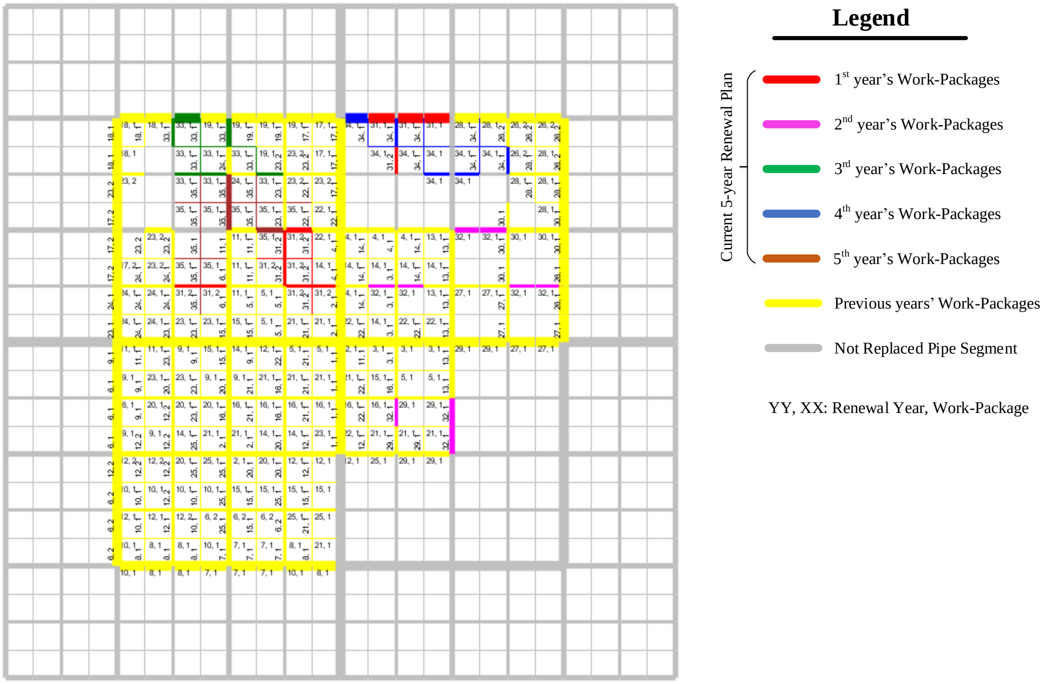

Figure C-50- Optimal grouping renewal plan for years 31-35 of Network C

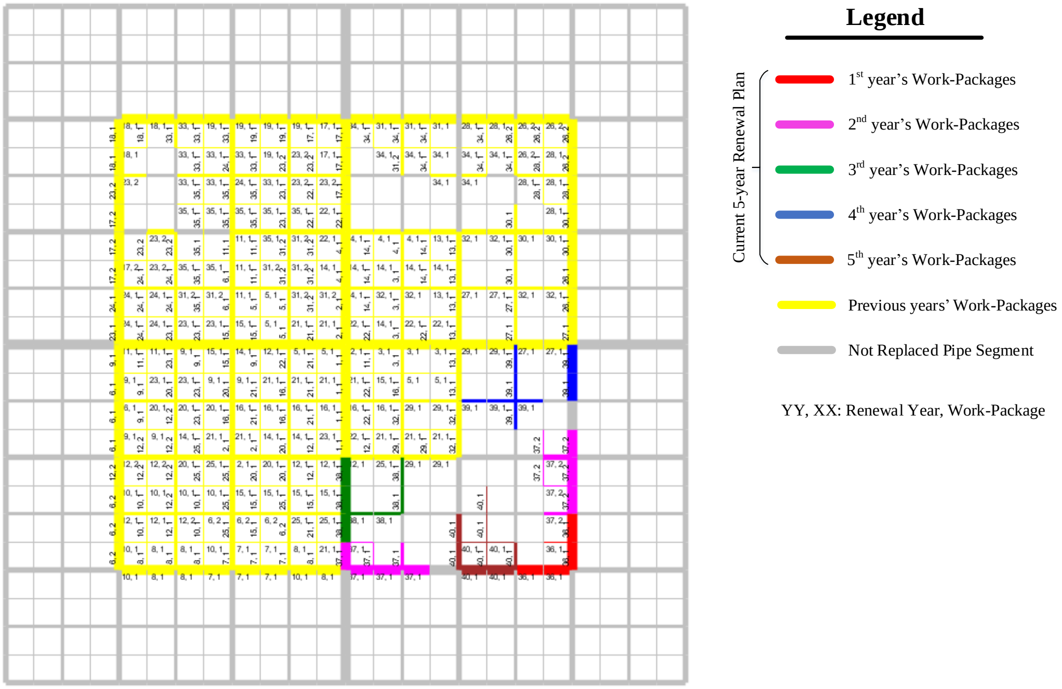

Figure C-51- Optimal grouping renewal plan for years 36-40 of Network C

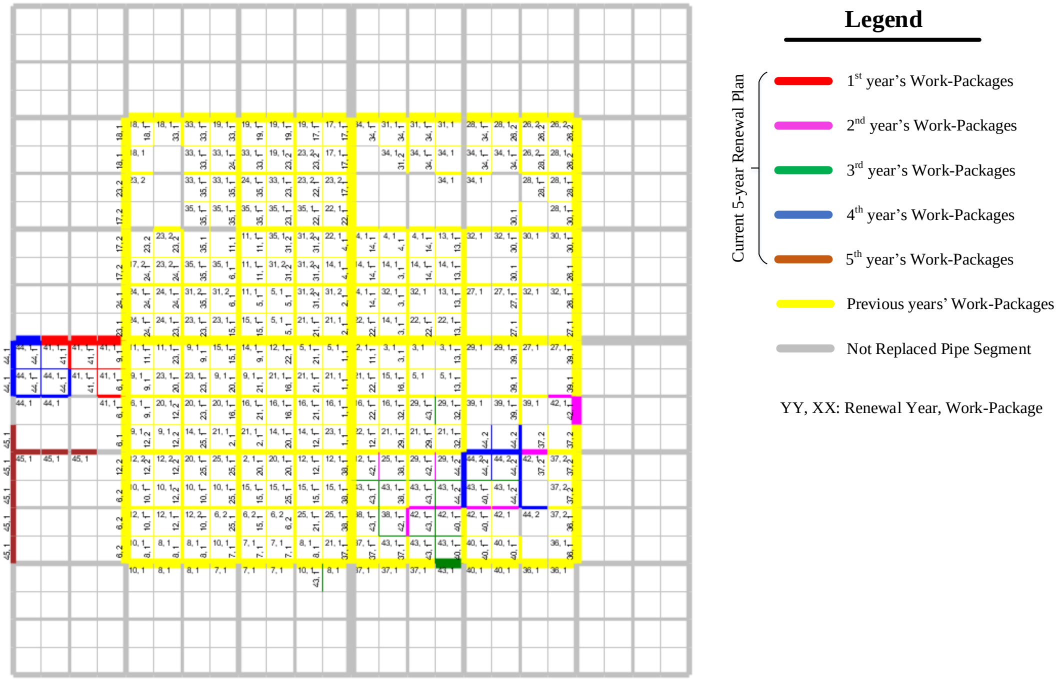

Figure C-52- Optimal grouping renewal plan for years 41-45 of Network C

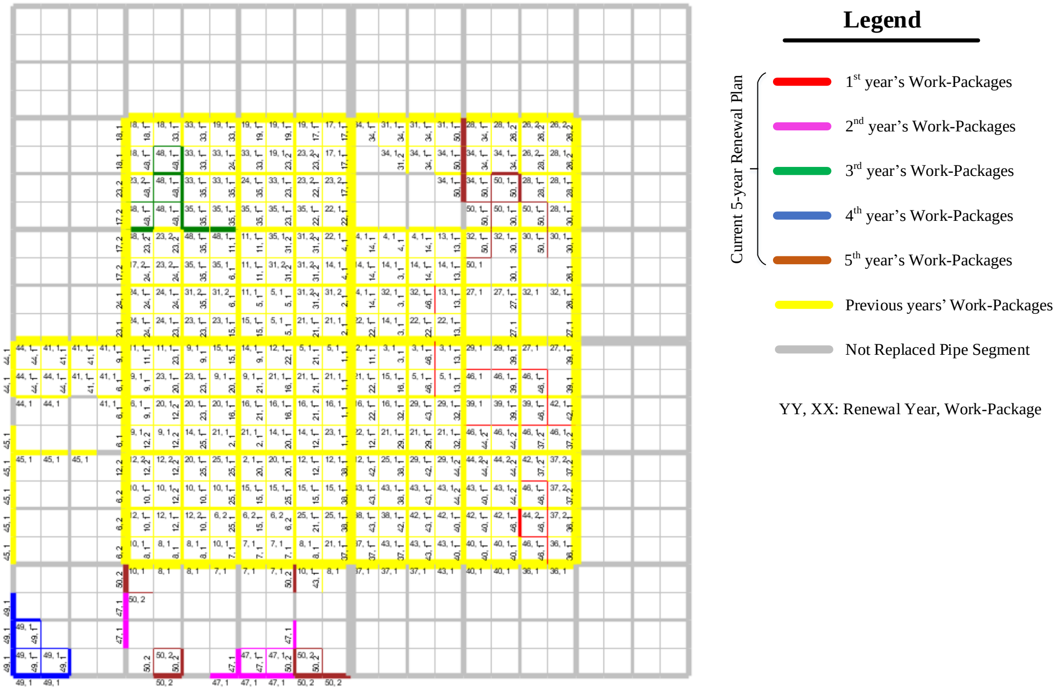

Figure C-53- Optimal grouping renewal plan for years 46-50 of Network C

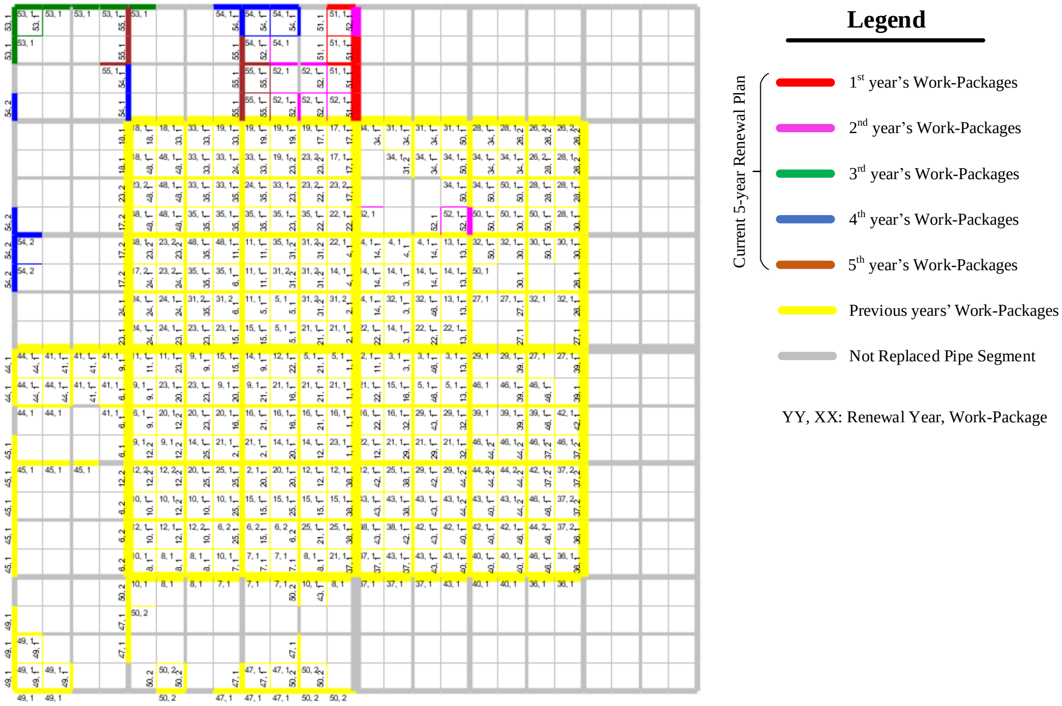

Figure C-54- Optimal grouping renewal plan for years 51-55 of Network C

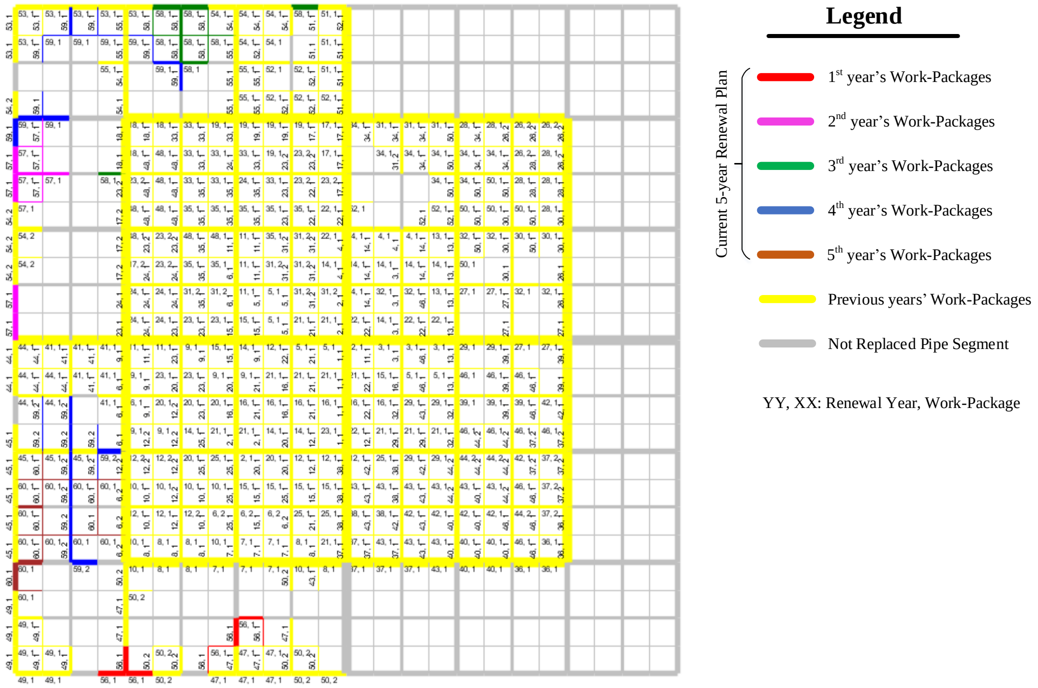

Figure C-55- Optimal grouping renewal plan for years 56-60 of Network C

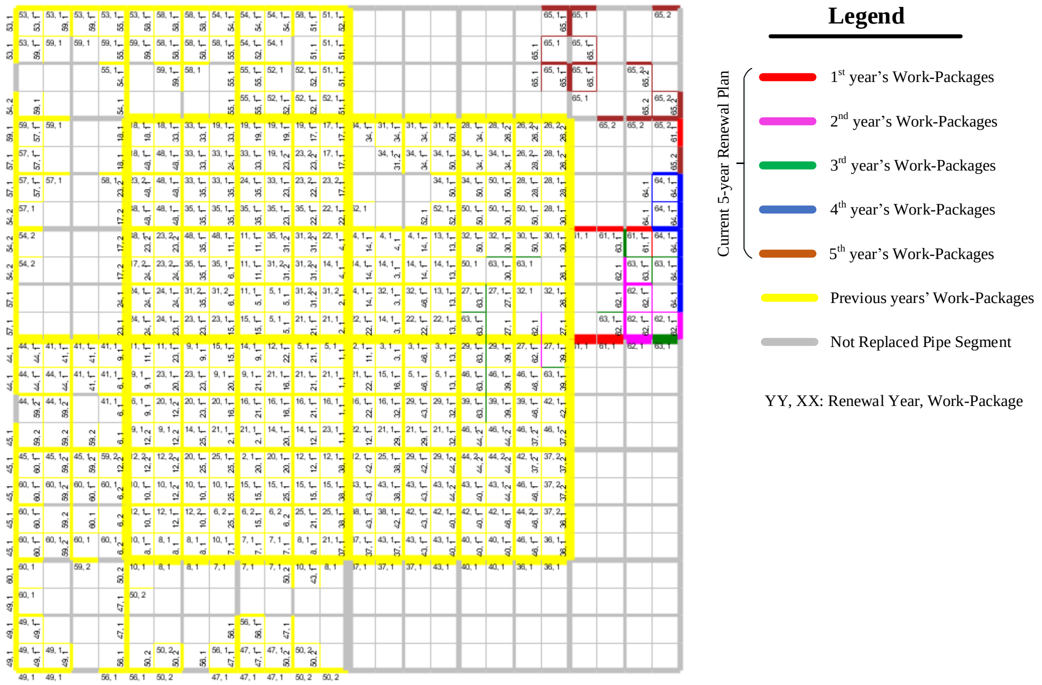

Figure C-56- Optimal grouping renewal plan for years 61-65 of Network C

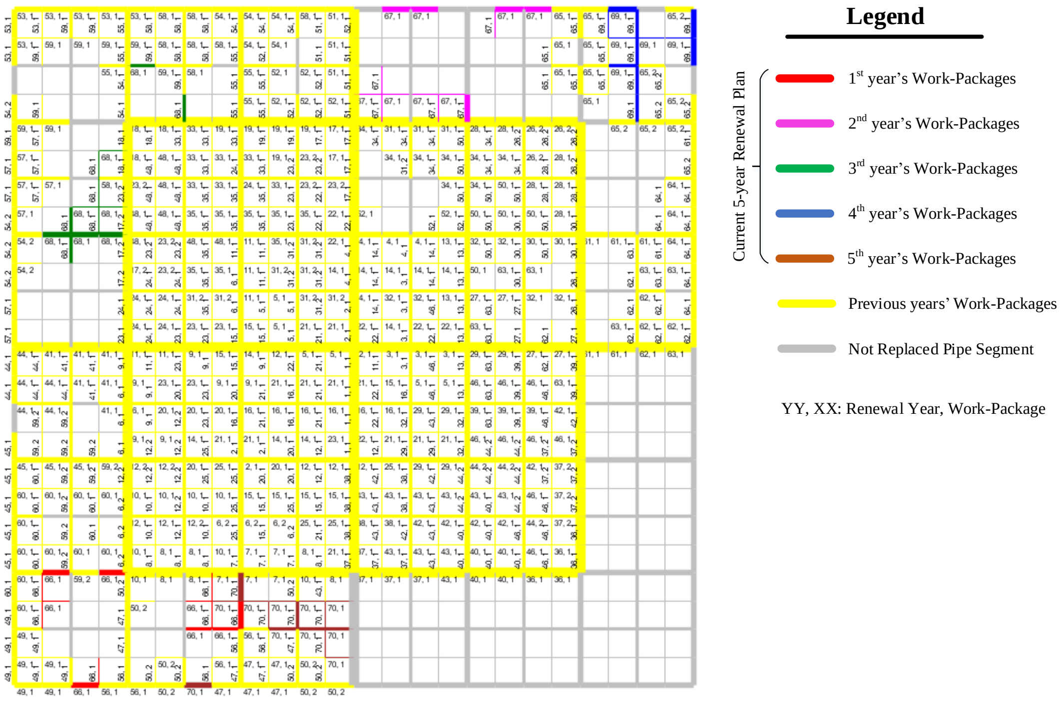

Figure C-57- Optimal grouping renewal plan for years 66-70 of Network C

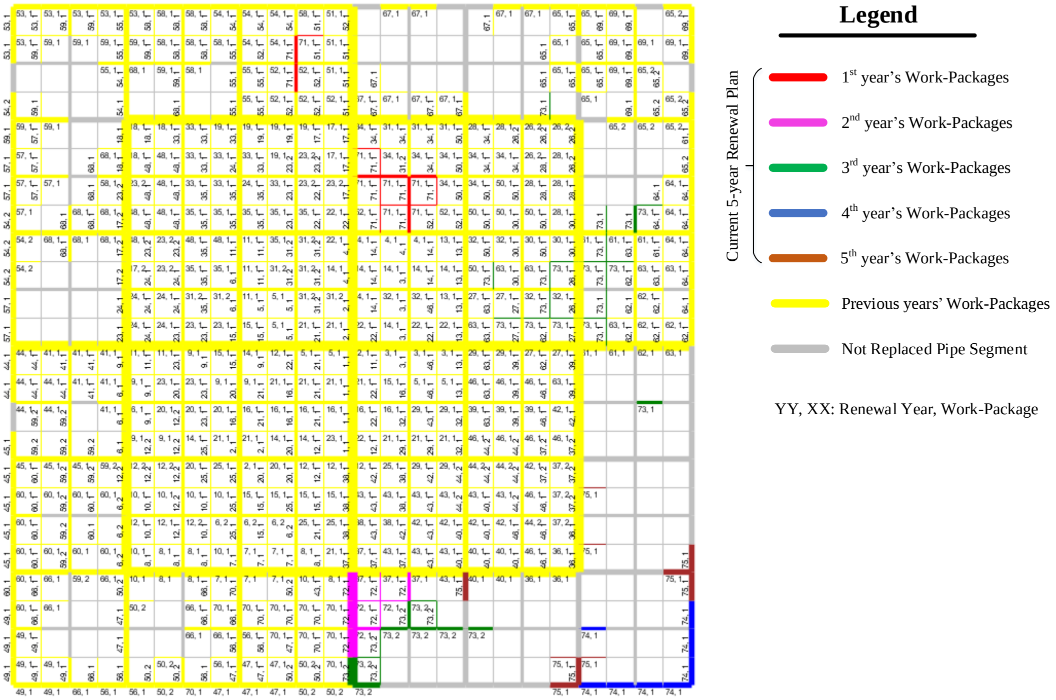

Figure C-58- Optimal grouping renewal plan for years 71-75 of Network C

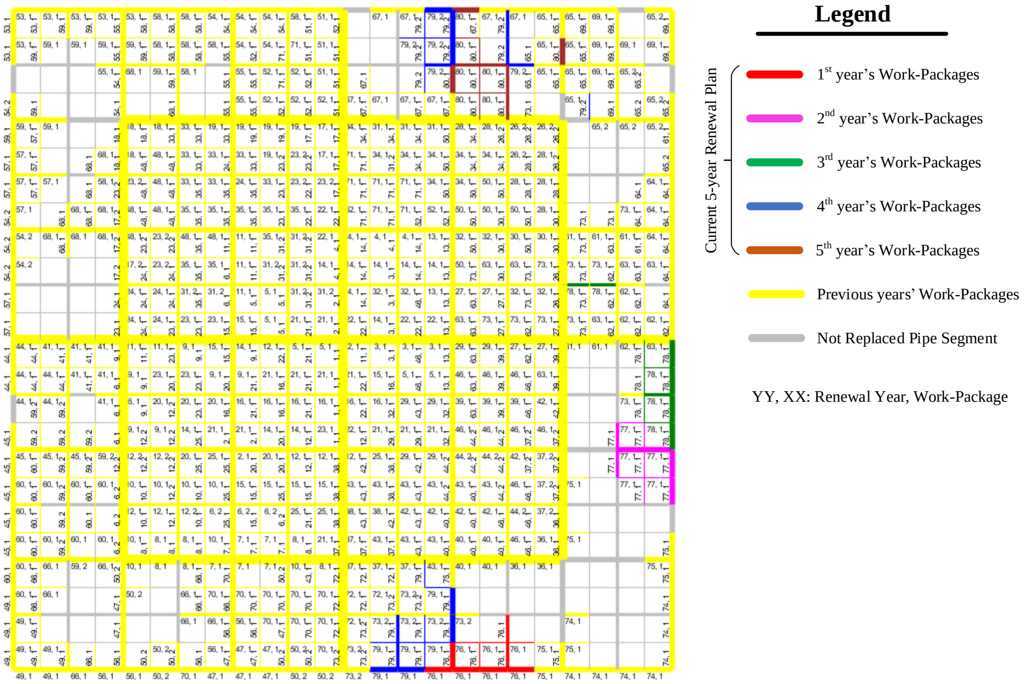

Figure C-59- Optimal grouping renewal plan for years 76-80 of Network C

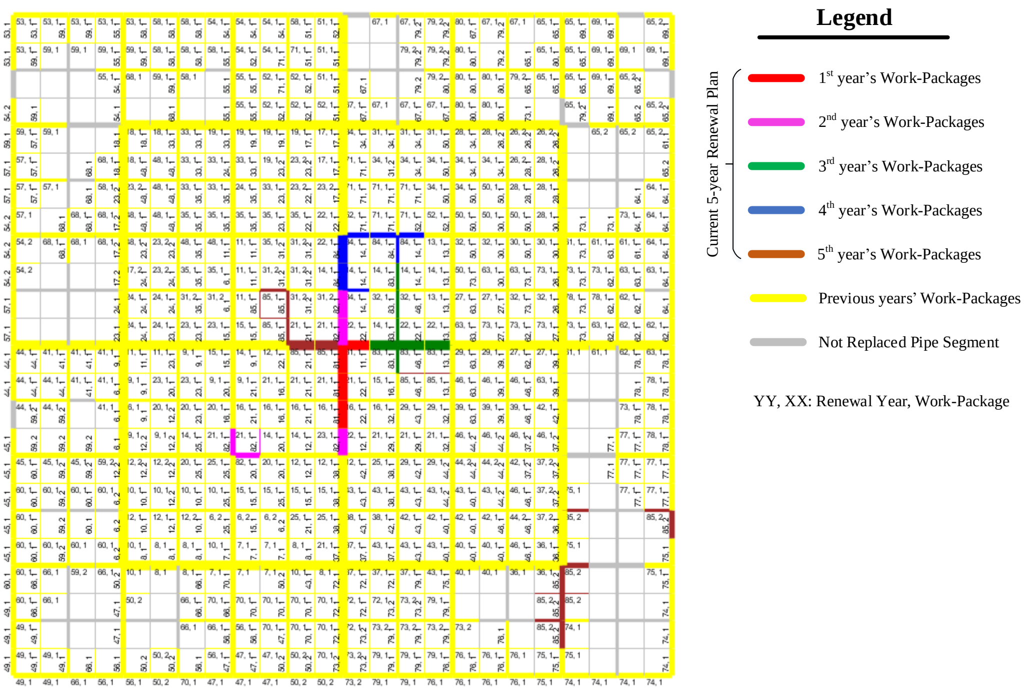

Figure C-60- Optimal grouping renewal plan for years 81-85 of Network C

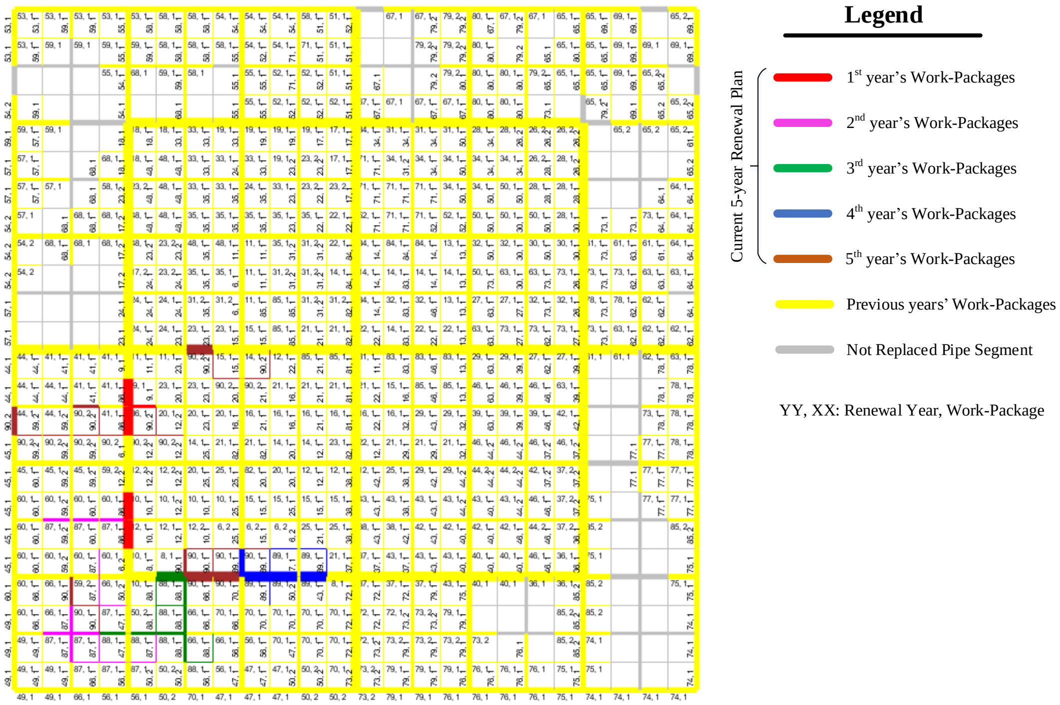

Figure C-61- Optimal grouping renewal plan for years 86-90 of Network C

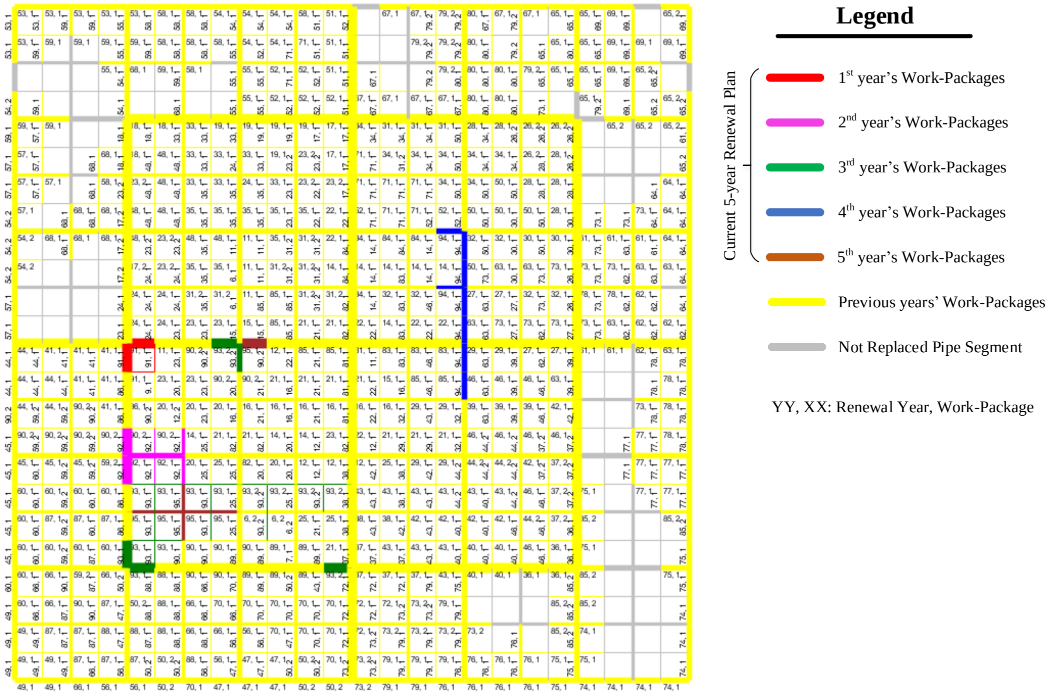

Figure C-62- Optimal grouping renewal plan for years 91-95 of Network C

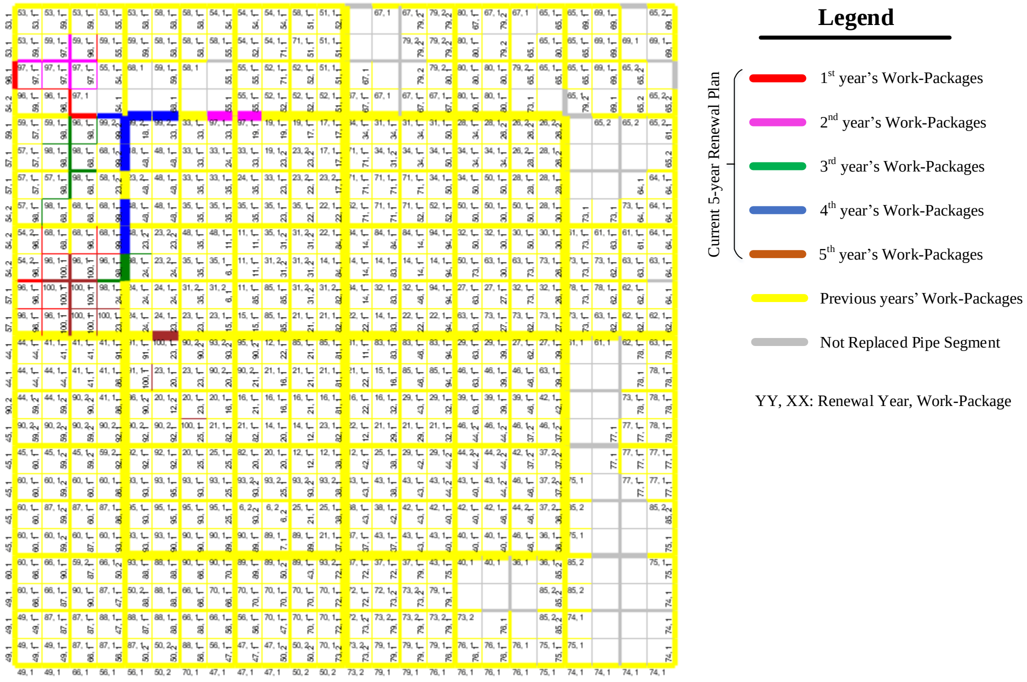

Figure C-63- Optimal grouping renewal plan for years 96-100 of Network C