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A Framework for Coordinating Water Distribution System and Pavement Infrastructure M&R Based on LCCA

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A FRAMEWORK FOR COORDINATING WATER DISTRIBUTION SYSTEM AND PAVEMENT INFRASTRUCTURE M&R BASED ON LCCA

A Thesis

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Dedicated to my parents Fedhi and Hussa,

my wife Sarah, and my son Ahmad

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ABSTRACT

Alinizzi, Majed Fedhi. M.S.C.E., Purdue University, December 2013. A framework for coordinating water distribution system and pavement infrastructure M&R based on LCCA. Major Professor: Amr Kandil.

The disruptions the public faces daily around the world due to urban infrastructure Maintenance and Rehabilitation (M&R) activities are having significant social, economic, and environment impacts on communities. With respect to water distribution systems, there have been millions of water main breaks in the U.S. since January 2000, with an average of nearly 700 water main breaks every day. The majority of these water utilities lie under paved roads, and the Open Cut method is the most widely used technology for repairing water main breakages. Subsequently, this continually increasing pipe breakage requires the destruction of pavements that may be in good condition and thereby results in not only untimely inconveniences to stakeholders, but can have large cost implications as well. Hence, in order to reduce the impact of pipe breakage on pavements in good condition and to minimize the user disruptions, it is essential to find a way to coordinate the M&R activities for both of these infrastructure systems. Therefore, this thesis presents a framework for coordinating pavement infrastructure and water distribution system M&R activities based on life cycle cost analysis. The proposed framework considers the costs and benefits associated with each treatment in a candidate scenario. The costs of each scenario consist of the agency costs (construction and subsequent maintenance) and the user costs incurred due to work zone activities. The benefits of each scenario are measured using monetized (savings in annual maintenance costs and vehicle operation costs due to pavement treatment and pipe valuation) and non-monetized (treatment service life) approaches.

To demonstrate the framework, three scenarios (maintenance only, rehabilitation only, and a combination of both) are considered for pavement treatments, while only replacement is considered for water pipelines. The results were evaluated using the EZStrobe discrete event simulation system. Highway agencies and water utilities can use this methodology to evaluate different scenarios and enhance the robustness of their decision-making processes.

CHAPTER 1. INTRODUCTION

1.1 Thesis Background

Most developed countries around the world face many challenges in managing their infrastructure assets (Too, 2012). In the U.S., existing underground assets consist of complex pipe networks with a valuation that surpasses several trillion dollars. These networks consist of more than 1,482,600 km of water, sewer, and storm water pipelines, of which 370,650 km have reached the end of their lives and need to be restored immediately (Jung and Sinha 2007). A great percentage of these water pipelines and 60% of the gas pipelines are located under paved roads. The deterioration of these buried pipelines is particularly problematic considering that water main breaks in the U.S. since January 2000 have been in the millions, with an average of nearly 700 water main breaks every day. The most widely used technology for repairing water main breaks is the open cut excavation method (Jung and Sinha 2007). The main issue with this method is that the pavement surface, which may be in good condition at the time, is destroyed, resulting in large cost implications. In addition, these pipe maintenance and rehabilitation (M&R) practices cause disruptions to the traffic and cause significant inconveniences to users. The extent of this disruption and the impact of pipe M&R activities on pavements in good condition can be minimized through coordinating the M&R of both infrastructure systems simultaneously.

Research studies that focus on the coordination of the M&R of different infrastructure assets are scarce. Oh et al (2011) proposed a framework for coordinating different highway construction projects, but did not consider coordination of dissimilar infrastructure assets.

Kleiner et al (2010) proposed a plan for water main renewal that considers the economies of scale and the scheduled work. A spatial coordination model was proposed by Islam and Moselhi (2012) to determine the spatial overlap between two assets. Despite these valuable efforts, the literature shows that substantial opportunities still exist in the area of infrastructure coordination. Many aspects can be addressed to further improve the robustness of the decision-making process in infrastructure asset coordination. The proper coordination of M&R activities of co-located assets leads to the minimization of disruption to the community and the reduction of costs to public agencies. The question to be investigated is when and how to coordinate M&R activities in order to develop the most cost-effective plans for these assets.

1.2 Problem Statement

A pipe failure that occurs at the beginning of the service life of a pavement treatment results in a great reduction in that pavement's service life and decreases its performance as shown in Figure 1-1(a). If the pipe failure takes place at the end of the service life of the pavement, the pavement service life and its condition would be less impacted as show in Figure 1-1(b). The third case is when pipe failure occurs in between the two aforementioned cases as shown in Figure 1-1(c). Focusing on the first case (early break) from the life cycle perspective, consider that three pavement treatment applications will follow the present treatment, which is the only one subjected to a pipe failure. The reduction in the service life and the performance of the first treatment would have an impact on the times at which subsequent treatments are applied.

Figure 1-2 (a) and (b) show the effectiveness of the three hypothetical pavement treatments with and without the impact of pipe failure. This impact, therefore, should be considered when attempting to coordinate water pipeline and pavement M&R activities.

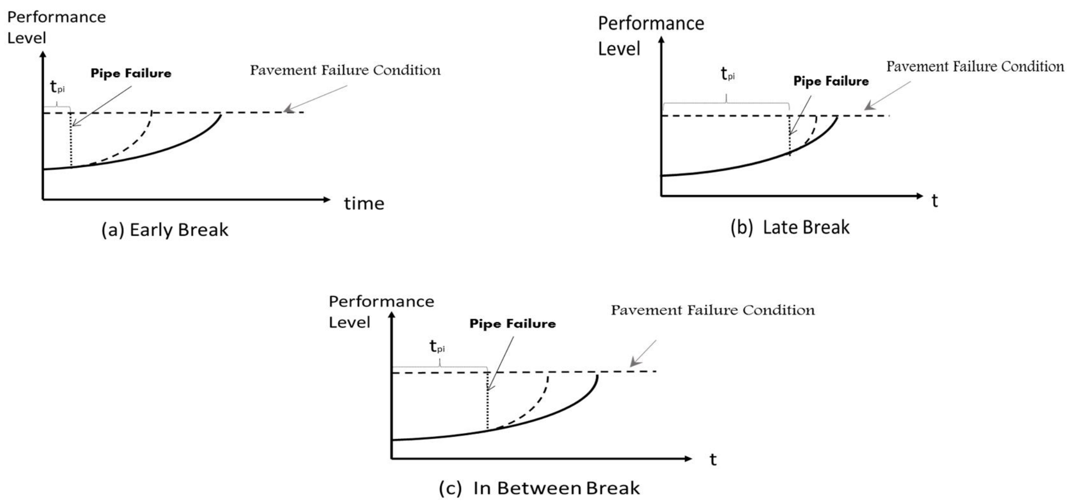
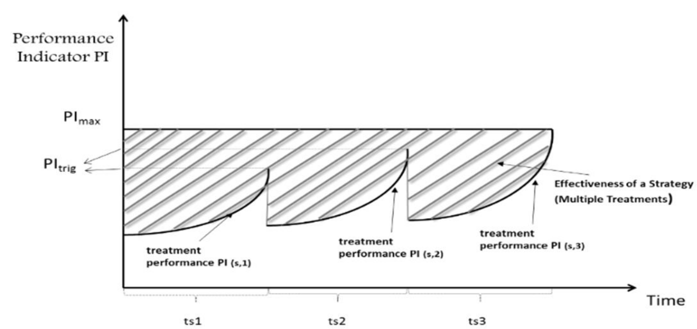
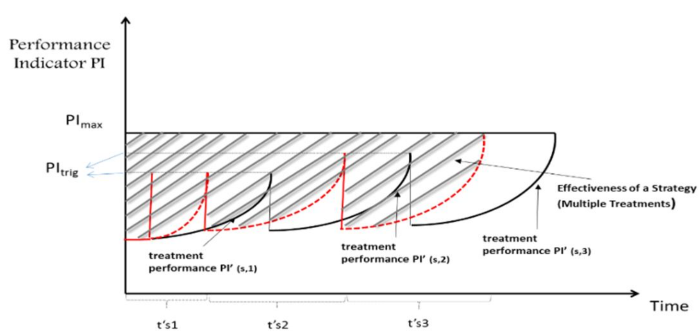


Figure 1-1 Graphical Illustration of Pipe Failure Impact on Pavement Treatment Performance



(a) Without Pipe Failure Impact



(b) With Pipe Failure Impact

Figure 1-2 Graphical Illustration of the Effectiveness of Three Pavement Treatment Applications

This thesis aims to develop a framework that addresses three main aspects in the asset management of water distribution systems and pavement infrastructure: (1) how to assess the impact of water pipeline M&R activities on pavement infrastructure using LCCA; (2) how to coordinate water pipeline and pavement M&R activities; and (3) how to assess the effect of coordinating these two systems based on the total LCCA of the two systems.

1.3 Research Scope and Objectives

The main goal of this thesis is to develop a project-level decision framework for coordinating M&R activities for water distribution systems and the pavement infrastructure based on LCCA. In order to achieve this goal, the follow secondary objectives need to be achieved:

- Assessing the impacts of water pipeline M&R on the road pavement, based on LCCA.
- Develop a decision matrix model to assess the interaction between M&R application timing of both assets.

The methodology of this thesis is designed to be applicable to flexible pavements, and different types of pipe materials (i.e., ductile iron pipe, PVC pipe, cemented mortar-lined, coated steel pipe, concrete cylinder pipe, and prestressed concrete cylinder pipe). To evaluate the effectiveness of a treatment, its monetized and non-monetized measures are considered, which include the following: treatment service life, savings due to reduction in agency maintenance cost and normal vehicle operating cost, pipeline useful life, and pipe valuation.

As noted, the costs considered include agency and user costs. Agency costs include the initial construction cost and the subsequent M&R costs. User costs, on the other hand, include travel time delay costs and vehicle operating cost incurred due to the work zone activities.

1.4 Research Methodology

In order to achieve the aforementioned objectives, the research tasks illustrated in Figure 1-3 are performed.

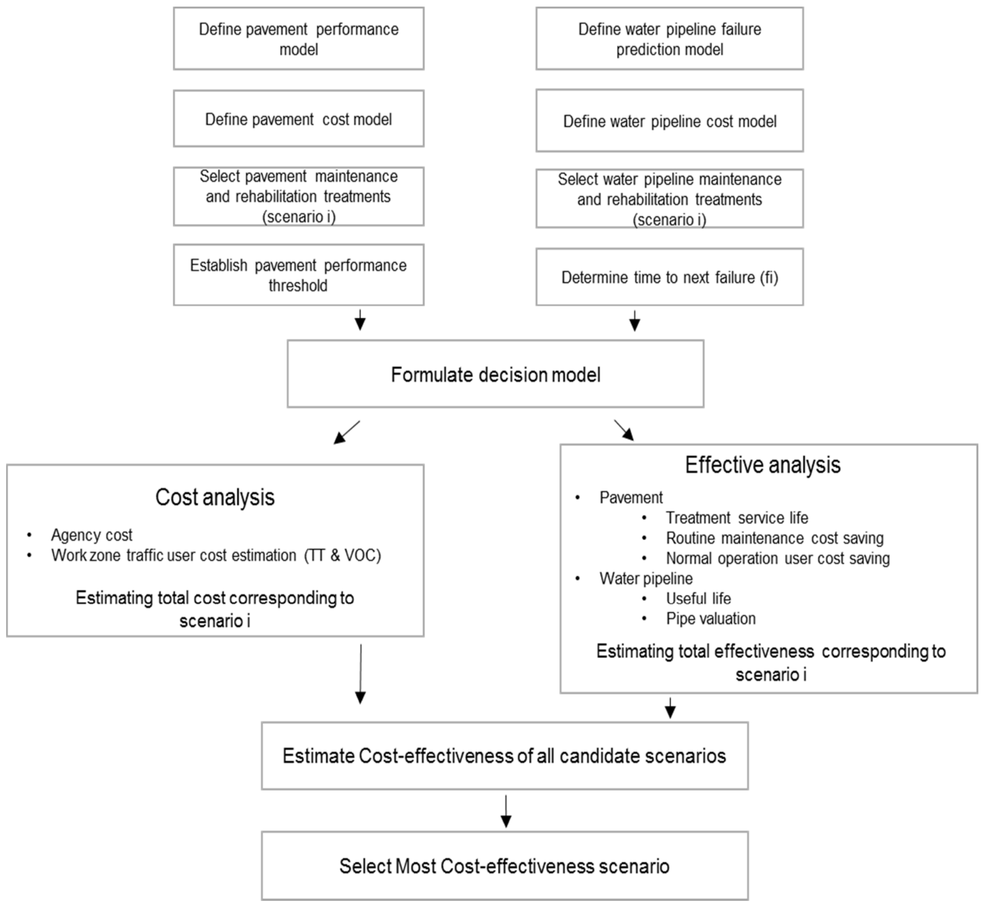


Figure 1-3 Overview of the Research Methodology

The research framework first defined the performance prediction models and costs models for water pipeline and pavement assets. Then, the interactions between the two assets were assessed and the costs and benefits associated with them were estimated. Finally, a cost-effectiveness analysis was conducted. These main research tasks were implemented using a discrete event simulation approach in the EZStrobe simulation software. Further, a sensitivity analysis was conducted using a Mont-Carlo simulation.

1.5 Thesis Organization

This thesis is organized into six chapters. The first chapter provides the background for the necessity of temporal coordination of co-located assets, states the problem statement, defines the scope and the objectives of the thesis, and provides an overview of the research methodology. The second chapter provides a literature review related to water pipeline failure prediction models and pavement performance prediction models. The third chapter presents the framework for coordinating the M&R activities of water pipeline and pavement assets using LCCA. The fourth chapter demonstrates the implementation of the developed framework using a discrete event simulation approach in the EZStrobe simulation software. The fifth chapter describes the verifications and testing of the proposed framework using hand calculations, which is then compared to the simulation outcome. Lastly, chapter six presents the conclusions and summary of the research, states the research contributions and limitations, and provides recommendations for possible future work.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Different managerial practices exist among the organizations responsible for infrastructure systems. Often these differing practices block the possible collaboration between these different organizations with unnecessary difficulties. This is particularly obvious when considering the possible collaboration between departments of transportation (DOTs) and utilities. The assets owned by these two types of organizations are managed independently despite the fact that they are often co-located and that they interact with each other significantly. Hence, there is a need to assess these interactions and thus help the decision- makers of both types of organizations to see the impact of coordinating the management of these assets. Therefore, a framework was developed in this research to demonstrate the feasibility of coordinating roadway and underground infrastructure assets analytically and assessing their impacts on each other objectively. Based on a review of the current literature, there are almost no studies that have addressed this issue. Therefore, this chapter discusses a number of past studies that are relevant to the development of performance models in water distribution system management and pavement management.

2.2 Pipe Failure Prediction Models

The first attempts to study and understand the failure patterns of pipelines and the factors that cause these failures were based on descriptive analysis. Descriptive statistical studies analyzed and found a variety of failure behaviors and factors that cause pipe breaks. One of the first descriptive studies was published in 1960 and was composed of several reports that determined pipe failure causes and pipe break patterns (Arnold 1960; Clark 1960; Niemeyer 1960; Remus 1960). The study was conducted in four different cities (Detroit, Indianapolis, New York, and Philadelphia) and one of the main conclusions was that the correlation between renewal cost and pipe rate failure should be assessed by utilities. Another descriptive study was performed by O'Day (1982) in the city of Philadelphia. The author found that pipes of small diameter (150-200 mm) tended to have circumferential breaks while pipes of large diameter (more than 250 mm) were vulnerable to longitudinal breaks (Rogers and Grigg 2006). Although this approach has produced valuable knowledge concerning pipe failure trends, it left many questions unanswered regarding the complexity of the circumstances in which pipe failures occur. One of the remaining controversial questions that was not fully addressed by these descriptive statistical studies is the relation between pipe aging and failure rates. The reason behind this controversy is, possibly, the complexity of the relationship between the age of the pipe and the failure rates, which necessitates the application of more comprehensive statistical analysis methods to address some of the main limitation of descriptive statistics. Some of the main limitations of these descriptive statistical studies in pipe failure models include the following (Andreou et al 1987): (1) they do not reveal sufficient knowledge regarding failure patterns of individual pipes; (2) they cannot define the complex interactions between the factors causing failure; and (3) they typically have a large number of statistical outcomes which are hard to use in predicting individual pipe failures. In addition, these descriptive statistical studies have failed to determine the need for individual pipe renewal rates. This particular limitation caused researchers to explore more advance techniques for prioritizing individual pipe failures. These techniques can be classified under four categories (Rogers and Grigg 2009): (1) deterioration point assignment (DPA) methods; (2) break-even analysis; (3) mechanistic models; and (4) statistical models. The following subsections present a review of these methods.

2.2.1 Deterioration Point Assignment Method

The DPA method is a weight-based technique where points are assigned to each factor which are deemed to contribute to pipe failure. First, a set of factors related to the pipe failure are identified, such as age of the pipe, pipe material, pipe size, soil type, location, water pressure, discoloration, and number of previous breaks. Then, these factors are clustered into different class intervals, and each of them is assigned a failure score. A total failure score for each pipe is obtained by summing its class interval failure scores. The pipe whose total failure score exceeds a predetermined threshold value becomes a candidate for renewal (Loganathan et al 2002). A Pipe Evaluation Model (PEM) used by the Louisville Water Company (LWC) is an example of the DPA method. A description of this model can be found in Dep et al (1995). The PEM includes 23 factors that classified four categories: geographical, service quality, hydraulics, and maintenance. Each of these factors is assigned points according to the defined scoring system. Despite its simplicity and ease of use, the DPA method has some limitations. One of the main limitations is its inability to predict future break times, which is essential for asset management and planning. Another limitation is its inability to prioritize two candidate pipes whose score points are equal.

2.2.2 Break Even Analysis

Break even analysis is an economic analysis approach where the cost of repair and replacement for a pipe is estimated over a specific period. The cost of repair and replacement is estimated for the present year taking into consideration the time value of money. While the present cost of the replacement decreases over time, the present cost of repair increases over the same period. Plotting these two cost curves over time gives the optimum time for pipe replacement, which is the minimum total (replacement and repair costs) present cost of the pipe. These costs are estimated without predicting future breaks; and hence, this approach needs to be supplemented with prediction models to predict pipe breakages (Agbenowosi

2000). Shamir and Howard (1979) analyzed the pipe break data of a single pipe, several pipes with similar characteristics, and a whole region of a pipe network and found that an exponential function is the best fit of these data. After obtaining the replacement and repair costs of the pipe and determining the appropriate interest rate value, a break-even analysis was implemented to determine the optimal time for replacing the pipe. Therefore, the Shamir and Howard (1979) study was one of the first to use statistical analysis of pipe break data as an analytical approach in determining the optimum time of pipe repair and replacement.

The main advantage of this analytical approach is the ease of its application; however, the approach has the following limitations as well (Andreou et al 1987): (1) some factors that are considered to be causes of failure of pipes (i.e., past break records of individual pipe, pipe characteristics, and environmental factors) are not incorporated in the developed model, which limits its ability to predict breaks; (2) it does not clearly represent information about the analyzed data, for example, the statistical significance of model coefficients was not elucidated; and (3) the very large inconsistencies that exist among individual pipe breaks lead to potentially defective outcomes. Additionally, the cost model proposed by Shamir and Howard (1979) was not as comprehensive as needed. It did not consider pipe size as a factor that could change replacement and repair costs. That is, their replacement and repair costs ($50/ft for pipe replacement and $1,000/break for pipe repair) were fixed among all pipes.

In order to address some of these limitations, Walski and Pelliccia (1982) used the approach proposed by Shamir and Howard (1979) for predicting break rates, taking into consideration a number of significant factors that are believed to contribute to pipe failure. These factors included previous breaks, pipe size, and the frost penetration effect. In their cost model, more factors also were considered, such as depth of cover, type of pipe, and diameter or flow. Walski and Pelliccia (1982) were the first as well to introduce the concept of establishing a threshold for the decision of whether to replace the pipe or to repair it. The driver behind developing this method was the unacceptable results of applying the Shamir and Howard (1979) models to their study. The Shamir and Howard (1979) models indicated that it is not cost-effective to replace any of the network pipes before they reach 100 years of age, regardless of whether or not they have previous breaks because the pipe segments analyzed in the study were several hundred meters long.

Another significant study by Male et al (1990) developed a simulation model to analyze New York City's replacement policies and determine the least-cost replacement practices that minimize the present value of the cost of the pipe break. The study did not consider a single pipe segment to be replaced. Instead, the following five strategies were analyzed: (1) replacing pipelines with one break or more; (2) replacing pipelines with two breaks or more; (3) replacing pipelines with three breaks or more; (4) replacing pipelines with four breaks or more; and (5) do nothing. The analysis showed that replacing mains that had one or two breaks was found to be the most economical policy for New York City's water distribution system.

2.2.3 Mechanistic Models

Mechanistic models are physical models that aim at determining the structural behavior that can cause a pipe break. Examples of such structural behaviors include pressure load, frost load, and temperature-induced stresses (Agbenowosi 2000). Implementing such models is restricted by the limited data availability on buried pipes. While these data may be obtainable now, it would require extensive time and cost for their collection, which usually can only be justified for large transmission water mains where the cost of failure is considerable. Furthermore, a complete understanding of the interactions between the factors causing pipes to fail is not yet available (Xu et al 2011). A comprehensive review of the physical/mechanical models can be found in Rajani and Kleiner (2001). Other studies on physical and mechanical models can be found in Doleac et al (1980), Kumar et al (1984), Philadelphia Water Department (1985), Makar (1999), Rajani and Makar (2000), and Makar et al (2001).

2.2.4 Statistical Models

Statistical models have been widely used by many researchers in modeling pipeline break patterns. These models use available historical data on past pipeline failures to determine these pipe failure patterns. An assumption is made that these patterns will continue into the future so that the breakage rates of water mains could be forecasted. Before explaining different types of statistical models, it is important to show the life cycle stages of a typical buried pipe. The life cycle of a typical buried pipe follows a particular form known as the “bathtub curve,” as illustrated in Figure 2-1. The bathtub curve has two main types, one deals with non-repairable units in which an instantaneous failure probability is described (hazard function), while the other is for repairable systems where the rate of occurrence of failure (ROCOF) is being described. The ROCOF bathtub curve is more illustrative for the pipe life cycle since the pipe is considered typically to be a repairable unit. This bathtub curve consists of three distinct stages that describe the life cycle of a buried pipe. The first stage, known as buried in, illustrates the period after installing pipes in the ground. In this period, the pipes are prone to failure, mainly as a result of defective construction practices or defective pipes. These breaks have a high decreasing failure rate. As soon as the pipe successfully passes through the “infant mortality” period, it goes to the next stage called “useful life” with a low, relatively constant, failure rate. This period is dominated by failures resulting from random events such as random high pressure, random heavy loads, third party intervention, etc. The third stage is also known as the “wear-out” stage, where the pipe exhibits an increasing failure rate as a result of deterioration and aging. It should be noted that not every pipe necessarily encounters all these three stages. Similarly, the length of each stage may significantly vary from one pipe to another, subject to the conditions of each pipe (Kleiner and Rajani 2001). Statistical models can be broadly categorized into two classes: deterministic and probabilistic models.

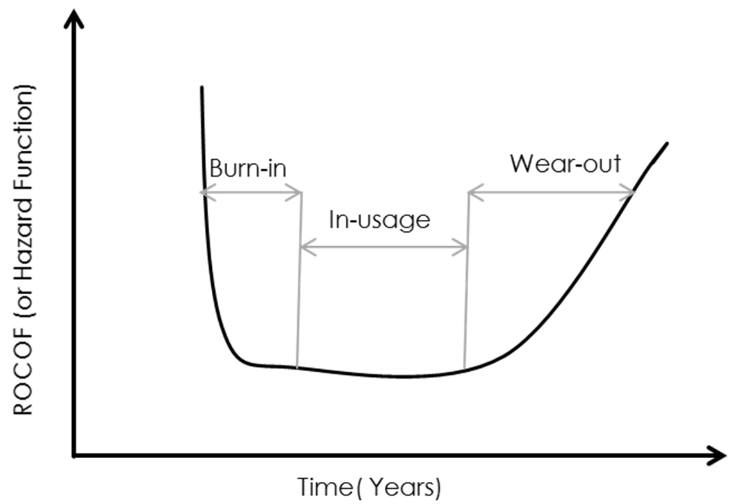


Figure 2-1 Life cycle of Typical Buried Pipe (Rogers and Grigg 2006)

Regression models are deterministic in nature and their prediction power highly depends on the historical performance data used. These models determine the relationship between the dependent variables (i.e., cumulative break history) and one or more independent variables such as pipeline age, pipeline diameter, pipeline length, pipeline corrosion, surrounding soil materials, etc. Shamir and Howard (1979) developed linear and exponential regression models to obtain the relationship between the pipe break rate and time. Walski and Pelliccia (1982) modified the Shamir and Howard (1979) models by incorporating additional factors (as mentioned earlier in Section 2.2.2). It is important to mention that these two models deal implicitly with only the wear-out phase of the bathtub curve. Therefore, if previous break records do have breaks that happened in the “bury in stage,” these break records are not incorporated in the regression analysis. Clark et al. (1982) was the first to consider two different deterioration stages by implementing a multiple linear regression approach.

Another study developed a linear regression model to predict the time to the first break after installation and an exponential regression model to predict successive break occurrences (Kleiner and Rajani, 2001). In a similar study, Yang et al (2009) developed five multiple regression models to predict the annual break rates of water mains considering several factors (i.e., pipe material, diameter, age, and length). These five regression models represent different types of pipe materials including: gray cast iron, ductile iron (without lining), ductile iron (with lining), and PVC and Hyprescon pipes. This study concluded that pipe length has a great impact on the annual break rate. Despite this important finding, one of the limitations of the study is that the next failure of an individual pipe cannot be predicted. McMullen (1982) proposed a linear regression model for the water distribution system of Des Moines, Iowa that predicted only the time to the first break and thus cannot be considered as a comprehensive prediction model. Kettler and Goulter (1985) developed linear regression equations to determine the number of breaks for the water distribution system of Winnipeg, Canada. They found a strong negative linear correlation between pipe diameter and pipe break rates, which indicates that large-diameter pipe has a lower tendency to break than smaller pipe. For a comprehensive review of traditional regression models, readers are referred to Kleiner and Rajani (2001). Despite the fact that a number of researchers continued to develop regression models through the 1990s, probabilistic models for modeling pipe failure have become more popular among researchers (Rogers and Grigg 2006).

Probabilistic models have more applications to water pipeline failure analysis, possibly due to the uncertainty involved in such systems since most of these pipelines are buried. One of the approaches for developing probabilistic models is the survival analysis approach. Survival analysis models estimate the time it takes for an event to occur (Fox 2002). An example of the survival analysis model is the proportional hazards model (PHM) developed by Cox (1972), which has the general form presented in Equation (1).

$$h\ (t, X) = h_0\ (t)\ \exp\ (b^T x) \tag{1}$$

Where: t = the time, h (t, X) = the hazard function (probability of failure at time t+Δt subject to survival to time t), h0(t) = the baseline hazard function, X = the Vector of covariates, and b = the vector of coefficients.

The PHM in Cox (1972) is performed using a *semi-parametric* model due to the fact that the baseline hazard h_0 is not pre-defined. The semi-parametric nature of the model makes it more robust and makes it capable of calculating the probability of survival while, simultaneously, other important factors could be corrected (Smith et al *no date is found*). PHMs were first applied by Marks et al (1985) to predict water main breaks. In this study, the probability of the time intervals between breaks was estimated and a multiple regression technique was implemented to determine the covariates. Kleiner and Rajani (2001) pointed out that a limitation of the Marks et al (1985) model is that the model is insensitive to left data censoring, which is certainly an important aspect to be considered since most water facilities have incomplete data records of pipe breakage. Additionally, Andreou (1986) developed Cox's semi-parametric proportional hazard model for analyzing water pipeline failure. Two pipe break categories were defined: 1) early stage, where pipes experience fewer breaks and 2) late stage, where pipes have multiple and frequent breaks. A PHM was used to represent the first category while the second stage was represented by a Poisson model. In the analysis, Andreou (1986) found that each break increases the chance of having a successive break, thus the time between breaks to occur becomes shorter as the number of breaks within the pipe increase. After the third break, the failure rate becomes constant and failures occur more often; therefore, the third break was the threshold between the two categories of breaks. Several researchers (Andreou et al 1987; Eisenbeis 1994; Gustafson and Clancy 1999) suggested that the number of previous breaks has a strong relation with failure tendency. In fact, the number of previous breaks was found to be an important factor in predicting the probability of failure (Pelletier et al 2003). However, the Andreou et al (1987) model was developed to predict the failure probability and was not intended to estimate the expected number of failures. Therefore, Li and Hamis (1992) utilized the Andreou et al (1987) model to develop a more complete decision-making process and proposed a semi-Markovian process to determine the optimal decision of either repairing or replacing an individual water main. The theoretical framework of the proportional hazard model was applied in Europe by Eisenbeis (1994), Brémond (1997), and Lie and Sægrov (1998).

An alternative method of modelling survival data is the Accelerated Life model. The general form of the accelerated model is given in Equation (2) (Kleiner and Rajani 2001):

$$\ln(T) = \mu + xT\ \beta + \sigma\ Z \qquad (2)$$

Where: T = time to next failure, X = vector of explanatory variables, Z = random variable distributed as Weibull, σ = parameter to be estimated by maximum likelihood, and β = vector of parameters estimated by maximum likelihood.

Unlike the PHM, the accelerated life model is a parametric model that incorporates an accelerated failure time model and creates a linear model in the log of failure time model. The covariates are acting multiplicatively on the failure time as it is represented by the accelerated failure time model (Zhang 2007). Lei (1997) conducted a study of the distribution system of the city of Trondheim, Norway, using both a PHM and an accelerated life model. The results of the two models were not considerably different from each other, which can be explained by the findings of Cox and Oakes (1984), who showed that the accelerated life model becomes a PHM when Z has a Weibull distribution. In view of that conclusion, the accelerated life model and the PHM could be considered similar. The only main difference between the two models is that the covariates in the accelerated life model act on the time to failure whereas, in the PHM, the covariates affect the failure rates (Kleiner and Rajani, 2001).

Another approach for developing a probabilistic model for predicting pipeline failure is the *cohort survival analysis*. Herz (1996, 1997, 1998) developed a new statistical distribution called the Herz distribution. The general form of Herz's model is as follows:

$f(t) = (a+1)be^{b(1-c)}/[a+e^{b(1-c)}]^2$

$S(t) = a+1/a+e^{b(1-c)}$

$h(t) = be^{b(1-c)}/a+e^{b(1-c)}$

Where: f(t) = probability density function, S(t) = hazard function and S(t) = survival function

In Herz's model, data are classified into cohorts of pipes based on their year of installation, pipe materials, and other important factors to create a mathematical model of these cohorts. This mathematical model was then integrated into a software package called KANEW developed by Deb et al (1998) and was applied to one British and four American water utilities. The KANEW model is not capable of prioritizing individual pipes for rehabilitation; and in addition, the model is based on past renewal rates, which reflect management practices rather than engineering best practices (Røstum, 2000).

From the above discussion it can be seen that survival analysis was proven to be a robust method of analyzing pipe failure when complete pipe break histories are available. This complete history of pipe breaks is, however, not available to many water utilities. Therefore, Mailhot et al (2000) extended the application of survival analysis to the case when pipes records are not complete. This study and its applications are explained in detail in the following chapter.

2.3 Pavement Performance Models

Pavement performance models are statistical models developed to represents the deterioration process of pavements under various conditions. Pavement performance models are functions of the significant factors that are believed to have an influence on the condition of the pavement and which could be a represented by structural performance (pavement distresses such as rutting) or functional performance (riding quality) (Irfan 2010). Pavement performance models are a key aspect in pavement management systems and are needed for quantifying the effectiveness of M&R alternatives (Helali et al 1996). Two main approaches are typically used in developing pavement performance, namely, deterministic and probabilistic approaches. Under each one of these approaches, three methods can be applied: empirical, mechanistic, and empirical-mechanistic (Shahin, 2005).

2.3.1 Empirical Models

Empirical models are entirely based on statistical analyses, where the development of the model specifically depends on the historical data utilized. In these models, the dependent variable can be any of the indicators that represent the performance of the pavement. Pavement performance indicators could be subjective (e.g., riding quality, serviceability, condition index, etc.) or objective (e.g., roughness, cracking, rutting, etc.). The indicators that are selected as dependent variables are then linked to one or several explanatory variables (e.g., environmental condition, traffic load, pavement strength, etc.) under a specific function form (Prozzi and Madanat 2003). In the early 1960s, the American Association of State Highway and Transportation Officials (AASHTO) developed an empirical linear model for predicting pavement deterioration patterns. Several researchers (Small and Winston 1988; Paterson 1987) pointed out the drawbacks of the AASHTO model, which included poor fitting of the data, inequitable unites, and unspecified models. The AASHTO model was revised a few times (1972, 1981, and 1985) and was published in the AASHTO guide (AASHTO 1993) to provide the basis for flexible and rigid pavement design. Small and Winston (1988) proposed a model similar to the one developed by AASHTO and concluded that the design equations overestimated the design life of thick pavement. A comprehensive study by the World Bank (Paterson 1987) developed a number of nonlinear empirical models that are statistically sound. Incremental models using the AASHTO Road Test data were proposed by (Prozzi and Madanat 2003, 2004; Hong and Prozzi 2006). These models contributed to the body of knowledge by including gradually increasing loads, along with other independent variables, such as structural design and environmental conditions, which have incremental impacts on pavement condition. In addition, these studies indicated that decisions in pavement management systems usually are taken based on incremental predictions for short periods of time (Chu and Durangu-Cohen 2008). Although the literature indicates that much effort has been spent to develop pavement performance models relying on empirical deterministic techniques, several researchers have used stochastic modeling approaches. One of these approaches is survival curves that are a common technique used to predict infrastructure asset deterioration. Several researchers used this technique including Lytton (1987), Eltahan et al (1999), and Gharaibeh and Darter (2003). Another stochastic technique to predict the time to failure, assuming it follows a Weibull distribution, was introduced by Prozzi and Madanat (2000). The main purpose of this technique was to improve the equations developed in the AASHTO study (1993), and the developed model was able to predict failure time more accurately than the original AASHTO model. The model was also more robust since it was not based on any subjective assessments (Prozzi and Madanat 2000). Several researchers (Kulkarni et al 1980; Feighan et al 1987; Davis et al 1988; Harper et al 1991; Wang et al 1994;

Li et al 1996) developed pavement performance prediction models using a Markov process. A Markov process is a common approach in modeling pavement deterioration. However, these models had a number of shortcomings that were pointed out by Madanat et al (1995). Additionally, the assumption of state dependency in pavement deterioration modeling was found to be not very realistic (Irfan 2010).

There have been significant efforts toward developing general pavement performance models. In contrast, a smaller number of studies developed treatment-specific performance models (Sebaaly et al 1995; Livneh 1996; Kerali et al 1995; Gulen et al 2001; Labi and Sinha 2003 and 2005; Lamptey 2004; Dadang et al 2005; Irfan et al 2009). Rajagopal and George (1991) developed a treatment-specific performance model for six preventive treatments: chip seal, crack sealing, slurry seal, thin overlay, joint and crack sealing, and undersealing. Al-Mansour et al (1994) studied the effect of various routine maintenance activities on pavement roughness and concluded that routine maintenance has little impact when pavements are in good condition and has an increasing impact as pavements deteriorate.

2.3.2 Mechanistic Models

Mechanistic models are physical models that rely completely on the mechanics of materials (e.g., stress, strain, and deflection). They represent pavement responses as they are subjected to loads in various conditions, such as environment and traffic conditions. Several studies developed mechanistic pavement performance models, however, a comprehensive model has yet to be found. The existing models were developed under specific conditions, which make an empirical validation under different conditions difficult. This has decreased the prevalence of these models and indicates the complexity of the pavement deterioration process and the difficulty of properly modeling it (Prozzi and Madanat 2003). In addition to this difficulty, obtaining the data needed to develop those models is very challenging (ONYANGO, 2009).

Interested readers wanting to acquire more details about mechanistic models are referred to the following studies: Whiffin and Lister (1962), Klomp and Niesman (1967), Gusfeldt and Dempwolff (1967), Nijboer (1967), Hicks and Finn (1970), Thrower et al (1972), Ros et al (1982), Bao (2000), Ullidtz (2002), and Barrett and Timm (2005). A review of these studies can be found in a study by Selvaraj (2012).

2.3.3 Empirical-Mechanistic Models

Empirical-mechanistic models are developed based on testing the material properties using pavement response models (e.g., finite element) to determine pavement behavior. The pavement responses then are calibrated based on an actual pavement structure (Prozzi, 2001). Empirical-mechanistic models are currently the focus of attention of researchers and transportation agencies that have started to direct their efforts toward these models (Prozzi 2001; Sun 2003). To illustrate this interest from transportation agencies, the AASHTO Design Guides (1986) has been applied by the Michigan Department of Transportation (MDOT 1993) for modeling flexible and rigid pavement performance (Irfan 2010). The California Department of Transportation (Caltrans) also developed a mechanistic-empirical design guide (1990) motivated by the need to draw attention to pavement rehabilitation and preservation activities (Mandapaka et al 2012).

Pavement condition models, in general, show performance jumps and performance trends, which are indicators representing pavement conditions in the short-term and long-term analyses, respectively. Performance jumps (PJ), or sudden increases in pavement condition, have been used in modeling pavement performance after M&R activities (Lytton 1987; Colluci-Rios and Sinha 1985; Rajagopal and George 1991; Markow 1991; Mouaket et al 1992; Li and Sinha 2000). A comprehensive literature review regarding short and long-term maintenance effectiveness evaluation can be found in Li and Sinha (2000). For the purpose of creating the framework developed in this thesis, the prediction models for short and long-term pavement performance developed by Irfan (2010) were implemented. The main advantage of the Irfan models is that they were developed based on treatment-specific pavement performance and therefore allow for predicting the pavement performance for each candidate treatment. A discussion of the model and its implications follows.

2.4 Assessing the Impact of Utility Cuts on Pavement Infrastructure

Failure of a buried pipe located under a paved road requires immediate intervention to repair or replace it. Fixing this pipe will usually require the use of the open-cut excavation method, which is the most widely used method for accessing buried pipelines (Yeun and Sinha 2007). The use of this method has an impact on the surface condition of the pavement located above the pipe, which can be mainly attributed to the cutting and patching of the existing pavement. The cutting and patching activities accelerate the pavement deterioration process, reduce pavement service life, and shorten time periods between required M&R applications. Several cities (Burlington, VT, Los Angeles, CA, San Francisco, CA, and Sacramento, CA) conducted studies to assess the impact of utility cuts on pavements in order to transform such impacts to monetary values that could be applied as fees to the utility company when performing the cutting and patching processes to city streets. The following is a brief description of these efforts.

The City of Burlington, VT performed a study that consisted of 50 pavement sections randomly chosen and tested. A Pavement Condition Index (PCI) survey was used to assess the impact of utility cuts on the pavements' functional condition. The structural condition was also assessed by performing a nondestructive deflection test (NDT) using a falling weight deflectometer (FWD). From the PCI analysis it was found that utility cutting and patching reduced the pavement life by a factor of 1.64. That is, if the estimated service life of a specific pavement section is 20 years, the pavement service life was reduced to approximately 12.2 years after the cutting and patching to that pavement section. The NDT indicated that the patched area required about 0.75 in. to 1.5 in. in depth of overlay thickness. An estimated increased cost of pavement M&R due to the cutting and patching was found to be about $500,000 annually (Stephen and Katherine 1999).

The City of Los Angeles, CA tested a random 100 pavement sections; half of them consisted of local streets and the other half were major streets. Along with the PCI survey analysis and the NDT assessment, a standard penetration test was also performed to test the soil strength. The factor of pavement service live reduction was found to be 1.21 and 1.52 for local streets and major streets, respectively. The patched area required about 0.66 in. and 2.31 in. in depth of the overlay thickness for local streets and major streets, respectively. The estimated cost of M&R for the local streets was about $3.5 million and $12.9 million for the major streets. The cost of the calculated fees was further classified on the basis of pavement age as shown in Table 2-1 (NCE Inc. 2007)

Table 2-1 Fee Costs for the City of Los Angeles (NCE Inc. 2007)

Road Classifications	Pavement Age (Years)	Cost Fee ($/Sq. ft.)
Local	1-5	5.15
	5-10	4.57
	10-15	4.29
	15-20	3.88
	20-25	3.43
Major	1-5	14.08
	5-10	11.73
	10-15	9.39

The City of San Francisco, CA conducted a study in 1992 to assess the effect of utility cuts in pavements and found that they caused a 50% reduction in pavement service life. However, the data and the methods used in the study were questioned by local companies (No information was found regarding the doubt of local companies about the study’s outcomes).

Therefore, the city engaged an expert panel to reconsider and modify the study. The conclusion of the expert panel study supported the original study (BRP Inc. 1998).

The City of Sacramento, CA performed an analysis on a sample of streets that were grouped into four areas on the basis of soil and traffic conditions. Only a NDT using Dynaflect was performed to assess the impact of utility cuts on pavement service life. The assessment was carried out for two types of cuts (i.e., longitudinal and transfers cuts). It was concluded that for the longitudinal cuts, an additional 1.5 in. overlay was required. Moreover, the extent of the damage from the patch edge was found to be around 3.64 ft. Based on the analysis, a fee cost for each of the two types of cuts were calculated, which are presented in Table 2-2 (NCE Inc. 2007).

The City of Seattle, WA applied two methodologies to determine the impact of utility cuts on pavement performance (i.e., the overall condition Index (OCI) survey and the FWD). The two methods were used to test around 300 pavement sections; and it was found that, as a result of utility cuts, all pavement sections required an additional overlay ranging from 0.3 in. to 3.3 in. of thickness with a mean of 1.6 in. A recommended fee cost was estimated to be $17.70 per sq. ft. (Yapp et al 2001).

Table 2-2 Fee Costs for the City of Sacramento (NCE Inc. 2007)

Road Classifications	Pavement Age (Years)	Cost Fee ($/Linear ft.)
Longitudinal	<5	3.5
	5-10	3.0
	10-15	2.0
	>15	1.0
Transvers	<5	7.0
	5-10	6.0
	10-15	4.0
	>15	2.0

In addition to the reduction in service life that was established by the above studies, pavement condition indexes for sections with utility cuts were found to have lower values than sections without them. Additionally, these cuts also were found to have extended impacts on the adjacent areas of the pavement where an alligator cracks might develop. Therefore, based on these findings, the economic impact of utility cuts are assessed and usually estimated as the cost of the required increased overlay thickness. Some agencies (e.g., Union City, CA and Seattle, WA) developed a flat fee for compensating for damages to pavements due to utility cuts. However, more agencies (e.g., Sacramento, CA, Los Angeles, CA, and San Francisco, CA) use specific fees based on the age of the pavement; and their rationale is that pavements which have reached 20 to 25 years of age require rehabilitation irrespective of the existence of utility cuts. For non-emergency cuts, agencies often freeze such action on new pavements. The City of Sacramento, CA encourages utility companies to provide established five-year repair plans to allow for coordinating pavement rehabilitation. Utility companies that are successful in the coordination process may be eligible for a fee waiver ("Impact of utility cuts" 2000). Along with the aforementioned public agency funded studies, utility companies have funded and continue to fund studies in response to the changes to trench repair specifications made by public agencies. For example, a study was conducted for the SoCalGas by ARE Engineering Consultants, Inc. to assess the impacts of different backfill types and cut configurations (i.e., standard and T-section) on pavements. A street with 16 cuts was examined and no significant deformation or distress were noted (Todres and Wu 1990).

Although investigating the short-term effects of utility cuts on pavement is essential, analyzing and evaluating the impacts of utility cuts on the pavement life cycle is equally important. The evaluation of lifecycle impacts leads to a comprehensive assessment of the problem under consideration (coordination of pipeline and pavement M&R activities). During the pavement life cycle, a combination of M&R activities possibly could be implemented and thus, different pavement scenarios might respond differently to utility cuts. Therefore, this thesis develops a methodology for assessing the impact of water pipeline M&R activities (i.e., utility cuts) on the pavement infrastructure based on LCCA. The developed methodology is presented in the following chapters.

2.5 Chapter Summary

This chapter presented a comprehensive literature review on pipe failure prediction models and pavement performance models. Pipe failure prediction models are developed to predict probable pipe failures while pavement performance models are used to approximately represent the status of pavement deterioration. Deterministic modeling approaches are widely accepted in modeling pavement performance; but due to the uncertainty involved in predicting pipe failure, probabilistic modeling approaches were found to be more applicable to pipe failure prediction. Pavement performance models and pipe failure prediction models are essential tools from a management perspective in analyzing M&R alternatives.

CHAPTER 3. THESIS FRAMEWORK

3.1 Introduction

The thesis framework (presented in Figure 3-1) addresses three main aspects of asset management of water distribution systems and the pavement infrastructure: (1) how to assess the impact of water pipelines M&R activities on the pavement infrastructure based on LCCA; (2) how to coordinate water pipeline and pavement M&R activities; and (3) how to assess the effects of coordinating these two systems on the total LCCA of both systems.

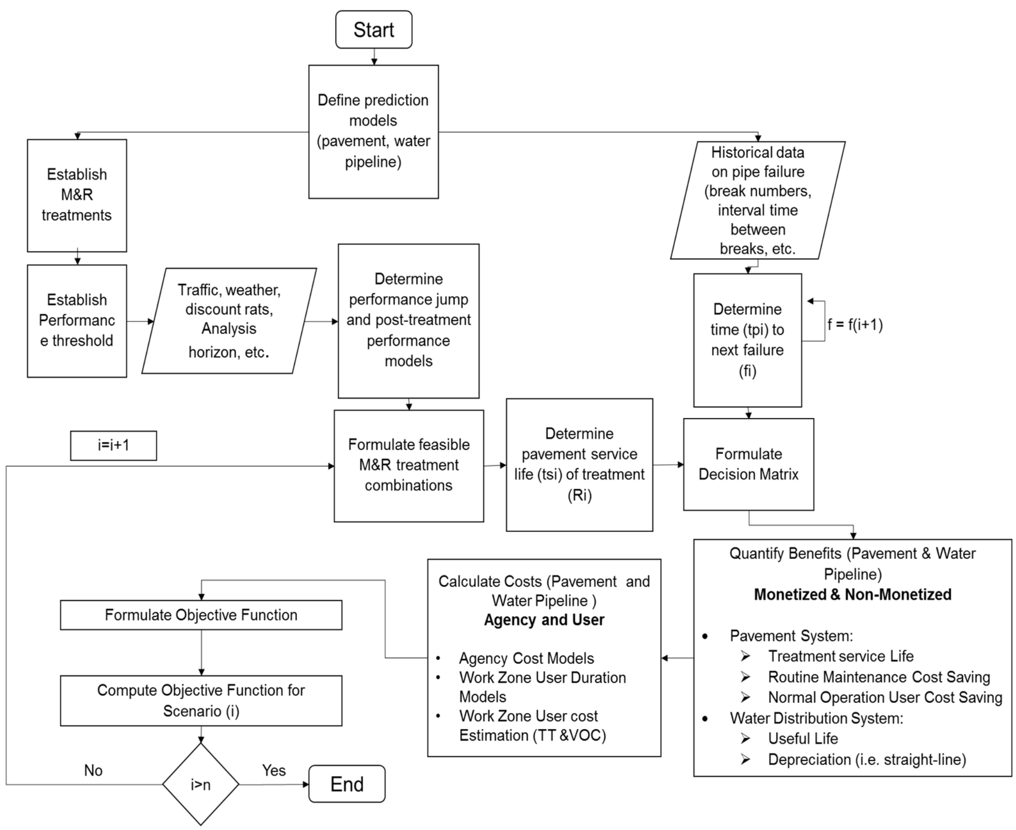


Figure 3-1 Flow Chart of Selecting Best Scenario of Coordinating Pavement and Water Pipeline Based on LCCA

The framework accomplishes the following goals: (1) defines a pavement performance model and a water pipeline failure prediction model; (2) establishes the pavement M&R treatments to be evaluated; (3) defines a pavement performance threshold; (4) develops an analytical decision approach to regulate the interactions between M&R activities in the two systems; (5) determines the treatment cost for both assets; (6) defines the treatment effectiveness for both assets; and (7) formulates a cost-effectiveness analysis. The thesis framework is discussed in detail in the ensuing sections.

3.2 Pavement Performance Model - Introduction

The pavement performance model is a key aspect in pavement management systems, particularly in planning M&R activities. Knowing the condition of the pavement helps in formulating effective decisions and to develop realistic schedules and budgets for the short and long term. This knowledge is also needed in estimating treatment performance jumps and post-treatment performance, which are the techniques used to evaluate treatment effectiveness in short and long-term analyses, respectively. The performance jump represents the immediate change, right after applying the treatment, in pavement condition. A performance trend, on the other hand, represents the gradual changes in pavement condition throughout the treatment service life that follows the application of a treatment. Figure 3-2 depicts the concepts of treatment performance jump and post-treatment performance. Pavement performance models determine the pavement condition over its life cycle and, therefore, serve as a critical input for determining intervention times in any simulation process that aims at modeling pavement condition. For the purpose of demonstrating the framework developed in this thesis, the pavement performance models (i.e., performance jump and post-treatment performance) developed by Irfan (2010) and presented in the ensuing section are implemented.

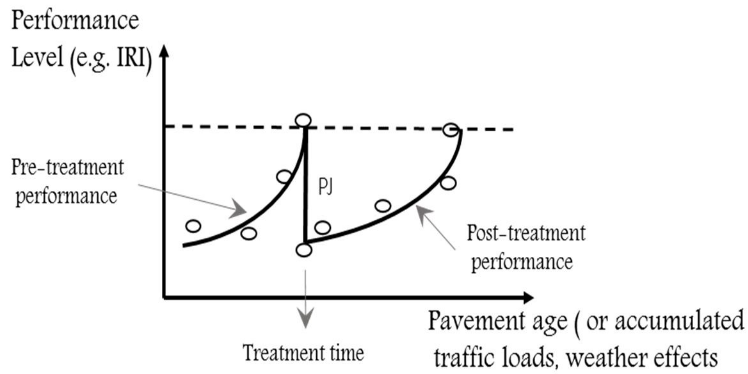


Figure 3-2 Treatment Performance Jump and Post Treatment Performance

3.2.1 Pavement Performance Model

Irfan (2010) developed deterministic models based on treatment-specific pavement performance. The general form of the developed performance jump and post-treatment performance are indicated in Equations (3.1) and (3.2), respectively.

$$PJ_s = \mu(1)_s + \mu(2)_{s.}[lnPI_{trig}] \tag{3.1}$$

Where: PJ_s = performance jump at time of applying treatment s, μ1 = constant term, μ2 = parameter to be estimated based on the explanatory variables, PI_{trig} = pavement performance trigger value for treatments at the time of application.

$$PI = e^{[\alpha+\beta.AATA.t+\gamma.ANDX.t]} \tag{3.2}$$

Where: PI = performance indicator measured in term of IRI (in in/mi), t = treatment service life (years), AATA = accumulated annual truck traffic loadings (million-years), ANDX = accumulated annual freezing index (thousands-years), α = constant, and β&γ = estimated parameters of the explanatory variables.

Several types of pavements and M&R treatments were considered in developing the performance jump and post-treatment performance models. The pavement types were classified by surface type and functional classification. The main pavement types considered included flexible, rigid, and composite pavements, while the main functional classifications considered included Interstate, Non-National Highway System (NHS) (Non-Interstate), and (NHS). Irfan (2010) developed performance models for various flexible and rigid pavement M&R treatments. Figure 3-3 shows the considered M&R treatments. More details concerning pavement types and M&R treatment types can be found in Irfan (2010). The estimated performance jump and post-treatment performance values for each of the flexible pavement treatment types and functional classes are provided in Appendix A.

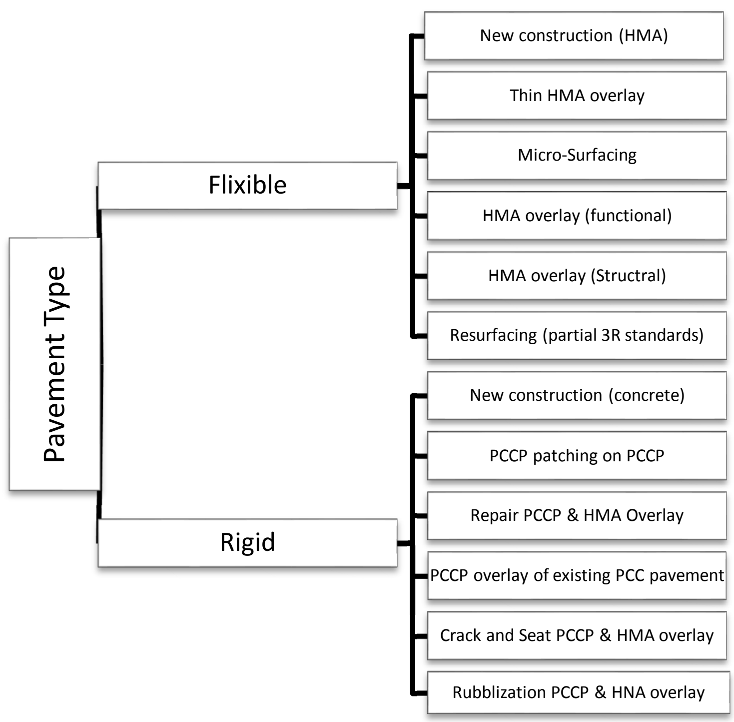


Figure 3-3 Considered M&R Tretments in Irfan’s Study

The developed models are statistically significant at 95% confidence level and represent a good fit. Furthermore, validation (i.e., 80% of the data to calibrate the models and 20% to validate them) was carried out to test the prediction power of the developed performance models and were found to have a high ability to predict pavement performance. These pavement performance models are employed in this thesis to predict the time of the M&R activities to be taken and thereby assist in coordinating them with the M&R of the water distribution system (discussed in Section 3.6.3).Therefore, knowing the time for the M&R interventions of the water pipeline system is, similarly, critical in the coordination development. The following sections discuss water pipe failure prediction models.

3.3 Water Pipeline Failure Prediction Models – Introduction

Forecasting water pipeline performance is vital in managing this infrastructure system. This forecasting process requires the development of pipe performance prediction models that can determine pipe failure time and thus assist in creating M&R schedules and associated budgets. Estimating the occurrence of individual pipe failures would help in determining when pipes need to be maintained, which is an essential requirement for coordinating water pipeline and pavement M&R (as discussed in Section 3.6.3). As such, the individual water pipeline failure prediction model in the framework proposed in this thesis was based on the work of Mailhot et al (2000). The subsequent section presents the model in detail.

3.3.1 Water Pipeline Failure Prediction Models

The pipeline failure prediction model that will be used in the present framework is a probabilistic model for predicting individual pipe breaks (Mailhot et al 2000). As explained earlier, the main advantage of this model is its capability of predicting pipe failure with an incomplete pipe break history, which is very common among municipal water infrastructure agencies. The time between breaks is modeled based on two types of probability distribution:

a two-parameter Weibull distribution and a one parameter exponential distribution. Various combinations of different orders of breaks are modeled using these two probability distributions. Survival analysis is then used to estimate the model parameters using the likelihood function. The model is, therefore, developed based on the break history data associated with each pipe in the network. The main advantage of the model is its prediction power and its insensitivity to missing or unrecorded break data. The model was previously applied to the municipality of the City of Chicoutimi, Quebec, Canada (Mailhot et al 2000). The total length of the Chicoutimi's water pipeline system was about 353 km and the number of pipe segments was 2096, 86% of which were less than 300 m in length. The total number of breaks observed during 21 years (1976-1996) was 2,289, 1,719 of which were related to a single pipe segment. Four models were considered for different break orders. These models and their estimated parameters are presented in Appendix B. The estimated model parameters are used in this thesis to predict the time of M&R activities (i.e., the time of pipe failure) for water pipelines in order to coordinate them with pavement M&R activities.

3.4 Establishing Pavement M&R Treatments

M&R activities are necessary to sustain pavement quality and improve its structural and functional condition. M&R activities typically encompass preventive and rehabilitation work. Preventive maintenance corrects minor defects and is applied subject to several factors, such as the traffic volume and the type of road to be treated. Thin hot-mix asphalt (HMA) overlay, micro-surfacing, chip sealing, and crack sealing are examples of preventive maintenance work for flexible pavement. Thin HMA overlay is intended mainly to enhance the pavement structure (e.g., surface roughness, rutting, and ride quality enhancement) and to decelerate the pavement deterioration process. Micro-surfacing is applied to slightly enhance pavement service, for example, by enhancing pavement skid resistance (Irfan 2010). Sealing and filling the cracks in pavements is a common pavement preventive maintenance practice that aims to fill and prevent cracks in order to stop the intrusion of water in the pavement, which makes the pavement more susceptible to damage from freezing and thawing).

Rehabilitation activities are major works that upgrade the pavement condition and thereby delay the deterioration process. Functional HMA overlay, structural HMA overlay, and resurfacing (partial 3R) are types of flexible pavement rehabilitation activities. Functional HMA overlays contribute mainly to the functional performance of pavement (e.g., pavement smoothness) and adds little, if anything, to its structural performance. Structural HMA overlays, on the other hand, mainly strengthen the pavement structure. After a period of time, the constructed pavement would reach the end of its service life regardless of the M&R activities performed on it. At this time, new construction would be needed. During a pavement's life, combinations of M&R might be performed. In fact, hundreds of these combinations can be formulated. Therefore, in this thesis, several M&R scenarios are implemented and analyzed to assess and evaluate the effectiveness of each scenario while considering the impact of the pipeline infrastructure.

3.5 Establishing Threshold Values

Threshold values for performance indicators are established to ensure an acceptable pavement condition. An optimal performance threshold aims to sustain a pavement condition that maximizes the effectiveness and minimizes the cost of M&R activities. Threshold values might vary depending on the treatment type and external conditions. Unfortunately, there is no unified set of threshold values for different pavement treatments and each agency has its own values. These values are established either on the basis of expert opinion or on customary practices, and they can be time-based or performance–based. The latter has been applied more than the former by transportation agencies due to its technical basis. A framework was developed by Khurshied et al (2010) that proposed a methodology for obtaining optimal performance thresholds for highway asset interventions. In this thesis, different threshold values were chosen (based on the 2001 Indiana Department of Transportation (INDOT) standards) and were executed while assessing their impacts on the LCCA considering the impact of pipe failure on pavement condition.

3.6 Formulating Decision Model

The objective of the decision model is to regulate the interactions of M&R interventions in the pavement and water distribution infrastructure systems utilizing the aforementioned prediction models of both systems. Prediction models serve to define the time that these interventions are needed as well as the procedure for coordinating the M&R activities of both systems. This procedure is hereafter named "Decision Model" and is explained in detail in the following section.

3.6.1 Assessing the Impact of Water Pipeline Intervention on Pavement Infrastructure Based on LCCA

Despite the fact that there is a common agreement on the effect of utility cuts on pavement service life, the effects of consecutive cuts on a specific pavement section has not been well established. The question of whether the first cut has the same impact on pavement service life as the second cut, third cut, fourth cut, etc. remains to be answered. If these cuts have different impacts, what is the percentage of pavement service life reduction associated with each cut? In addition, the performance of pavement after a utility cut has taken place has not yet been established. For instance, if pavement service life has been reduced to 50% by a utility cut, would that cause a similar reduction in the pavement condition? A methodology is developed in this thesis for quantifying the impact of pipe failures on both pavement service life and pavement condition. A description of the methodology is presented in the following sections.

3.6.1.1 Pipe Failure Impact on Pavement Service Live

For the purpose of this thesis, only the first utility cut during the service life of a specific pavement will be considered to have an impact on pavement service life (the impact of pavement treatment types on pipe failure is not considered in this thesis). This reduction will be considered as 30% of the total service life, which is a conservative estimate (see Section 2.4). For instance, suppose that a water pipeline under an existing new pavement failed and needed be restored using the open-cut method, which requires the cutting of the pavement. The performed cut impacts the pavement service life after restoring the pavement by reducing its life by 30%. In the case of subsequent breaks taking place under the considered pavement section, their impacts, if any, are not accounted for and only the first break is considered to have an impact on pavement service life. After carrying out a new treatment on the same pavement section, the first cut during that treatment service life is also considered to have an impact while the following cuts do not have impacts. This pattern continues until the end of the analysis period. An illustration of the impact of pipe failures (and hence utility cuts) on new pavement service life is depicted in Figure 3.4.

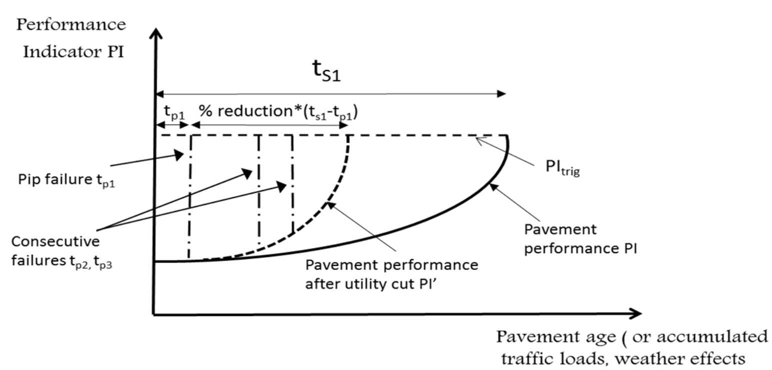


Figure 3-4 Graphical Illustration of Pipe Failures Impact on New Pavement Service Life

In Figure 3-4, the service life of the new pavement (t_{s1}), when no pipe failures are encountered, is the time from constructing the pavement until the pavement condition reaches the maximum (in case of an increasing performance index or a minimum for a decreasing performance index) performance level or the optimal performance triggering (PI_{trigg}). When a pavement experiences utility cuts which could be due to the need to fix a failed buried pipe using the open-cut excavation method, the pavement service life becomes the sum of the time to the first pipe failure (t_{p1}) and the estimated percentage reduction in life caused by the utility cut multiplied by the difference between the pavement service life with no cuts (t_{s1}) and the time to the first pipe failure (t_{p1}). The estimated pavement service life with one or more cuts are termed hereafter the "actual pavement service life" (t'_{s1}) and can be estimated using Equation (3.3). A general form of Equation (3.3) is presented in Equation (3.4)

$$t's1 = tp1 + \%\ \text{estimated reduction of pavement service life} * (ts1 - tp1) \quad (3.3)$$

$$t's_i = tp_i + \%\ \text{estimated reduction of pavement service life} * (ts_i - tp_i) \quad (3.4)$$

Where: t'_{si} = the actual pavement service life of treatment i, t_{pi} = the time to the first pipe failure occurs during the ith treatment service life and t_{si} = the service life of treatment i.

Having determined the pavement performance indicator as stated in Equation (3.2), the pavement service life (ts1) and the actual pavement service life (t's1) can be estimated using Equation (3.5).

$$ts = \frac{\ln(PItrigg) - a}{\beta.AATA + \gamma.ANDX} \quad (3.5)$$

Performing a utility cut on a pavement would have a noticeable impact on the following M&R treatments. Accordingly, in the given example, subsequent treatments shall start when the actual pavement performance (PI') reaches the optimal triggering value (PI_{trig}). Figure 3.5

illustrates the application time of the subsequent treatment (s2) when the prior treatment has encountered a utility cut during its service life

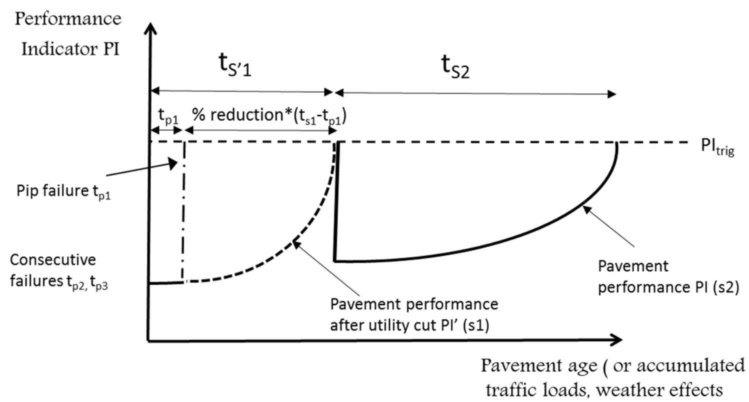


Figure 3-5 Graphical Illustration of the Application Time of Second Treatment

It can be seen in Figure 3-5 that the second treatment (s2) is not subject to pipe failures and, thus, no reduction on the second treatment's service life (t_{s2}) is shown. If pipe failures occur during the service life of the second treatment, these failures would result in the reduction of the second treatment's service life (t_{s2}). The estimation of the actual second treatment's servce life (t'_{s2}) is obtained using Equation (3.5). The consecutive treatment applications during the life cycle analysis are treated as explained for the first and second treatments.

3.6.1.2 Pipe Failure Impact on Pavement Condtion

Any type of asset can have a prolonged service life with an observable poor condition. This is also a fact for pavement assets where some pavement sections have a long service life (typically, the deterioration rate remains relatively constant at the end of its service life) with a noticeably poor riding quality. Therefore, not only do utility cuts affect pavement service life, but they also diminish pavement condition, which may lead to road user dissatisfaction.

Accordingly, having determined the actual service life (t'_{s1}), from Section 3.6.2.1, the actual performance is estimated using the general Equation 3.6.

$$PI'_i = PI_{tpi} + PI_{ts''I} \qquad (3.6)$$

$$PI_{tpi} = e^{[\alpha+\beta.AATA.t+\gamma.ANDX.t_{pi}]} \qquad (3.7)$$

$$PI_{ts''i} = e^{[\alpha+\beta.AATA.t+\gamma.ANDX.t_{s''i}]} \qquad (3.8)$$

Where: PI'_i = actual performance indicator for treatment i measured in term of IRI (in in/mi), PI_{tp1} = actual performance indicator for treatment i before pipe failure takes place measured in terms of IRI (in in/mi), $PI_{ts''1}$ = actual performance indicator for treatment i after pipe failure takes place measured in terms of IRI (in in/mi), and ts''_i = % of reduction in treatment service life (years) after pipe failure multiplied by the difference between ts_i and tpi. All other notations used have the same meaning as formerly explained.

Similarly, the performance of subsequent treatments is evaluated on the basis of whether or not pipe failures occur during their service lives. If a pipe failure takes place during the service time of treatment (i), then the condition of treatment (i) is calculated using Equation (3.6). However, if no pipe failures are experienced throughout the service life of treatment (i), Equation (3.2) is applied.

3.6.2 Formulating Decision Matrix

The decision matrix provides guidelines, in the form of if-statements, which determine when pipe failures occur with respect to the service life of the pavement. The time of pipe failure incidents, which already has been determined, is linked to which pavement treatment they have occurred under (i.e., first treatment, second treatment, etc.). The formulation of the decision matrix for the first pipe failure is illustrated in Figure 3-6. In this decision matrix, when the time to the first pipe failure (t_{p1}) (as depicted in the right graph) is greater than the first pavement treatment service life (t_{s1}), no intervention would take place during t_{s1} and the pavement condition and service life thus remain unaffected. In case t_{p1} is less than t_{s1}, an intervention would be necessary, causing reduction to both the pavement condition and the service life and, therefore, t_{s1} becomes $t_{s'1}$ as shown on the left graph. Pipe failures subsequent to the first failure that occur during (t_{s1}) are considered to have no further impact (as shown in Figure 3-6) on the first treatment service life (t_{s1}), however recording their occurrence time (represented by the "&" notation in Figures 3-6, 3-7, and 3-8) is essential for estimating the agency cost and user cost associated with each failure in LCCA. Figure 3-7 illustrates the effects of consecutive pipe failures on the first pavement treatment service life (t_{s1}).

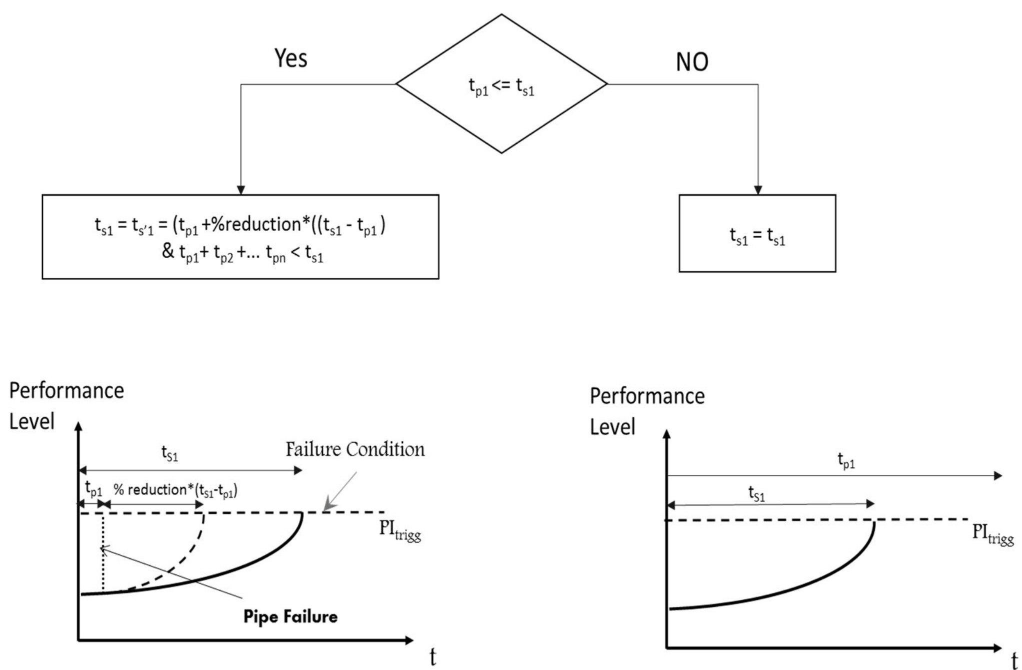


Figure 3-6 Decision Matrix with Illustration Graphics for First Pipe Failure

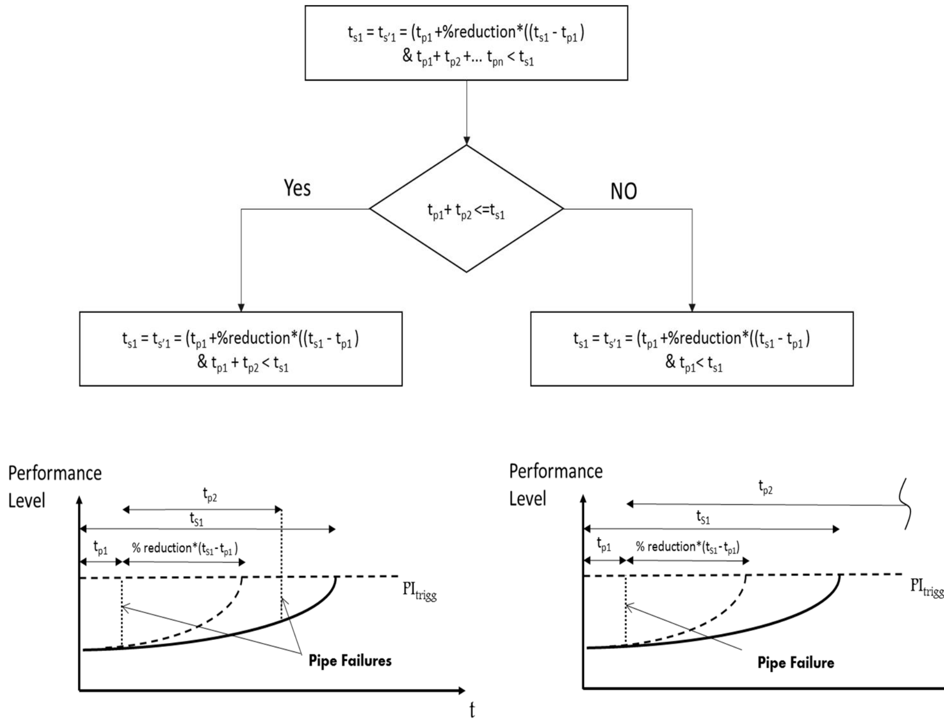


Figure 3-7 Decision Matrix with Graphical Illustration of Consecutive Pipe Failures

From Figure 3-7, when both cases (i.e., second pipe failure (tp2) occur during the first pavement treatment life (ts1) or after the first treatment service life (ts1)), the pavement treatment service life becomes the actual pavement service life. However, the two scenarios have different costs and benefits analyses that certainly need to be considered.

Knowing that the first pipe failure (p1) did not occur during the first pavement treatment service life (t_{s1}) leads to the second stage in the decision matrix explained in Figure 3-8. The second stage is concerned with pipe failures taking place during the second pavement treatment service life (t_{s2}). In the case where no pipe failures are encountered during the t_{s2}, the resulting service life of the treatments, as illustrated on the right graph in Figure 3-8, would be the sum of t_{s1} and t_{s2}. If this continues to the subsequent treatments, the service life of all treatments that are not affected on a specific section would be the sum of all applied treatments that did not experience pipe breaks (i.e., $t_{s1} + t_{s2} + ... + t_{sn}$). However, if during the second pavement treatment's service life (t_{s2}) a pipe failure is experienced, the resulting service life would be the sum of the service life of the first pavement treatment (t_{s1}) and the service life of second pavement treatment (t_{s2}) with the reduction to its service life that resulted from pipe failure. Similarly, only the first pipe failure during the second pavement treatment service life (t_{s2}) is considered to have an impact while the following pipe failures are counted to be used in the LCCA. The same procedure is, then repeated until the end of the analysis period.

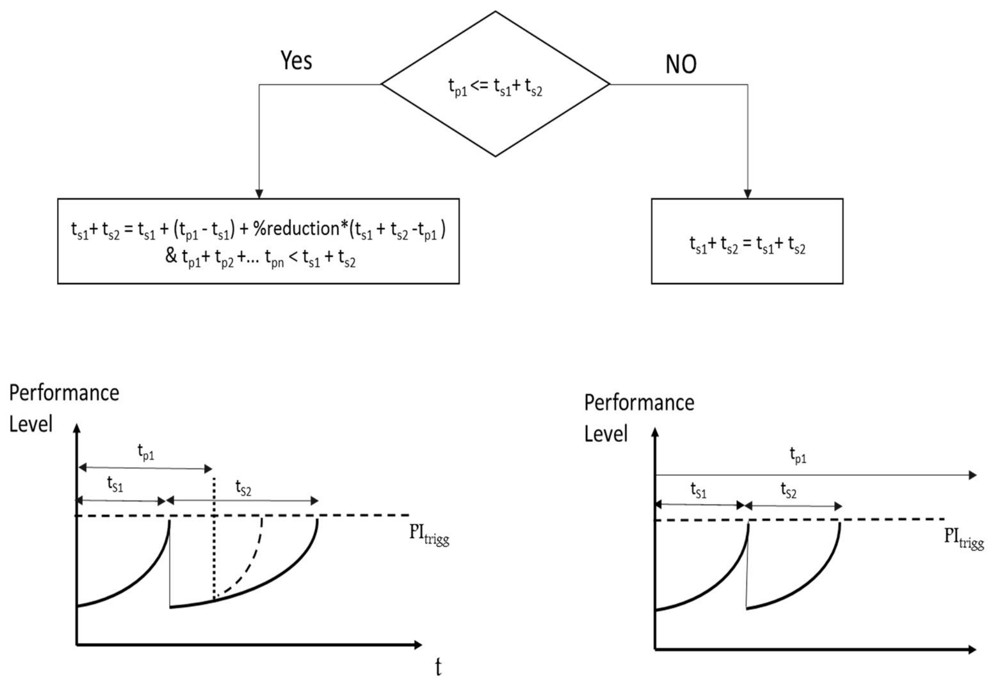


Figure 3-8 Decision Matrix with Illustration Graphics for First Pipe Failure–Second Stage

When an event takes place (i.e., pavement condition reaches the threshold and/or the pipe needs to be maintained), an immediate action needs to be taken. The action to be taken is mainly influenced by the state of both assets (i.e., pavement and water pipe). Once either of the assets requires intervention, the other asset condition would govern the decision taken. For instance, if the pipe fails and the pavement treatment service life ends at the same time, fixing both assets might lead to reduction in agency and user costs. However, it is unlikely to have both assets fail at the same time; hence, in the case of the pipe failing prior to the end of pavement treatment service live, the time of applying subsequent treatment might be adjusted to match the expected time of pipe failure and thus allow possibly restoring both assets concurrently. Figures 3-9 and 3-10 graphically illustrate the pavement life cycle profile with and without considering the concept of coordination.

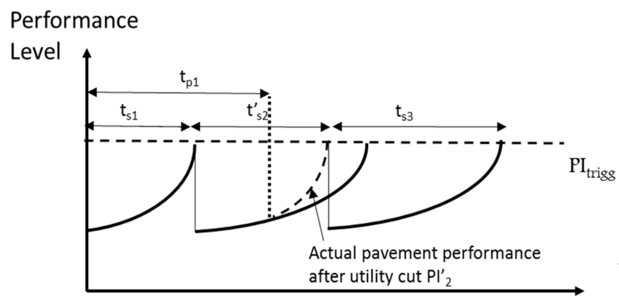


Figure 3-9 Graphical Illustration of Pavement Life Cycle Profile – Without Coordination

Figure 3.9 indicates that the pipe failure (represented by the vertical dashed line) occurred during the second pavement treatment service life and caused a reduction to its service live (t's2). At the end of ts2, a subsequent treatment is then applied. Noticeably, only the impact of the pipe failure on the pavement service life is considered, and there is no change in the time of application of the third treatment in response to the pipe failure time.

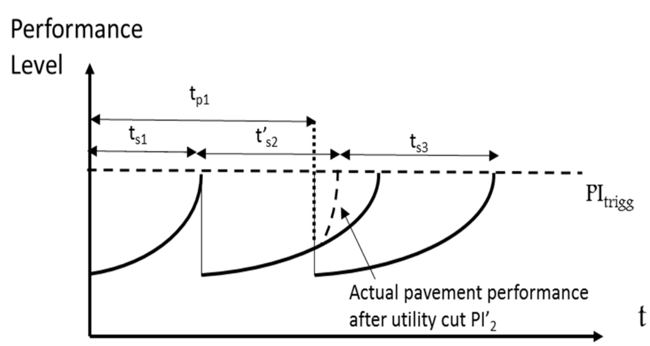


Figure 3-10 Graphical Illustration of Pavement Life Cycle Profile – With Coordination

In the case where the concept of coordinating between the two systems is considered, the application of the third treatment would take place at the time of pipe failure even though the second pavement treatment has not yet reached the end of its service life. This creates a tradeoff between losing the benefits of the remaining useful life of the second pavement treatment and the cost savings resulting from the minimization of disturbances to users by having both assets restored at the same time. To determine when it is cost effective to carry out the treatment before its scheduled time, an analysis will have to be performed considering different scenarios of possible pavement treatment combinations. For each scenario, the benefits (effectiveness) and the costs for candidate combinations of M&R activities for both types of assets are evaluated and LCCA is performed. The evaluation of the treatment benefits (effectiveness) and the costs for water pipeline and pavement is explained in ensuing sections.

3.7 Effectiveness (Benefits) Evaluation

The effectiveness of asset treatment can be modeled by the change in the asset's attributes impacted by the treatment application. These attributes are either desirable (positive), such as increases in asset service life, or undesirable (negative), such as reductions in asset service live. The effectiveness (benefits) can be measured using different approaches on the basis of short or long-term impacts. These approaches are presented in subsequent sections.

3.7.1 Pavement M&R Effectiveness (Benefits) Evaluation

Pavement M&R effectiveness has been evaluated in numerous past studies. The studies that used statistical data to evaluate M&R treatments for flexible and rigid pavement include Morian et al (2003), Ambroz and Darter (2005), Khurshid et al (2009), and Irfan et al (2009). Relatively fewer studies were performed to develop mathematical functions for measuring the effectiveness of any pavement treatment in the short and long term. These studies included the work of Labi and Sinha (2003) and Labi et al (2005). Effectiveness in these studies was approached using the concepts of monetized and non-monetized effectiveness for short-term and long-term analysis. In this thesis, the monetized and non-monetized long-term effectiveness of a treatment are considered and are discussed in the ensuing section.

3.7.1.1 Estimating Pavement M&R Long-Term Effectiveness (Benefits) –Non-Monetized

The long-term effectiveness of a pavement treatment is typically assessed using three measures: 1) treatment service life (TSL), 2) increased averaged pavement performance over the treatment service life, and 3) increased area under or above performance curve for decreasing or increasing the performance indicators, respectively.

Asset treatment service life (TSL) can be estimated by determining the period between the time of treatment application and the time of applying the subsequent treatment. This life can be represented by time, accumulated traffic, or climatic effects. The data requirements to obtain treatment service life are less intense, which is considered an advantage of this method. However, the method has a major drawback in that treatment application times are influenced mainly by budget limitations and political decisions, which are not considered by the method. Another common approach for estimating asset treatment service life is using performance curves developed from collected asset condition data. At the point where the curve reaches a determined threshold, the corresponding time represents the end of treatment service life. Thus, the difference between the time of implementing the treatment and the time where the curve reaches the predetermined performance threshold is the amount of time the asset would survive in an acceptable condition. This time can be estimated using Equation (3.5). Figure 3-11 shows a graphical representation of pavement treatment service life.

$$ts = \frac{\ln(\mathrm{PItrigg}) - a}{\beta.\mathrm{AATA} + \gamma.\mathrm{ANDX}} \tag{3.5}$$

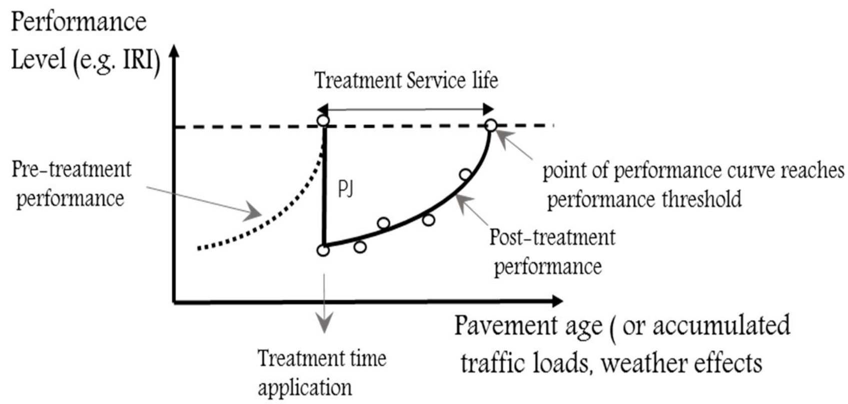


Figure 3-11Graphical Illustration of Treatment Service Life

3.7.1.2 Estimating Pavement M&R Long-Term Effectiveness (Benefits) - Monetized

The monetized approach expresses treatment effectiveness in terms of dollar values. Increasing the average asset performance over the treatment service life is an approach typically used to measure the treatment's long-term effectiveness. Having determined the asset performance model, the average value of the asset performance then can be estimated (see Figure 3-12). The average treatment performance indicator value can be calculated as shown in Equation (3.9):

$$PI_{Avg} = \frac{PI_0 + PI_1 + PI_2 + \cdots + PI_{Th}}{t_s} \tag{3.9}$$

Where PI_{AVg} = the average asset performance (e.g. IRI), PI_0 = Performance level just after treatment. PI_0, PI_1, PI_2, PI_{Th-1} = asset performance level at the in-between years, PI_{Th} = asset performance level when asset condition reaches the performance threshold, ts = treatment service life.

The increased average asset performance then is used to estimate the benefits related to the agency, such as annual maintenance cost savings, and the benefits gained by the users, such as vehicle operation cost savings.

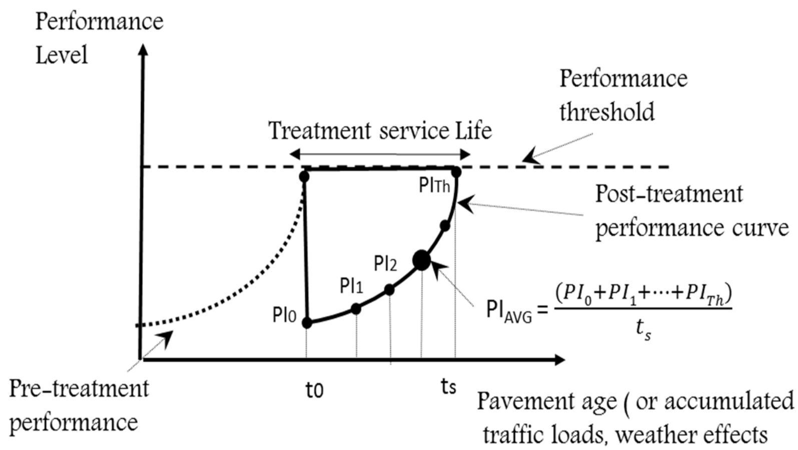


Figure 3-12 Graphical Illustration of Increased Average Asset Performance

<u>Maintenance cost savings (MCS)</u> is a method used to estimate the benefits related to the agency. Possible savings in annual maintenance costs are considered to be beneficial for the agency, and the resulting reduction in expenditures thus is a type of monetized benefits. An example of these annual maintenance cost savings can be the reduction in maintenance costs resulting from applying treatments at the proper time. When treatments are applied while the pavement is in fairly good condition, the expected improvement to the pavement would not be considerable. On the other hand, applying treatment at a late stage where the pavement has deteriorated to the point that replacement is needed would increase the expected costs. To address this issue, the Average Annual Maintenance Expenditure (AAMEX) model was developed by Labi and Sinha (2003). Al-Mansour and Sinha (1994) also developed annual basic routine maintenance cost models for the state of Indiana. They developed two models for roadway maintenance based on low or high traffic and another two models (similarly based

on low/high traffic) for shoulder maintenance. The general function of the model is presented in Equation (3.10). The model is a function of pavement performance in terms of the PSI at the time of treatment application. Table 3-1 presents the model parameters and their associated statistical values.

$$LogAMC = a + b.(PSI) \qquad \text{(Al-Mansour and Sinha, 1994)} \qquad (3.10)$$

Where: AMC = Annual roadway or shoulder maintenance expenditure $/lane-mail.

a, b = Estimated regression parameters; PSI = Pavement Serviceability Index.

Table 3-1 Estimated Regression Parameters of Annual Basic Routine Maintenance

Maintenance Type	Traffic level (AADT)	Overall Model Statistics			Estimated Parameters	
		No. of Observations	R2	p value	a	B
Roadway Maintenance	High Traffic AADT>2000	55	0.5193	0.0001	4.0283	-0.462
	Low Traffic AADT<=2000	67	0.5887	0.0001	3.7781	-0.4621
Shoulder Maintenance	High Traffic AADT>2000	14	0.4099	0.001	3.3221	-0.3547
	Low Traffic AADT<=2000	27	0.5693	0.0001	3.5323	-0.4573

[Adopted from Al-Mansour and Sinha, (1994)]

The performance indicator used in Equation (3.10) is PSI and to convert it to IRI, a model developed by Gulen et al (1994) can be used (as shown in Equation 3.11).

$$PSI = 9.0 * e^{(-0.008747 * IRI)} \qquad (3.11)$$

Where: IRI = International Roughness Index (in/mile)

The maintenance cost savings (MCS) corresponding to each treatment is calculated by computing the difference between the annual maintenance cost savings before and after applying the treatment. Equation (3.12) shows the general method for estimating maintenance cost savings.

MCSi=AMCi –AMCAvg(i) (3.12)

Where: MCSi = Maintenance cost saving corresponding to treatment i, AMCi = annual maintenance cost before applying treatment i, AMCAvg (i) = average annual maintenance cost after applying treatment i.

<u>Vehicle operation cost savings (VOCS)</u> is a method of quantifying treatment benefits gained by users in monetized terms. VOCS result from pavement condition improvements after treatment application. Such improvements can include, for example, increased road capacity which reduces travel time and thus less spending on fuel. The worse the pavement condition is, the more likely users are to spend money on operating their vehicles due to accelerated vehicle deterioration. A study in New Zealand (Opus 1999) developed the relationship between pavement performance and VOC (as shown in Figure 3-13). It suggests that the VOC start to occur and increase when the IRI exceed 100 in/mi.

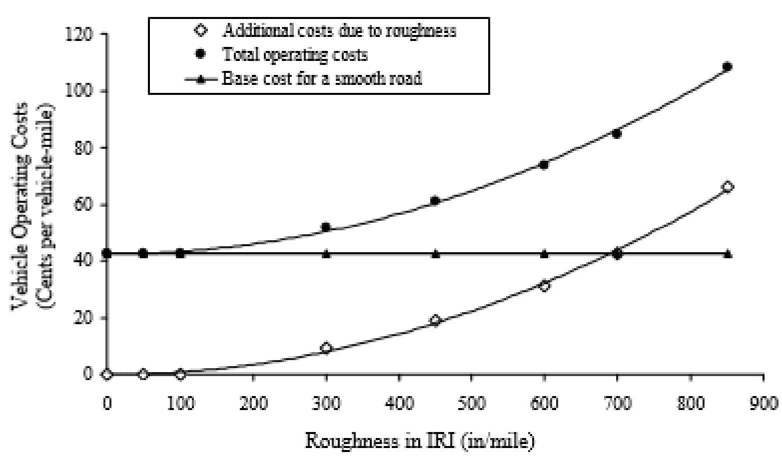


Figure 3-13 Relationship between Pavement Performance and Vehicle Operation Cost (adopted from Opus, 1999)

The vehicle operation cost savings (VOCS) corresponding to each treatment is calculated by computing the difference between the annual VOCS before and after the treatment. Equation (3.13) shows the general method for estimating VOCS.

$$VOCSi=VOCi-VOCAvg(i) \quad (3.13)$$

Where: VOCSi = vehicle operation cost saving corresponding to treatment i, VOCi = estimated annual vehicle operation cost before applying treatment i, VOCAvg (i) = estimated average annual vehicle operation cost after applying treatment i.

3.7.2 Water Distribution System M&R Effectiveness (Benefits) Evaluation

An extensive literature review was performed, which produced no studies that have assessed the effectiveness of the different types of M&R activities conducted by a water distribution system utilizing the open cut excavation method. One of the widely used approaches for the probabilistic modeling of water distribution systems is called the Rate of Occurrence of Failure (ROCOF) approach. This method simply depends on the recorded incidents of breaks during the pipe's life cycle. The ROCOF approach considers that replacing one broken pipe does not necessarily bring the system back to the "as good as new" condition; however, the system condition is assumed to be "as is" since the age and condition of other pipes in the system are variable. Therefore, the ROCOF approach assumes that the condition of the system remains unaffected by the type of the intervention after failure and therefore the system condition never becomes better than before the failure. This assumption has been assessed by several studies including Goulter and Kazemi (1987). Also, it was found that nearly 68% of the pipe breaks in Winnipeg's water distribution system are within 20 meters distance from preceding failures (Peter and Grigg 2006). Two proposed approaches for estimating the effectiveness of M&R activities for a water distribution system are discussed and presented in the ensuing sections.

3.7.2.1 Estimating Water Distribution System M&R Long-Term Effectiveness (Benefits) – Non-Monetized

The service life of M&R activities ($M\&R_{SL}$) is used to evaluate the non-monetized long-term effectiveness of water distribution system M&R efforts. The $M\&R_{SL}$ is estimated by determining the time between M&R activities and the time of pipe failure. Assuming that a failure occurs at time (t) in pipe (i) and a repair type (j) was chosen to be applied. The failure time (Ft) of pipe (i) is predicted in advance from the failure prediction model. Therefore, the time of applying repair type (j) is known and the time to next failure (using the same prediction model) is also known. The difference between these two times is the considered effectiveness of the repair type (j). This concept could be applied to all types of M&R activities (i.e., repair, rehabilitation and replacement) for water distribution systems. The general method for estimating $M\&R_{SL}$ is presented in Equation (3.14). Figure 3-14 is an illustration of the life cycle profile of a typical water pipeline subject to two types of M&R activities.

$$M\&R_{SL}\,(j, i) = Ft\,(j, i) - Ft\,(j-1, i) \tag{3.14}$$

Where: M&RsL (j, i) = service life of maintenance and rehabilitation activity type (j) at pipe (i), Ft (j, i) = failure time of M&R type (j) at pipe (i), Ft (j-1, i) = failure time of previous M&R type (j-1) at pipe (i).

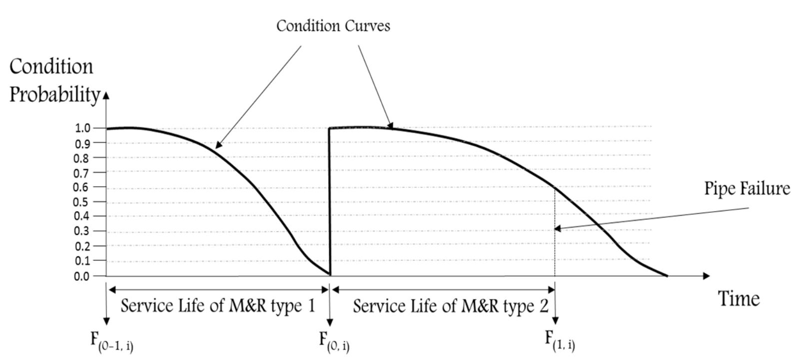


Figure 3-14 Graphical Illustration of Water Pipeline Life Cycle Profile – Two Types of M&R Activities.

From Figure 3-14, the application time of M&R type 1 is the taken time at F (0 -1, i), which indicates that no previous M&R activity (i.e. j = 0) was performed on pipe (i). The notation “F (0, i)” represents the end of the M&R type 1 service life and therefore its service life can be calculated by taking the difference between the end of M&R type 1 service life and the application time of M&R type 1 [i.e., F (0, i) - F (0 -1, i)]. The M&R type 2 at pipe (i) is performed immediately after the first one at F (0, i). Similarly, the service life of M&R type 2 is calculated by taking the difference between the end of its service life F (1, i) and its application time F (0, i). The end of the service life of any M&R activities throughout pipe’s life cycle are determined either by failure or when that M&R reaches an established condition threshold.

3.7.2.2 Estimating Water Distribution System M&R Long Term Effectiveness (Benefits) - Monetized

The asset valuation method is employed in this thesis to estimate the long-term effectiveness of M&R activities in water distribution systems in monetized terms. There are numerous approaches that have been proposed in determining infrastructure asset value (Lemer 1998). For the purpose of this thesis, the “adjusted value with respect to condition threshold” method is applied. The asset valuation calculation method is shown in Equation (3.15).

$$\text{Asset valuation} = \text{HC} * \left(\frac{\text{E(t,C)} - \text{Worst condition}}{\text{Best.condition} - \text{Worst.condtion}}\right) \tag{3.15}$$

Where: HC = Estimated historical cost, E (t, C) = expected condition at year t.

To illustrate the proposed approach of estimating M&R effectiveness in water distribution systems using the asset value method, assume a pipe has design life x. The ultimate benefit is to have this pipe functioning until reaching the end of its design life. When the pipe reaches its design life, the pipe is expected to be in very bad condition. Therefore, the effectiveness (benefits) can be determined by calculating the difference of the pipe's original cost and its value at the end of its life. Another case is when the pipe does not reach its design life (i.e., failure occurs during the service life). If the failure takes place at an early stage, less benefits would be obtained since the pipe is still in good condition. The worst case (i.e., zero benefits) is when pipe failure occurs just after performing the M&R activity. The pipe value, in this case, is equal to the original cost (no depreciation take place) and no benefits thus can be gained. The general method for estimating water distribution system M&R effectiveness is presented in Equation (3.16).

$$M\&R_{Benefits\ (i,\ j)} = M\&R_{OC\ (j,\ i)} - M\&R_{AV\ (j,\ i)} \tag{3.16}$$

Where: M&RBenefits $_{(j,\ i)}$ = benefits of maintenance and rehabilitation type (j) at pipe (i),M&R$_{OC\ (j,\ i)}$ = original cost of M&R type (j) at pipe (i), M&R$_{AV\ (j,\ i)}$ = asset valuation of M&R type (j) at pipe (i); estimated as shown in Equation (3.15).

For further illustration, consider a pipe (i) was subject to three types of M&R activities during the service life (as shown in Figure 3-15).

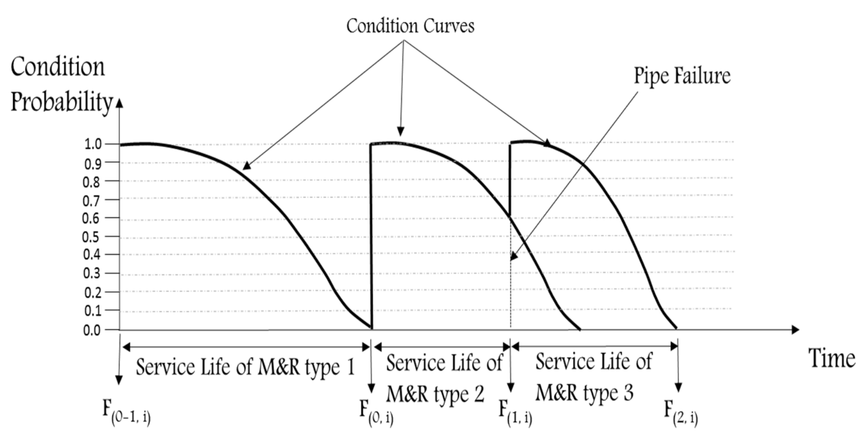


Figure 3-15 Graphical Illustration of Water Pipeline Life Cycle Profile – Three Types of M&R Activities.

The original cost of M&R type 1 at pipe (i) (i.e. $M\&R_{OC\,(1,\,i)}$) would be incurred at F (0-1, i) and its valuation ($M\&R_{AV\,(1,\,i)}$) would be assessed at F (0, i). Similarly, the $M\&R_{OC\,(2,\,i)}$ and $M\&R_{OC\,(3,\,i)}$ would be incurred at F (0, i) and F (1, i) and their valuations would be estimated at F (1, i) and F (2, i), respectively. The asset service life is either the expected design service life or the actual service life. In the former, a failure has not occurred during the asset life while in the latter a failure has occurred.

According to Equation (3.15), the pipe structural condition at year t has to be estimated in order to estimate its value at the same year t. Determining the structural condition scores for sewer and water pipelines remains a major challenge. For the purpose of this thesis, the methodology of quantifying an individual pipe's structural condition proposed by Opila and Attoh-Okine (2011) is employed. The proposed method is based on the economic concept of discounting, where the mean time to failure (MTTF) of the pipe is used to determine the condition. The MTTF is estimated from developed pipe failure models. The general form of the proposed model is presented in Equation (3.17).

$$S = \frac{S_{Max}}{(1+d)^{MTTF}} \tag{3.17}$$

Where: S = condition score of a specific pipe, S_{Max} = maximum (worst) condition score, d = determined discount rate, MTTF= mean time to failure of a specific pipe.

3.8 Cost Evaluation

The costs incurred due to asset preservation can be generally classified into agency and user cost. Agency costs are typically those incurred in the process of constructing and maintaining the asset. User costs include the initial costs, such as costs incurred during the time of an M&R intervention, and upcoming costs, such as normal operation costs during the life-cycle.

The agency and user costs of M&R activities of pavements and water distribution systems are presented in the ensuing sections.

3.8.1 Estimating Pavement Infrastructure M&R- Agency Cost

Two approaches are typically used to estimate the pavement infrastructure's agency cost. The average unit cost is one of them, where the cost is expressed in dollars per unit output (e.g. $/lane-mile). The drawback of this approach is inaccurate estimation results, which might be noticed from one project to another, especially where site conditions (e.g., land price, traffic loading) vary (Hartgen and Talvitie 1995). The other approach is cross-sectional models, where the estimates are based on defining factors (e.g., location, condition) that are believed to have an influence on the construction cost. A literature review on the applications of the aforementioned approaches and their shortcomings can be found in Irfan (2010). Irfan (2010) developed cost models based on historical contract costs for several pavement M&R activities in order to estimate agency cost as a function of asset attributes. That cost model is presented in Equation (3.17).

$$T_{AC} = f(x_1, x_2 \ldots x_n) \tag{3.17}$$

Where: T_{AC} = the total agency cost of treatment, f(x1, x2 … xn) = the function of attributes (e.g. material type, asset condition).

Several function forms were examined to determine the best fit model to the data. The models were developed for different treatment types that included thin HMA overlay, micro-surfacing, HMA overly functional, and HMA overlay structural and Resurfacing (Partial 3R standards). The developed functions are presented in Equations (3.18), (3.19), (3.20) and (3.21). The estimated parameters of these forms are presented in Appendix C.

Function form (1) [Cobb – Douglas I]:

$$T_{AC} = \alpha * (L)^{\beta} * (N)^{\gamma} * [\ln (PI_{trrig})]^{\delta} \tag{3.18}$$

Function form (2):

$$T_{AC} = \alpha + (\beta * L) + (\gamma * N) + (\delta * [\ln (PI_{trrig})]) \tag{3.19}$$

Function form (3) [Cobb – Douglas II]:

$$T_{AC} = \alpha * (L)^{\beta} * (N)^{\gamma} \tag{3.20}$$

Function form (4):

$$T_{AC} = \alpha + (\beta * L) + (\gamma * N) \tag{3.21}$$

Where: T_{AC} = the total agency cost of treatment, L = total length of construction (miles). N = number of lanes, PI_{trrig} = pre-treatmnet performance of the asset, and α, β, γ, and δ = estimated parameters.

The developed models are statistically significant at 95% confidence level and represent a good fit. Furthermore, validation (i.e., 80% of the data were used to calibrate the models and 20% to validate them) was carried out to test the prediction power of the developed cost models and showed the models to have a high ability to predict pavement M&R costs. These models therefore were employed in this thesis to predict the cost of M&R activities during the pavement life-cycle and thus assist in performing LCCA of the coordinated M&R activities of pavements and water distribution systems.

3.8.2 Estimating Pavement Infrastructure M&R – User Cost

Typically, user costs include initial costs and upcoming costs. Initial costs often consists of the delay and safety costs incurred by users during the time of an M&R intervention (i.e., work zone time). On the other hand, upcoming costs are those incurred by users due to their normal use of the asset over its service life. An example of user costs is vehicle operating costs (VOC), travel delay costs, crash costs, etc. Only work zone costs (i.e., travel delay costs and vehicle operating costs) that occur due to the construction or maintenance of pavement asset are considered in this thesis.

The work zone travel delay cost can be estimated as shown in Equation (3.22) (AASHTO 2003; Labi et al 2007; Irfan et al 2009).

$$UC_{ttd} = WZ_d * \sum_j^J (V_j * TTD_j * DC_j) \tag{3.22}$$

Where: UC_{ttd}= work zone travel delay cost, WZ_d = work zone duration; V_i = number of vehicle delayed by the speed change for vehicle class j, TTD_i = travel time difference for the speed changes due to work zone for vehicle class j in hrs, DC_i = delay cost rate for vehicle class j in \$/mile, j = vehicle class (truck or auto).

The work zone duration (WZ_d) is estimated as given in Equation (3.23). (Irfan et al 2010a).

$$WZ_d = e^{a + \sum_{k=1}^{K} B_k * X_k} \tag{3.23}$$

Where: WZ_d = work zone duration, X_k = is a vector of explanatory variable (i.e. agency cost, contract type, etc.).

The work zone vehicle operating costs incurred as a result of increased fuel consumption can be estimated using AASHTO methodology as shown in Equation (3.24) (AASHTO 2003).

$$UC_{voc} = WZ_d * \sum_j^J (V_j * TTD_j * Fg_j * Fp_j) \tag{3.24}$$

Where: UC_{vod}= work zone vehicle operation cost, Fg_i = amount of fuel consumed due to delay in gallon/hr for vehicle class j, Fgi = average fuel price in $/gallon consumed by vehicle class j,

3.8.3 Estimating Water Distribution System M&R – Agency Cost

The cost of a water pipe failure can be grouped into direct and indirect costs of repair. The direct costs are the agency's out of pocket expenses, such as the cost of restoring the pipe (where pipe material, diameter, depth, etc. are factors that contribute to the overall cost). The indirect costs, on the other hand, are those associated with the amount of lost water, compensation paid to consumers due to service disruption, penalty payments due to customer complaints, and the cost of losing expected profits due to temporarily discontinued service. This thesis is only concerned with the direct costs of water distribution system M&R activities which can be estimated using the developed statistical cost models that are based on historical construction cost data. Several factors that are believed to have an influence on the overall cost are assessed to determine their significance and then modeled to predict the total cost. The accuracy of these models depends mainly on the amount of detailed data used in their development. Dickson (1972) used construction cost data obtained from real-world projects to develop cost curves for pipe construction. Walski (1985a) developed a prediction model for estimating the cleaning and lining costs for water mains based on the actual costs of 51 projects. Selvakumar et al (2002) calculated a rehabilitation and repair cost per linear foot of water distribution component. The aforementioned studies considered only the costs of the pipes and associated installation. The cost of other items (e.g., valves) are known to heavily impact water system rehabilitation costs (Shehab et al 2010). Clark et al (2002) developed several statistical cost models for estimating the costs of individual water pipe rehabilitation activities. The costs that were considered in this model included excavation, embedment, pipe materials, dewatering, sheeting, shoring, backfilling, compaction, pavement repair and replacement, utility interference, traffic control, valves, fitting, hydrant, service connection, corrosion control, and household service connection. In addition, cost models were developed for several trenchless techniques. These trenchless techniques include horizontal boring, cement mortal lining, and slip lining.

Cost models that were developed by Clark et al (2002) are employed in the present thesis to calculate the direct cost of water pipe M&R activities. This is the most comprehensive model was found in the literature since it considers the cost of excavation, embedment, pipe materials, dewatering, sheeting, shoring, backfilling, compaction, pavement repair and replacement, utility interference, traffic control, valves, fitting, hydrant, service connection, corrosion control, and household service connections. The general form of the model is shown in Equation (3.25). The estimated parameters of the model are presented in Appendix D. Only water pipeline replacement costs are considered in this thesis (i.e., pipe repair and rehabilitation costs are not considered).

$$AC = a + b\,(x^{c}) + d\,(u^{e}) + f\,(x.u) \qquad (3.25)$$

Where: AC = agency cost of a specific component ($/ft), x = design parameter (e.g. pipe diameter, soil type), u = indicator variable, and a, b, c, d, e, and f = coefficients to be estimated.

3.8.4 Estimating Water Distribution System M&R – Traffic User Cost

Social costs are typically incurred during the performance of M&R activities on water distribution systems. However, there are social costs that could be experienced by users during normal operation such as those caused by changes in water quality and quantity. These costs are not considered in this thesis due to the difficulty of quantifying them. These social costs can be further classified into direct costs, such as the costs associated with traffic congestion, and indirect cost, such as those associated with business disruption. Only the user costs associated with traffic are considered in this thesis. These costs can be estimated using the aforementioned explained methodology (presented in Section 3.8.2.) for estimating the user costs associated with the performance of pavement M&R activities. The only modification that is made to that methodology is the work zone duration, which represents the time that would be taken to perform a specific type of M&R activity to the asset. Therefore, work zone durations vary depending on the type of asset since different construction means would be employed. The work zone duration for water pipeline replacement activities are affected by various factors, such as pipe depth, pipe size, site location, weather condition, number of laborers, etc. In this thesis, the work zone duration was obtained from the literature and the work zone travel delay costs can be estimated as shown in Equation (3.26) (AASHTO 2003; Labi et al 2007; Irfan et al 2009).

$$\mathrm{UC_{ttdp}} = \mathrm{WZ_{dp}} * \sum_{j}^{J}(\mathrm{V_j} * \mathrm{TTD_j} * \mathrm{DC_j}) \tag{3.26}$$

Where: UC_{ttd}= work zone travel delay cost caused by water pipeline M&R intervention, WZ_{dp} = work zone duration associated with water pipeline, V_i = number of vehicle delayed by the speed change for vehicle class j, TTD_i = travel time difference for the speed changes due to work zone for vehicle class j in hrs, DC_i = delay cost rate for vehicle class j in \$/mile, and j = vehicle class (truck or auto).

The work zone duration associated with water pipelines (WZ_{dp}) is estimated as given in Equation (3.27). (Irfan et al 2010a).

$$WZ_{dp} = e^{a+\sum_{k=1}^{K} B_k * X_k} \tag{3.27}$$

Where: WZ_{dp} = work zone duration, X_k = is a vector of explanatory variable (i.e. agency cost, contract type, etc.).

The work zone vehicle operating costs incurred as a result of increased fuel consumption can be estimated using the AASHTO methodology shown in Equation (3.28) (AASHTO 2003).

$$UC_{vocp} = WZ_{dp} * \sum_{j}^{J}(V_j * TTD_j * Fg_j * Fp_j) \tag{3.28}$$

Where: UC_{vod}= work zone vehicle operation cost due to water pipeline M&R intervention, Fg_i = amount of fuel consumed due to delay in gallon/hr for vehicle class j, Fg_i = average fuel price in $/gallon consumed by vehicle class j

3.9 Cost Effectiveness - Concept

Cost-effectiveness evaluation is an economic technique for estimating the benefits received for the money spent (cost) of a particular investment. This investment could be (as an example) an M&R alternative for a particular asset. Such an evaluation could help decision- makers select the best M&R activity to implement. One of the main objectives of this research is to assess the impact of water pipeline M&R interventions on the pavement infrastructure using LCCA. Having determined the benefits and the costs of a chosen set of M&R alternatives for each asset (i.e., water pipeline and pavement), the cost-effectiveness concept can be applied to quantify the water pipeline M&R intervention impacts on pavements. Another objective of this research is to conduct a LCCA for coordinated M&R activities for pavements and water distribution systems. Similarly, a cost-effectiveness approach was employed. The method of calculation of cost-effectiveness is presented in Equation (3.29).

$$\text{Cost Effectiveness Index} = \frac{\text{Effectiveness}}{\text{Cost}} \qquad \text{See Equations (3.30 \&3.31)} \qquad (3.29)$$

3.9.1 Cost-Effectiveness - Evaluation

One of the recommended cost effectiveness analysis approaches is the benefit (monetized and/or non-monetized benefits) to cost ratio (Khurshied 2010). In this approach, the benefit cost ratio (BCR) concept is used to estimate the maximum cost-effectiveness corresponding to each scenario composed of several candidate M&R interventions. The benefits and the costs of each of the candidate M&R activities for pavement and water pipeline assets can be estimated as discussed in Sections 3.7 and 3.8.

3.9.1.1 Cost Effectiveness Evaluation - (Monetized Benefits)

The estimation of the cost effectiveness of M&R interventions for water pipelines and pavement assets, using benefits in monetized terms, can be calculated as given in Equation (3.30).

$$\mathrm{CE} = \frac{\sum_{s=1}^{m}.\,[\{\mathrm{MCS,i}\} + \{(\mathrm{VOCS,i}) + \mathrm{CRF\ r\%T}\ .\,[\sum_{j=1}^{m}.\sum_{i=1}^{n}.\,\mathrm{PWF\ r\%,t,}\{(\mathrm{M\&}R_{\mathrm{Benefits}}\ \mathrm{,j,i}\}]]}{\mathrm{CRF\ r\%T.}\,[\{(\mathrm{T_{ACc},i}) + (\mathrm{WZpvC,i}) + (\mathrm{ACc,i}) + (\mathrm{WZpC,i})\} + \sum_{j=1}^{m}.\sum_{i=1}^{n}.\,[\mathrm{PWF\ r\%t,i}\{(\mathrm{ACpv,i}) + (\mathrm{WZpv,i}) + (\mathrm{ACp,i}) + \mathrm{WZp,i}\}]]}$$

Where: MCS,i = annual agency basic routine maintenance cost savings due to improved pavement performance as calculated in Equation (3.12), VOCS,i = annual user VOC savings due to improved pavement performance and it is calculated using Equation (3.13), M&R $_{\text{Benefits (j, i)}}$ = benefits of maintenance type j applied for pipe i as estimated using Equation (3.16), $T_{ACc\ (j,\ i)}$ & $AC_{c,\ i}$ = total agency cost of new construction of pavement and water pipeline assets at the beginning of analysis period as calculated using Equations (3.17) and (3.25), WZpvC, i and WZpC, i = user costs incurred due to work zone activities for the construction of a new pavement and water pipeline taking place at the beginning year of the analysis period as estimated using Equations (3.22), (3.24), (3.26), and (3.28). ACpv, i and ACp, i = total agency cost of M&R treatment applications for pavement and water pipelines during the life cycle of both assets as calculated using Equations (3.17) and (3.25), WZpv,I and WZp, i = user costs incurred due to work zone activities needed for the M&R treatment applications of pavement and water pipeline during the life cycle of both assets as estimated using Equation (3.22, 3.24) and (3.26, 3.28), $CRF_{r,\ \%T}$ = Capital Recovery Factor (CRF) for calculating the Equivalent Uniform Annual Cost (EUAC), $PWF_{r,\ \%t}$ = present worth factor used to estimate the time value of money using single payment present worth at the beginning of the analysis period (first year).

3.9.1.2 Cost Effectiveness - Evaluation (Non-Monetized)

The calculation of the cost effectiveness of M&R intervention of water pipeline and pavement assets using benefits in non-monetized terms can be performed as shown in Equation (3.31).

$$\mathrm{CE} = \frac{tsc + \mathrm{M\&}R_{\mathrm{SLc}} + \sum_{\mathrm{i=1}}^{\mathrm{n}}[ts, i + M\&R_{SL}\ (j, i)]}{\mathrm{CRF\ r\%T.}\ \left[\{(\mathrm{T_{ACc}, i}) + (\mathrm{WZpvC, i}) + (\mathrm{ACc, i}) + (\mathrm{WZpC, i})\} + \sum_{\mathrm{j=1}}^{\mathrm{m}}.\sum_{\mathrm{i=1}}^{\mathrm{n}}.\ [\mathrm{PWF\ r\%t, i}\{(\mathrm{ACpv, i}) + (\mathrm{WZpv, i}) + (\mathrm{ACp, i}) + \mathrm{WZp, i}\}]\right]}$$

Where: tsc = treatment service life of new pavement construction (in years) and estimated using Equation (3.5), $M\&R_{\ SLc}$ = treatment service life of new water pipeline construction (in years) and estimated using Equation (3.14), tsc,i = treatment service life (in years) of applying pavement M&R treatments during pavement life cycle and estimated using Equation (3.5), $M\&R_{\ SLc\ (j,\ i)}$ = treatment service life (in years) of M&R treatments applications of water pipeline during the life cycle and estimated using Equation (3.14).

CHAPTER 4. APPLICATION OF THE RESEARCH METHODOLOGY

4.1 Introduction

To coordinate the M&R activities for water distribution systems and pavement infrastructure and to assess their interactions using LCCA, a number of mathematical models (e.g., agency cost models, user cost models, benefit models, etc.) needed to be integrated. Due to the difficulty of integrating these mathematical models and the uncertainty represented by the stochastic nature of the problem, simulation was chosen for implementing the developed framework. Simulation techniques have been proven to be very capable of modeling real-world complex problems. There are many general purpose and specialized simulation modeling software tools available. Readers interested in a review of these tools are referred to a published dissertation by Martinez (1996) for more information. Martinez (1996) developed a simulation software for construction activities called Stroboscope that has many features. The Stroboscope simulation software is discussed in the ensuing section.

4.2 Simulation Model -Stroboscope

Stroboscope is a discrete event simulation software developed using general purposes programming languages. It can be implemented for representing a wide range of complex processes in different fields, such as construction, transportation, manufacturing, service). Some of the main features of Stroboscope that are needed for modeling such complex problems include the following: built-in multiple random number streams (which help in conducting Monte Carlo simulations to determine pipe failure time), sophisticated stream management (e.g. seed statements used to verify the outputs of the model by disabling the randomness), built-in logarithmic and trigonometric functions (to implement different mathematical models), built-in wide range of probability distributions (used for modeling the percentage of treatment service life reductions caused by utility cuts), and structured flow control (e.g. if-else if-else used to represents the decision matrix model). In addition, the Stroboscope has the ability to implement code written in other programming languages such as C, C++, Pascal, and Fortran. EZStrobe is a graphical discrete event simulation modeling system that uses Stroboscope's simulation engine. EZStrobe was used in this thesis to implement the developed framework. In addition to the aforementioned features, EZStrobe has a graphical representation which allows the designer to visualize the simulated elements step-by-step and therefore captures possible mistakes easily. Stroboscope and EZStrobe are free resources and can be downloaded from (*http://www.ezstrobe.com/*).

4.3 Simulation Model-Overview

The simulation model comprises several modules and sub-modules that include the following: pavement performance treatment module, pipe failure prediction module, decision matrix module, coordination module, pavement agency cost and user cost sub-modules, pavement monetized and non-monetized effectiveness sub-models, water pipeline agency cost and user cost sub-modules, water pipeline monetized and non-monetized effectiveness sub-models, and overall cost-benefit module. These modules and sub-modules interact with each other to perform the cost-benefit analysis of M&R activities over the life cycle of water pipeline and pavement assets. An overview of the input-output relationships of the simulation model is presented in Figure 4-1. These modules and sub-modules are explained in the following sections.

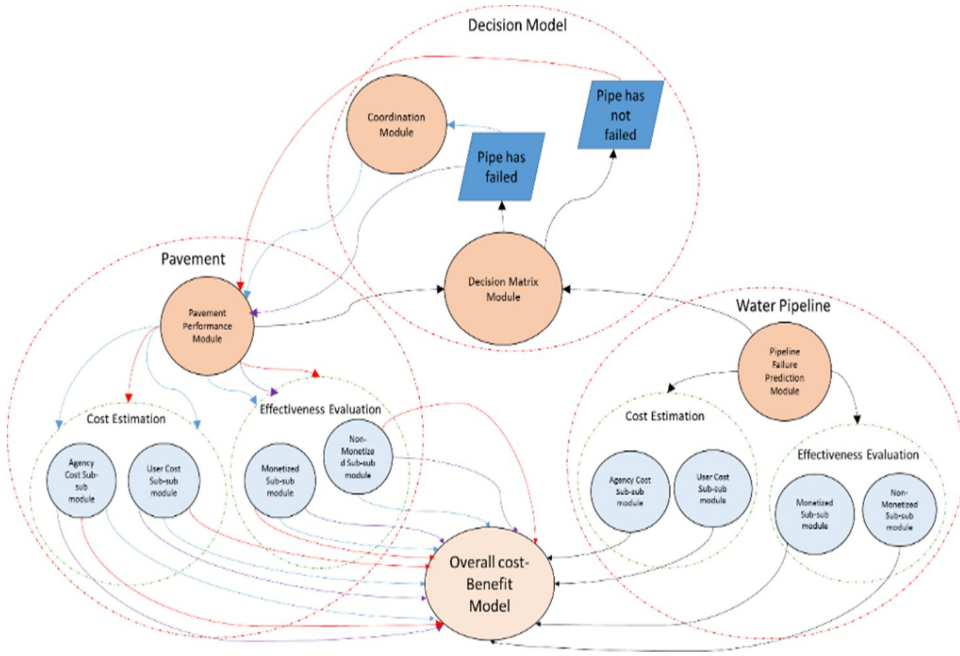


Figure 4-1 Overview Simulation Model - Input-Output Relationship

4.3.1 Pavement Treatment Performance Model

The pavement treatment performance module estimates treatment service life (tsi) using Equation (3.5). This treatment service life is loaded to the decision matrix module. Then, the decision matrix module decides (based on the pipe failure time which is obtained from the pipe failure prediction module) whether or not the treatment service life has encountered a pipe failure. Based on the output of the decision matrix module, three scenarios are formulated. The first scenario is when no pipe failure has occurred during a treatment service life (depicted in Figure 4-1 by the red arrows). In this case, the treatment service life remains unchanged and is then loaded to the pavement treatment performance module. This module then estimates the performance indicator values (i.e., IRI) at each year of the unaffected treatment service life (tsi) using Equation (3.2). The treatment service life and the performance indicator values are then used to estimate the cost and benefit of this scenario using the cost and benefit modules. The second scenario is when a pipe failure occurs during a treatment service life (depicted in Figure 4-1 by the purple arrows). In this case, the pipe failure will cause a reduction to the treatment service life and tsi becomes t'si and is estimated using Equation (3.4). This actual treatment service life (t'si) is then loaded to the pavement treatment performance module to estimate the performance indicator values using Equation (3.6). The third scenario is when the pipe has failed during the treatment service life and subsequent the pavement treatment is going to be executed concurrently with replacing the broken pipe (depicted in Figure 4-1 by the blue arrows). In this case, the outcome of the decision matrix is loaded to the coordination module. The coordination module (see Section 3.6.3) then will make the treatment service life equal to the pipe failure time (that is ts'i becomes tpi). The coordination module then loads the pipe failure time to the pavement treatment performance module to estimate the performance indicator values using Equation (3.2) by replacing the tsi with tpi. The costs and benefits of all three scenarios are estimated using the cost and benefit module. Figure 4-2 presents a screenshot of the process used for estimating the treatment service life and the pavement performance indicator values of a new pavement construction implemented using the EZStrobe simulation software.

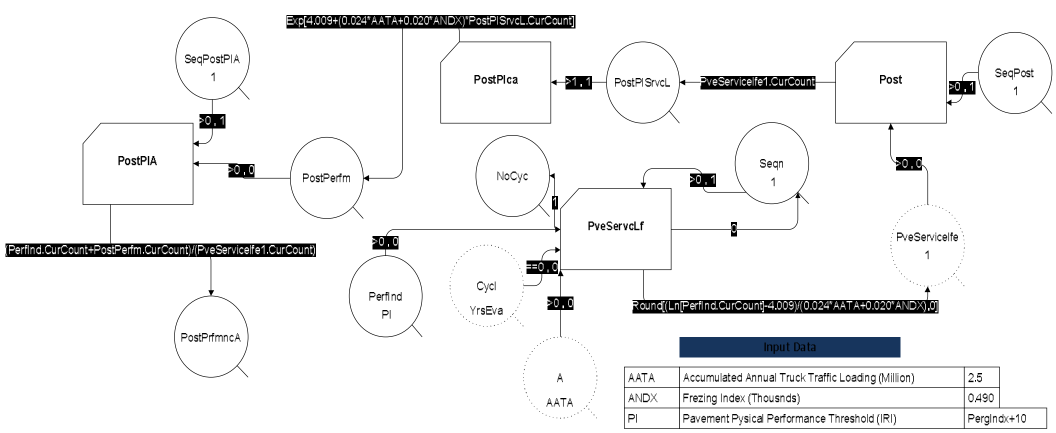


Figure 4-2 Screenshot of Pavement Performance Module

From Figure 4-2, users can set a pavement performance threshold value and assign values for the accumulated annual truck traffic loading at the time of treatment application and the freezing index (shown in the input data). On the basis of the entered data, the model will estimate the treatment service life and the average post-treatment performance.

4.3.2 Pipe Failure Prediction Model

The pipe failure prediction module determines the time of pipe failures using the prediction model. The prediction model estimates the probability of pipe failure based on yearly time steps. Then, a generated random number between 0 and 1 is compared to the probability value. If the probability value is greater than the generated random number, then it assumes that the pipe has not failed at that year. When the probability value is less than the generated random number, then it assumes that the pipe has failed in that year. The model is run to determine pipe failure times until the end of the analysis period. These failure times are then loaded to the decision matrix module. Since the effect of the pavement treatments on the water pipeline life cycle is not considered in this thesis, there will be no output from the decision matrix module that would need to be loaded to the pipe failure prediction module. The number of failures and their occurrence times are then loaded to the cost and benefit modules. Figure 4-3 is a screenshot of the pipe failure prediction model implemented utilizing the EZStrobe simulation software.

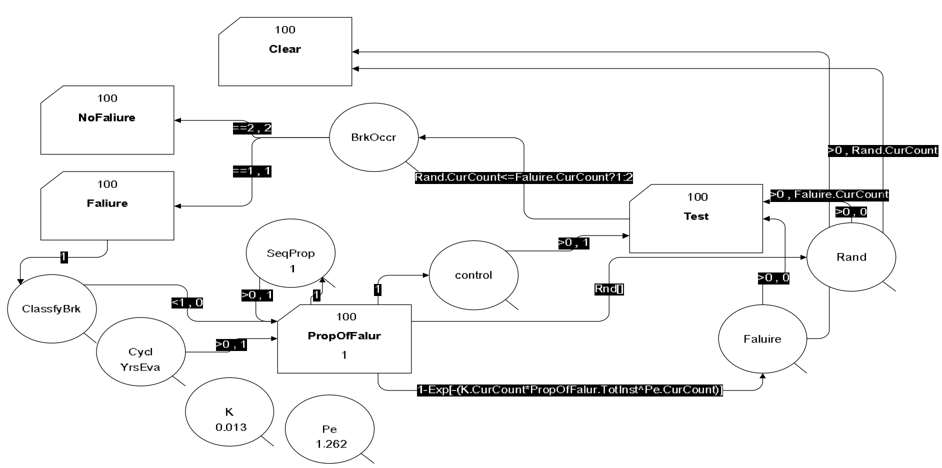


Figure 4-3 Screenshot of Pipe Failure Prediction Model

4.3.3 Decision Matrix Module

As explained earlier, the decision matrix module is a set of if-statements. These if-statements are modeled into the decision matrix module to determine pipe failure occurrences and their times corresponding in relation to pavement treatment service lives. The output of the decision matrix module is a determination of whether the pavement treatment service life has encountered a pipe failure during its service life. This determines whether the treatment's service life would be affected by the pipe failure, assuming that fixing the failure requires the pavement surface to be destroyed. If no pipe failures have occurred, the pavement treatment service life remains unaffected. A screenshot of the decision matrix module implemented using the EZStrobe simulation software is presented in Figure 4.4. It shows an example of the module assessing whether or not the time for the first pipe failure has occurred during the first, second or third pavement treatments.

4.3.4 Coordination Module

The coordination module determines if the last failure of a pipe j has occurred after a certain time of pavement treatment service life (i). If the failure has occurred after that point of the life of (i), then the end of the treatment service life (i) is determined by the time of pipe j's failure. Therefore, the subsequent treatment (i+1) will be carried out concurrently while fixing the broken pipe. Figure 4-5 illustrates how the coordination concept is applied during the service life of the second pavement treatment. If the time to first pipe break (tp1) is greater than the sum of the service life of the first pavement treatment (ts1) and the product of the second pavement treatment's service life (ts2) and the allowable percentage (%) (sensitivity analyses are conducted in Chapter 5 to see the impact of the allowable percentage on the model's output variables), then subsequent treatment would be applied just after fixing the pipe. In cases where tp1 is less, then only the pipe would be fixed using a cutting and patching method without changing the scheduled time of pavement treatment applications. The allowable percentage (%) is modeled as an input variable in the model to be decided by users, allowing for an assessment of the impacts of this variable on the LCCA. Figure 4.6 presents a screenshot of the coordination module modeled in EZStrobe.

Figure 4-6 is a representation of the coordination module that assesses whether the times to the first, second, or third pipe breaks is less than the product of the pavement treatment service life and the allowable percentage. The coordination module, in general, requires inputs from the decision matrix module to determine the occurrence times of pipe failures in relation to the pavement treatment service life. The outcome of the coordination module is a determination of the pavement treatment service life considering pipe failure.

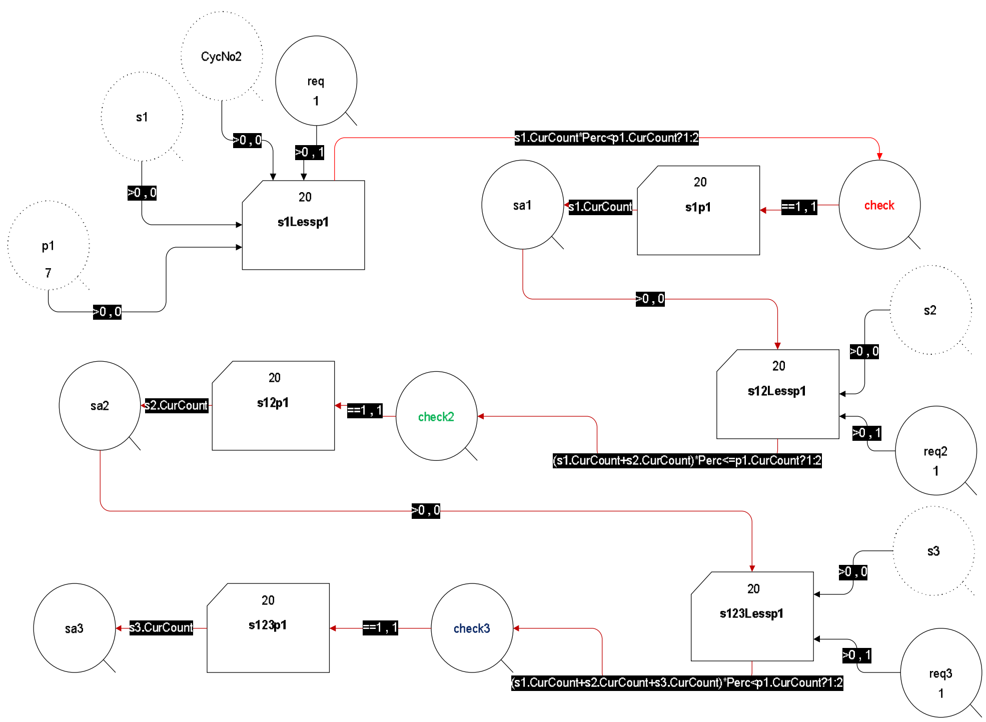


Figure 4-4 Screenshot of Decision Matrix Module

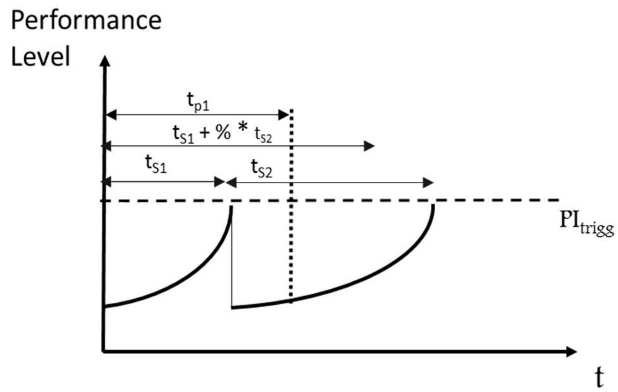


Figure 4-5 Graphical Illustration of the Coordination Concept

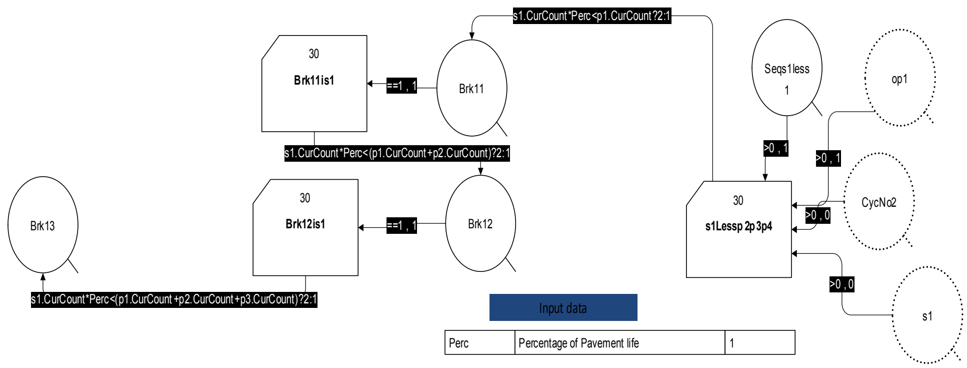


Figure 4-6 Screenshot of the Coordination Module

4.3.5 Estimating Pavement Treatments Effectiveness - EZStrobe

Pavement treatment effectiveness can be measured using two sub-modules: the monetized sub-module and the non-monetized sub-module. Considering the non-monetized sub-module, the estimated treatment service life that is obtained from the pavement performance module is used to represent the treatment's effectiveness. In the monetized sub-module, the effectiveness of the treatment is represented by the savings in the annual maintenance costs (MCSi) and vehicle operating costs (VOCSi) due to treatment application. Readers are referred to Section 3.7.1.2 for more details on quantifying treatment effectiveness in monetary values.

The annual maintenance cost savings are estimated using a sub sub-module presented in Figure 4-7.

Figure 4-7 shows a screenshot of the process of estimating the annual maintenance cost after treatment application subject to low/high traffic volumes using the post-treatment performance model. This cost is compared with the do-nothing scenario to calculate the annual maintenance cost savings due to the improvements to the pavement. The do-nothing scenario is estimated by applying the same procedure while substituting the average post-treatment performance values for the pre-treatment performance values.

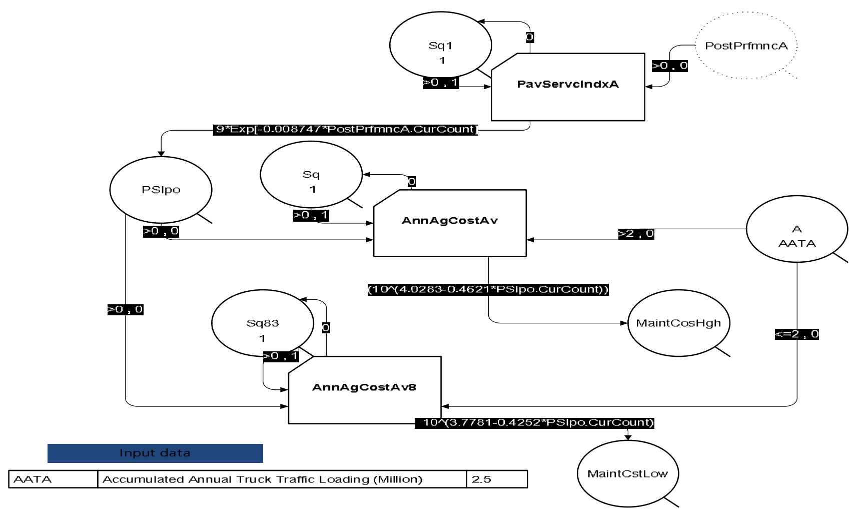


Figure 4-7 Screenshot of Annual Maintenance Cost Saving Sub Sub-Module - Pavement

The VOC savings sub-sub-module estimates the VOC before and after the treatment application. The VOC incurred before and after treatment are estimated for the pre- and post-treatment performance values using the Opus model. A screenshot of the VOC savings module is presented in Figure 4-8.

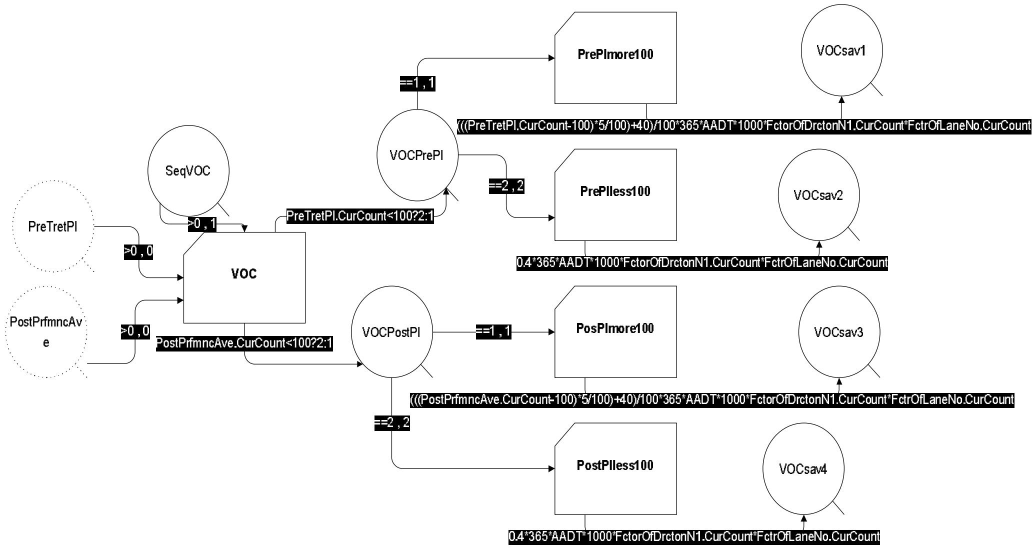


Figure 4-8 Screenshot of Vehicle Operation Cost Saving Sub Sub-Module – Pavement

4.3.6 Estimating Pavement Treatment Cost - EZStrobe

The costs associated with treatment applications can be measured using two sub-modules: the agency cost sub-module and the user cost sub-module. The agency sub-module uses Equation (3.17) as shown in Figure 4-9.

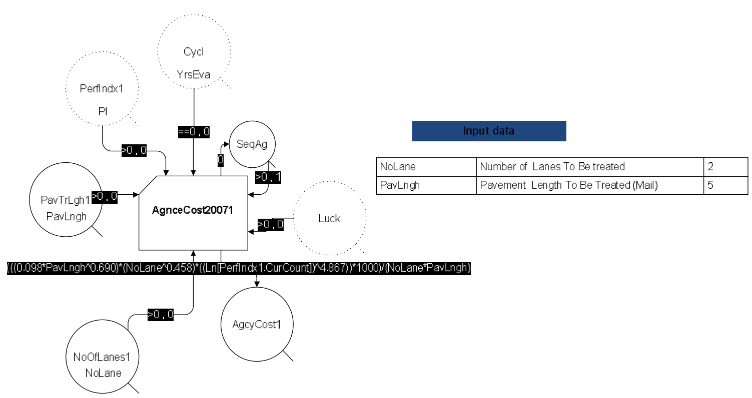


Figure 4-9 Screenshot of Agency Cost Sub-Module - Pavement

Figure 4-9 shows a screenshot of the agency cost sub-module modeled in EZStrobe. Based on the pavement length, number of lanes, and pavement performance indicators at the treatment application time, the agency cost can be estimated. The pavement length and the number of lanes to be maintained are modeled as input variables. The treatment performance indicator is taken as the prior treatment's performance threshold.

The user cost sub-module consists of two sub-sub-modules: the work zone travel delay cost (WZttd) and the work zone VOC (WZvoc) sub-sub-modules (see Section 3.8.2). The estimation of the work zone duration is essential for both WZttd &WZvoc and the module is presented in Figure 4-10. Based on the project type and the estimated agency cost, the work zone duration can be estimated using Equation (3.23).

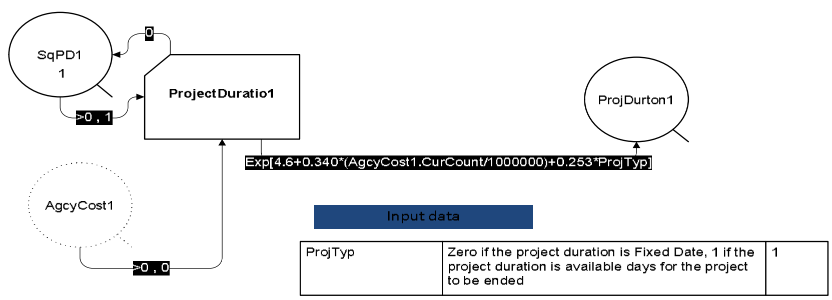


Figure 4-10 Screenshot of Project Duration Module - Pavement

Having determined the project duration, WZttd is estimated as depicted in Figure 4-11. Based on the number of lanes and directions of flow, the model will estimate the lane and direction distribution factors. These factors are then multiplied by the AADT to estimate the traffic per lane-mile. Based on the speed reduction (free speed – work zone speed), the travel time difference is then estimated. This time is multiplied by the unit travel time user cost (truck/auto). The outcome is then multiplied by the work zone duration (i.e., a percentage of the project duration) to estimate the total work zone travel time delay cost.

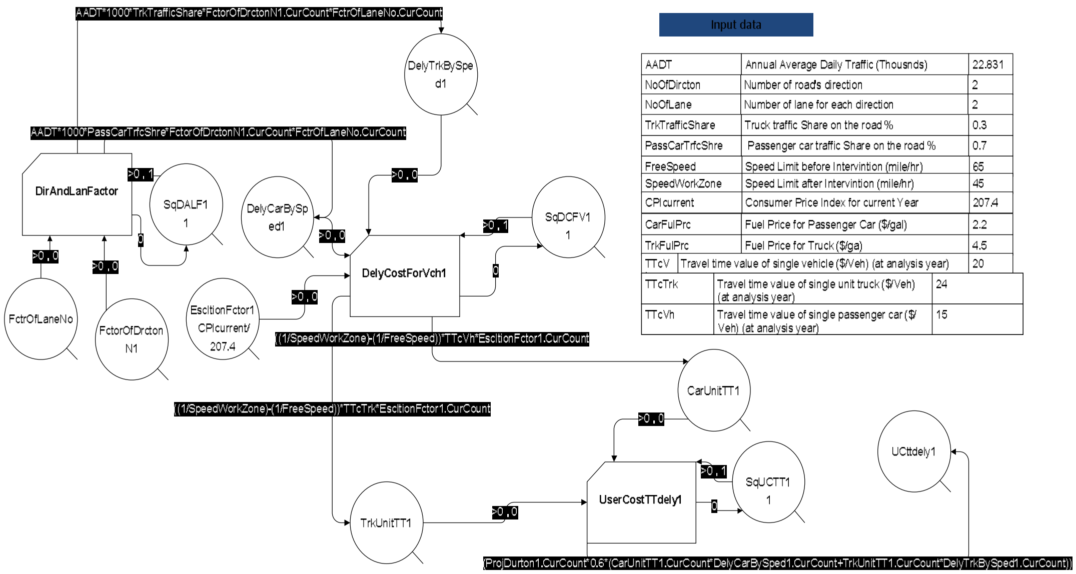


Figure 4-11 Screenshot of Work Zone Travel Time Cost Sub Sub-Module – Pavement

The work zone VOC sub–sub-module is estimated using the same process for estimating WZttd, except that fuel consumption and fuel prices are substituted for unit travel time user cost.

4.3.7 Estimating Water Pipeline Treatments Cost - EZStrobe

Similar to pavements, the water pipeline M&R effectiveness can be measured using two sub-modules: the monetized sub-module and the non-monetized sub-module. For the non-monetized sub-module, the estimated M&R treatment service life represents the treatment effectiveness. In the monetized sub-module, the effectiveness of the M&R treatment is estimated using Equation (3.16). In that equation, the M&R original costs ($M\&R_{OC}$) are estimated using the pipe agency cost sub-modules (see Section 4.4.7). The costs of M&R treatments are incurred during the life cycle of the pipe and, therefore, their time implications are needed for the LCCA and are determined by the times of pipe failures (estimated from the pipe failure prediction module). The valuation of M&R treatments is performed using Equation (3.15). The historical cost (HC) and pipe conditions (i.e., worst, best, and expected pipe condition) are also estimated from the pipe agency cost sub-module and the pipe failure prediction module.

4.3.8 Water Pipeline Cost Modules

Similar to pavements, the cost (i.e., agency and user costs) of pipe M&R treatments could be estimated at the beginning of their application times. These times can be obtained from the pipe failure prediction module that calculates the pipe failure times. At the end of each actual M&R treatment's service life, the subsequent M&R is assumed to be applied and, thus, the time of their applications is known. The water pipeline agency and the user costs modules are presented in the subsequent sections. Similar to the pavement asset, the costs associated with M&R treatment applications can be measured using two sub-modules: the agency cost sub-module and the user cost sub-module.

The agency sub-module uses Equation (3.25) and consists of several sub-sub-modules that include the excavation cost module, embedment cost module, pipe materials cost module, dewatering cost module, sheeting and shoring cost module, backfilling and compacting cost module, pavement repair and replacement cost module, and the traffic control cost module.

The excavation cost module is composed of four modules for different soil types. The types of soil considered are sandy gravel soil with 1:1 side slope, sandy gravel soil with vertical wall, sandy clay soil with vertical wall, and sandy clay soil with 3/4:1 side slope. First, the user selects the type of soil to be encountered during pipe installation and then determines the pipe depth and pipe diameter. On the basis of these inputs, the excavation cost can be estimated. These modules have some limitations, including the fact that only a specific range of pipe diameters and depths can be estimated (users are advised about these ranges while attempting to enter the inputs to the model). A screenshot of the excavation cost module is presented in Figure 4-12.

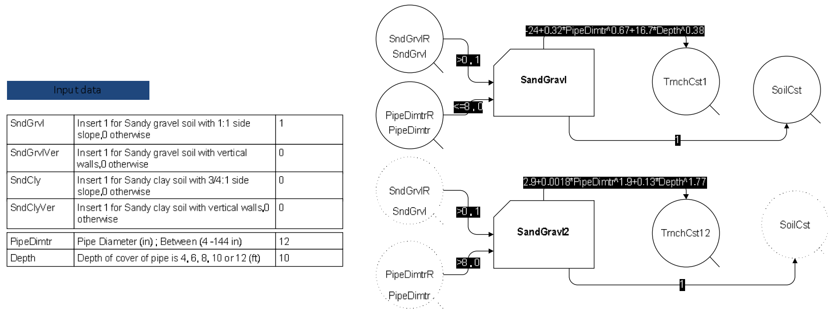


Figure 4-12 Screenshot of Excavation Cost Module – Water Pipeline

The embedment cost module contains three modules for different embedment types that include the concrete arch, first class, and ordinary. First, the user selects the type of embedment to be used and then determines the pipe depth and pipe diameter (pipe diameter range from 4 to 144 in.). On the basis of these inputs, the embedment cost can be estimated. A screenshot of the embedment cost module is presented in Figure 4-13.

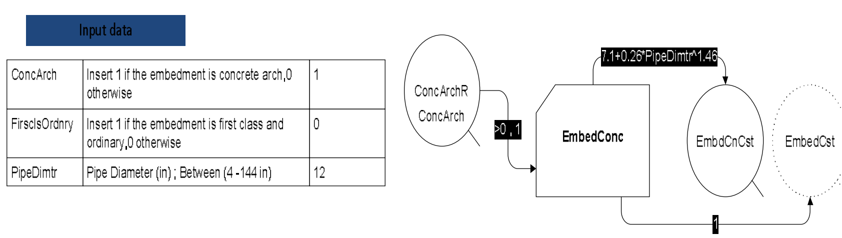


Figure 4-13 Screenshot of Embedment Cost Module – Water Pipeline

The pipe material cost module contains six modules for different material types. Ductile iron pipe, asbestos-cement pipe, PVC pressure pipe, cement mortar lined and coated steel pipe, concrete cylinder pipe, and prestressed concrete cylinder pipe are the pipe materials that were considered. The developed module allows users to select the pipe material type and diameter.

Further inputs by users are required, such as the joint type, class of ductile pipe, and pressure class rating for asbestos-cement and PVC pipe. Based on these inputs, the pipe material cost is estimated. These modules have some limitations, including the fact that specific types of joint (i.e., push and mechanical), and class 50 and 52 ductile iron and 150 to 200 of pressure class rating can be estimated (users are advised about these ranges while attempting to enter their inputs to the model). A screenshot of the pipe material cost module is presented in Figure 4-14.

The dewatering cost module contains two modules for moderate and severe dewatering conditions. Based on the chosen type of dewatering condition and pipe diameter (4 -144), dewatering costs could be estimated. A screenshot of the dewatering cost module is presented in Figure 4-15.

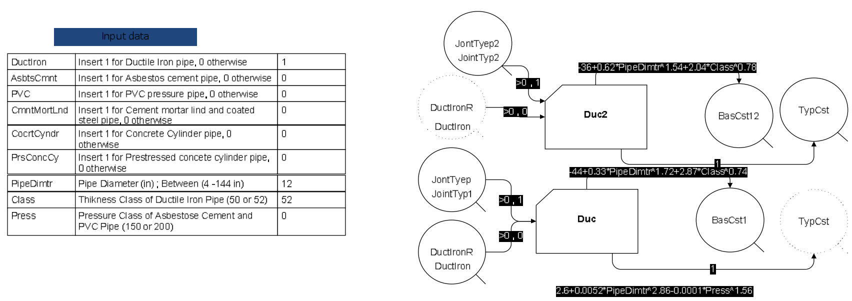


Figure 4-14 Screenshot of Pipe Material Cost Module – Water Pipeline

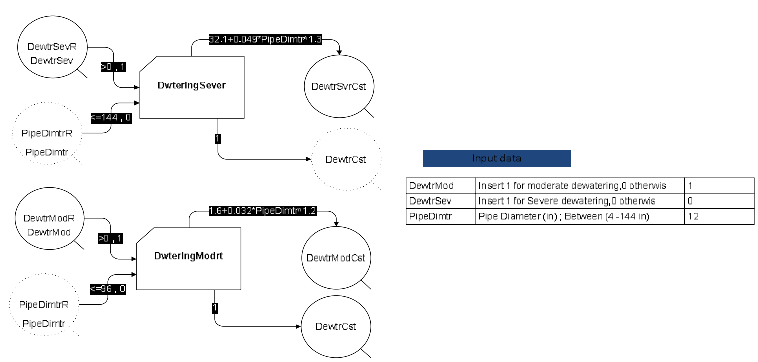


Figure 4-15 Screenshot of Dewatering Cost Module – Water Pipeline

The sheeting and shoring cost module is composed of three modules based on the sheeting and shoring conditions. These conditions are minimal (little or no ground water), moderate, and severe. Based on the chosen type of sheeting and shoring conditions and pipe diameter (4 - 144 in.), sheeting and shoring costs could be estimated. A screenshot of the sheeting and shoring cost module is presented in Figure 4-16.

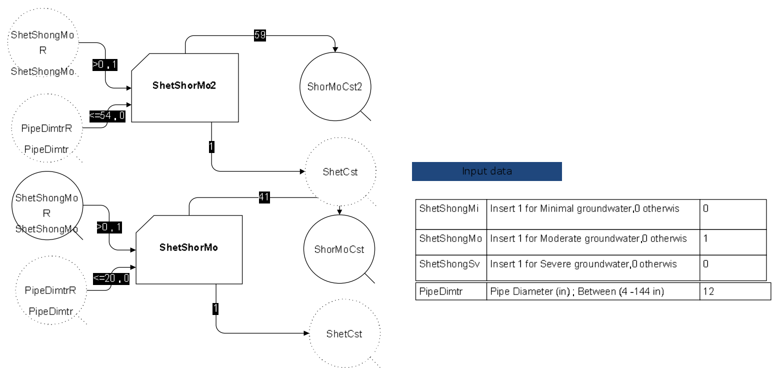


Figure 4-16 Screenshot of Sheeting and Shoring Cost Module – Water Pipeline

The backfilling and compacting cost module is composed of three modules based on soil types with an assumed 90% compaction. The considered soil types are sandy gravel native soil with 1:1 side slope, sandy gravel native soil with 3/4:1 side slope, and imported fill. The input needed for these modules are the pipe diameter and depth (only specific rang of pipe diameter and depth are considered). A screenshot of the backfilling and compaction cost module is presented in Figure 4-17.

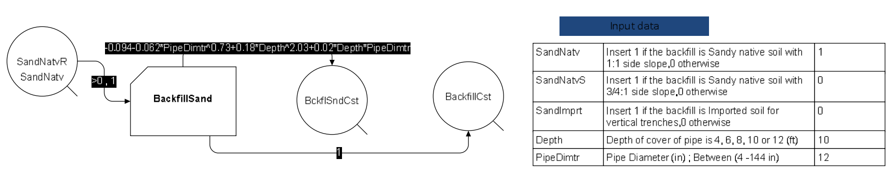


Figure 4-17 Screenshot of Backfilling and Compaction Cost Module – Water Pipeline

The pavement repair and replacement cost module contains two modules for asphaltic concrete and concrete pavement. The pipe diameters (4 – 144 in.) are needed for calculating the pavement repair and replacement cost. A screenshot of the pavement repair and replacement cost module is presented in Figure 4-18.

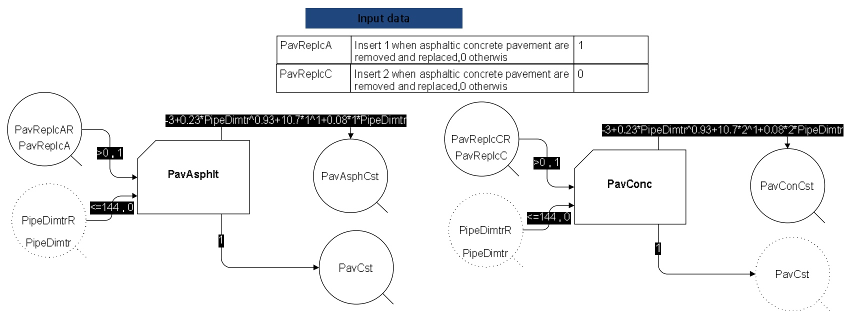


Figure 4-18 Screenshot of Pavement Repair and Replacement Cost Module – Water Pipeline

The traffic control cost module contains two sub-modules: moderate and heavy traffic. The pipe diameters are needed for calculating the pavement repair and replacement cost module. A screenshot of the traffic control cost module is presented in Figure 4.19.

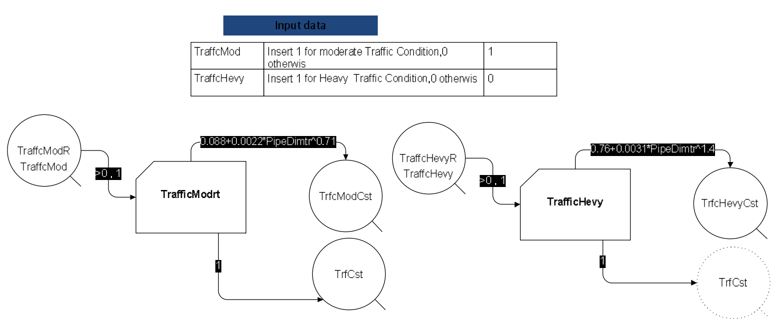


Figure 4-19 Screenshot of Traffic Control Cost Module – Water Pipeline

The outcomes of the water pipeline agency cost sub-modules are expressed in $/ft. Therefore, the total agency cost of replacing the pipeline is the product of the summation of the output of these modules and the pipe length. The water pipeline user cost module is similar to the pavement user cost module but the project duration is different and is modeled as an input (discussed in Section 3.8.4)

4.3.9 The Overall Costs and Benefits Module

The main task of the overall costs and benefits module is to perform cost-effectiveness analysis using Equations (3.30) and (3.31). Having estimated all the costs and benefits of both assets (i.e., water pipeline and pavement) as the outcomes of the aforementioned modules, the cost benefit ratio is formulated. The EZstrobe simulation model has two main parameters types: input and output. While the input parameters are designed to only take values, the output parameters allow for constructing mathematical equations. Therefore, Equations (3.30) and (3.31) were formulated using the output parameter.

4.4 Chapter Summary

This chapter presented the application of the framework developed using the EZStrobe software, a discrete event simulation software application. The developed simulation model is composed of several modules and sub-modules that include the pavement performance treatment module, pipe failure prediction module, decision matrix module, coordination module, pavement agency cost and user cost sub-modules, pavement monetized and non-monetized effectiveness sub-models, water pipeline agency cost and user cost sub-modules, water pipeline monetized and non-monetized effectiveness sub-models, water pipeline cost modules, and an overall cost-benefit module. These modules cooperate with each other to simulate the maintenance and rehabilitation strategies over the life cycle of two different types of infrastructure assets (i.e., pavement and water pipeline assets). The simulation model can help decision-makers to assess the impact of coordinating M&R interventions for both assets while acknowledging the impact of water pipeline failure on the pavement infrastructure.

Moreover, the simulation model is used to conduct cost-effectiveness analysis and select the best scenario among several combinations of M&R strategies.

CHAPTER 5. RESULTS, ANALYSIS, AND VERIFICATION

5.1 Introduction

The main goal of this thesis is to develop a decision framework that finds the best scenario, among a set of pavement treatment applications coordinated with water pipeline M&R interventions, that can lead to the overall maximum cost-effectiveness over the life-cycle of both systems. Three pavement treatment scenarios (i.e., preventive treatments only, rehabilitation treatments only, and a combination of the two) and only the pipe replacement scenario for water pipeline M&R are considered. The results of the simulation of the scenario of applying new full-depth construction followed by applying resurfacing (3R partial standards) twice during the life cycle are presented for each module and verified using hand calculation. Then, the overall results of the remaining scenarios are also presented. These simulation results are obtained using EZStrobe discrete event simulation software and are presented in the subsequent sections.

5.2 Pavement Treatment Performance Module - Results

As explained earlier, the pavement treatment performance module estimates treatment service life (tsi) using Equation (3.5). The service life of treatment (i) is modeled as yearly steps and is substituted for the variable (t) in the post-treatment performance model (Equation 3.2) to estimate the pavement treatment condition values at each year. The descriptions of the variables of these two models and their values are shown in Table 5-1.

Table 5-1 Descriptions and Assigned Values of the Variables in Equations (3.2 and 3.5)

Variables	Description	Values
Performance Indicator (PI)	Pavement treatment performance indicators estimated in terms of IRI (in/mi)	PI_{min} = 100 (in/mi) & PI_{Max} = 130 (in/mi)
Pavement performance trigger (PI_{trigg})	Pavement treatment performance trigger estimated in terms of IRI (in/mi)	$PI_{trigg(min)}$ = 100 (in/mi) & $PI_{trigg(Max)}$ =130(in/mi)
Service Life (t) in years	Time between treatment application and end of its service life.	Estimated using Eq. 3.5
Accumulated annual truck traffic loading (AATA) in millions-years	Average annual truck traffic volume (millions) occurring during pavement treatment service life (years).	The mean values of AADT = 2.5 millions
Accumulated annual freezing index (ANDX) in thousands-years	Average annual freezing index (thousands) occurring during pavement treatment service life (years).	The mean values of ANDX = 0.49 thousands
α	Constant term estimated for each type of treatment	See Table 1 in Appendix A
β & γ	Estimated coefficients for each type of treatment	See Table 1 in Appendix A

The scenario considered to demonstrate the calculations and verify the model results is a new full-depth HMA construction followed by applying resurfacing (partial 3R standards) twice. First, the calculations associated with estimating the service life and the post-treatment performance are presented, which then are compared with the outputs of the pavement treatment performance simulation module for verification purposes.

A new full-depth HMA construction type is the first treatment applied. The PI_{trigg} is set to be = 127 (in/mi), AATA = 2.5 (millions), ANDX= 0.49 (thousands), α = 4.009 (From Table 1 in Appendix A), β = 0.024 & γ = 0.02 (From Table 1 in Appendix A).

Equation (3.5) was used to estimate the treatment service life (calculated as follow):

$$ts = \frac{\ln(127)-4.009}{(0.024*2.5)+(0.02*0.49)} = 11.965 \approx 12 \text{ (year)}$$

Based on the estimated treatment service life (ts) (i.e., 12 years), the PI values are estimated for each year using Equation (3.2), and the overall post-treatment average performance then is calculated. These values are presented in Table 5-2.

Table 5-2 Estimated PI Values of New Full-Depth HMA Construction Type at Each Year

Time since the treatment application, ti	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year	9th year	10th year	11th year	12th year
PI value (in/mi)	59.07	63.35	67.92	72.84	78.10	83.75	89.80	96.29	103.25	110.72	118.72	127.30

Based on the PI values and ts, the post-treatment average performance is estimated using Equation (3.9).

$$\text{PI}_{\text{Avg}} = \frac{PI_0 + PI_1 + PI_2 + \cdots + PI_{Th}}{t_s}$$

$$\text{PI}_{\text{Avg}} = \frac{1071.11}{12} = 89.25 \text{ (in/mi)}$$

Figure 5-1 shows a screenshot of the simulation model while running, and it can be seen that the queue named "PavServicelif" has a value of 12 on the top, which represents the estimated pavement service life in years for the new full-depth HMA construction. The arrow which is directed toward that queue has the formula for estimating post-treatment performance and associated parameters. The queue named "PostPrfmncA" has the average post-treatment performance, which is 89.235 in in/mi as shown in Figure 5-1. These values correspond to the values obtained by the hand calculation and therefore assuring that the model is performing as planned.

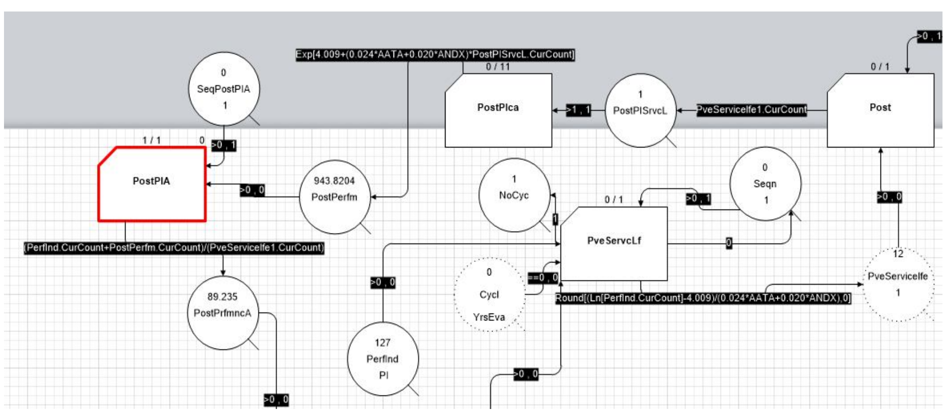


Figure 5-1 Screenshot of Pavement Treatment Performance Module - Results of Estimating Service Life and PI_{Avg} Values of New Full-Depth HMA Construction Type

The second treatment application is resurfacing (3R partial standards). The PI_{trigg} was set to be = 127 (in/mi), AATA = 2.5 (millions), ANDX= 0.49 (thousands), α = 4.183, β = 0.015 & γ = 0.101.

Similarly, Equation (3.5) was used (calculated as follows):

ts = $\frac{\ln(127)-4.183}{(0.015*2.5)+(0.101*0.49)} = 7.6 \approx 8$ (year) (rounded to the nearest integer)

Based on the estimated treatment service life (ts), the PI values are estimated for each year using Equation (3.2); and the overall post-treatment average performance then is estimated. Since this treatment is a subsequent treatment and is influenced by the condition of the pavement at the time of application, the PI value of the first year is estimated by taking the difference between pre-treatment performance and the performance jump (PJ) of that treatment. The performance jump is estimated using Equation (3.1).

PI_{trigg} = 127 (in/ mi), $\mu\ (1)_s$ = -424.006 and $\mu(2)$ = 104.216

PJ_s = -424.006 + 104.216* Ln(127) = 80.77 (in/mi)

Therefore, the PI at 1st year = PI_{pre} – PJ = 127- 80.77 = 46.23 (in/mi)

The values of PI of the resurfacing (3R partial standards) treatment are presented in Table 5-3.

Table 5-3 Estimated PI Values of Resurfacing (3R Partial Standards) Rehabilitation Treatment at Each Year

Time since the treatment application, ti	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	8th year
PI value (in/mi)	46.23	78.02	85.11	92.85	101.29	110.49	120.53	127

Based on the PI values and ts, the post-treatment average performance is estimated using Equation (3.9).

$$\text{PI}_{\text{Avg}} = \frac{PI_0 + PI_1 + PI_2 + \cdots + PI_{Th}}{t_s}$$

$$\text{PI}_{\text{Avg}} = \frac{761.52}{8} = 95.19 \text{ (in/mi)}$$

Figures 5-2 and 5-3 show a screenshot of the simulation model for estimating the performance jump (PJ) and average post-treatment performance for resurfacing (3R partial standards), respectively. The PJ and PI_{Avg} are depicted in the queues named “PJ1” and “PostPrfmncAe”, respectively. The values are 95.1898 (in/mi) and 80.7785 (in/mi) for the PJ and the PI_{Avg}, respectively. These values also match the hand-calculated values.

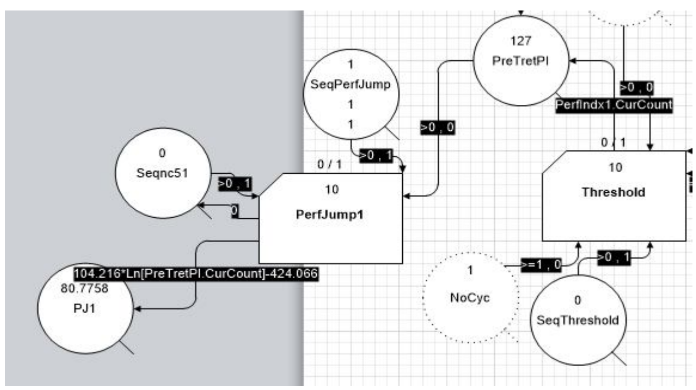


Figure 5-2 Screenshot of Pavement Treatment Performance Module - Results of Estimating Performance Jump PJ Values of Resurfacing (3R Partial Standards) Rehabilitation Treatment

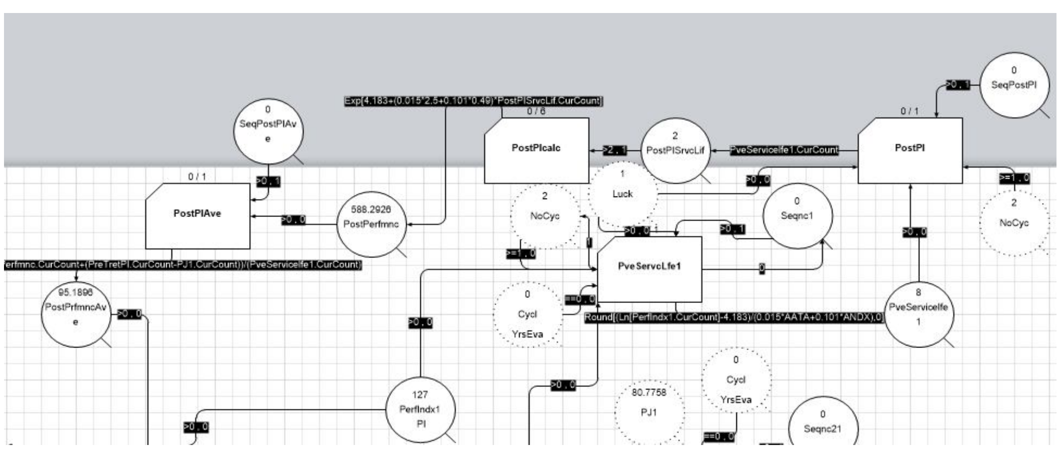


Figure 5-3 Screenshot of Pavement treatment Performance Module - Results of Estimating Service Life and PI_{Avg} Values of Resurfacing (3R Partial Standards) Rehabilitation Treatment

The third treatment to be applied is also resurfacing (3R partial standards). The service life and PIAvg values for the third application (i.e., Resurfacing 3R partial standards rehabilitation treatment) are similar to the estimated results of the second treatment application. Table 5-4 summarizes the assessment of the impact of alternative treatment applications.

Table 5-4 Summary of the Impact of Alternative Treatments of a Candidate Scenario.

Treatment Type	Service life (tsi) (year)	PI_{trigg} (IRI in/mi)	PJ After Intervention (IRI in/mi)	Post-Treatment Average PI (IRI in/mi)
New Full-Depth HMA Construction	12	127	-	89.25
Resurfacing (3R partial standards) rehabilitation	8	127	46.32	95.19
Resurfacing (3R partial standards) rehabilitation	8	127	46.32	95.19

5.3 Pipe Failure Prediction Module - Results

The pipe failure prediction module determines the number of times the pipe will fail. The prediction model estimates the probability that the pipe will fail and then compares that with a randomly generated number between 0 and 1. In each run, the generated random number is going to be different, and the number of pipe failures and their times of occurrence therefore are going to also be different. For the purpose of verifying the model, a seed statement (i.e., 2233) is used to disable the randomness aspect in the model. The break occurrence times obtained from the pipe failure probability model are tp1 = 11 and tp2 = 11. A screenshot of the pipe failure prediction module depicting the occurrence of the first failure is presented in Figure 5-4.

The queue named “Failure” in Figure 5-4 represents the estimated probability of the pipe to fail. At the 11th year (represented by number 11 above CombiAct named “Test”), after replacing the pipe, the probability of failure is 0.2351 and the random number generated by the model is 0.0122. Since the probability of failure is greater than the picked random number, then failure is considered to have occurred. The remaining failures and their occurrence times are estimated following the same procedure.

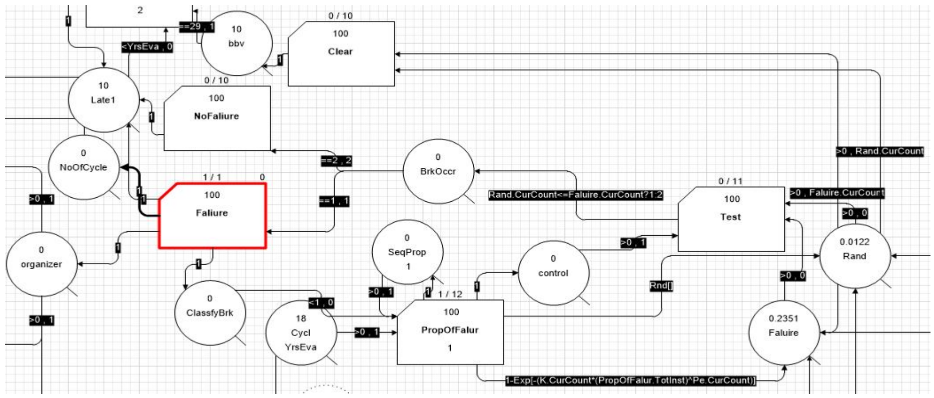


Figure 5-4 Screenshot of Pipe Failure Prediction Module - Results of Estimating Pipe Failure Times

To determine the pipe failure probability at each year, the model developed by Mailhot et al (2000) was used and the general form of the model is presented in Equation (5.1).

$$P = 1 – e^{-kt^{p}} \quad (5.1)$$

Where: P = probability of pipe failure, t = time since last break and k & p are estimated coefficient (see table2 in Appendix B).

The probability of the pipe failing at the 11^{th} year is estimated using Equation (5.1).

$$P = 1 – e^{-0.013*(11)^{1.262}} = 0.2351$$

5.4 Decision Matrix Module - Results

Based on the estimated treatment service life of each treatment and the pipe break times during the life cycle of the assets, the decision matrix module is used to link the times of pipe failure to the corresponding treatments (i.e., first, second, and third treatment) and to assess the impact of these failures on that treatment. In addition, this coordination can take place if the pipe failure occurred at the end of the treatment service life. To determine the pipe failure times and the corresponding treatment, Equation (3.4) was used. In the present example, the first treatment application (ts1) experienced pipe failure during its service life. The percentage of treatment service life reduction due to cutting and patching when fixing broken pipes is assumed to be %30 (which is a conservative estimate). Thus:

t’s1 = tp1 + %reduction*(ts1 - tp1)

t’s1 = 11 + (1- 0.3)*(12 - 11) = 11.7 ≈ 12 years

The second treatment application (ts2) has experienced no pipe failure during its service life.

ts2 = ts2 = 8 years

The third treatment application (ts3) has experienced the second pipe failure and its service life is estimated as follow:

ts3 = (tp1 + tp2 - ts1 + ts2) + %reduction*(ts1 + ts2 + ts3 - tp1 + tp2)

ts3 = ((11 + 11) – (12 + 8)) + (1- 0.30) * ((12 + 8 + 8) – (11 + 11)) = 6.2 ≈ 6 years

Figure 5-5 shows a graphical illustration of the service life of pavement treatments and their corresponding pipe failure times for the considered scenario.

The results of the EZStrobe simulation model with respect to whether the pipe has failed during first pavement treatment service life or not is shown in Figure 5-6.The queues named “p1” and “s1” have values of 11 and 12 years (as shown in Figure 5-6). These values represent the time of the first pipe failure and the service life of the first treatment, respectively. The arrow between the CombiAct named “S1LessP1” and the queue named “Check” represents the if-statement that determines whether the s1 is less than p1. If yes, then a CombiAct named “s1p1” is initiated and s1 remains unchanged. If not, as it is in this case, then a CombiAct named “s2p2” is initiated and s1 encounters pipe failure after 11 years (as shown in the queue named “sa1”). The remaining pipe failure times are linked with the associated pavement treatment service lives using the same procedure. Based on the model results, the first and second pipe breaks were found to occur during the first and third pavement treatment service lives, respectively.

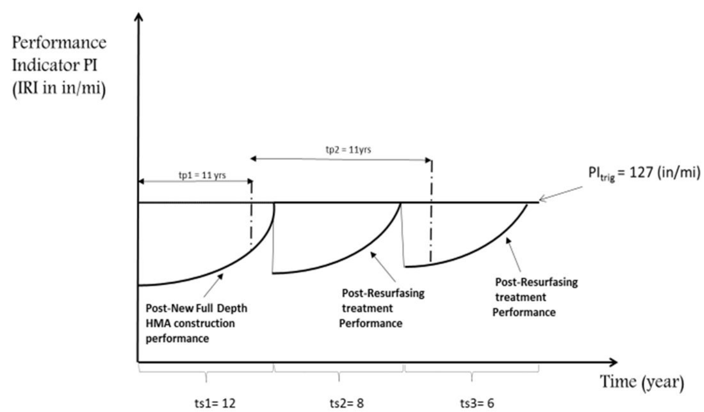


Figure 5-5 Graphical Illustration of Pavement Treatments Service Life and Corresponding Pipe Failure Times

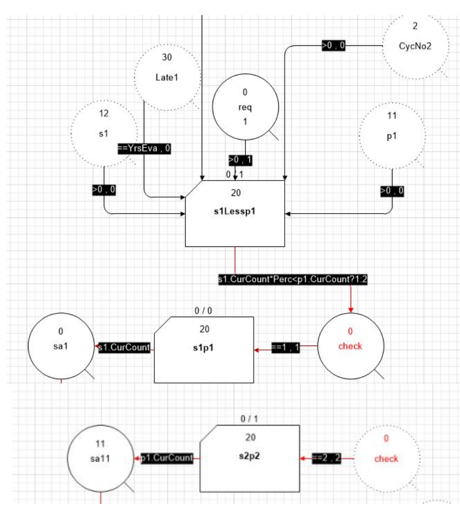


Figure 5-6 Screenshot of Pipe Failure Prediction Module - Results of Estimating Pipe Failure Times

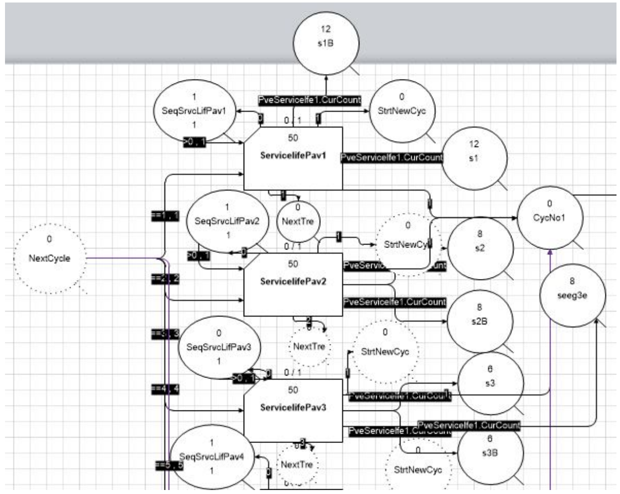


Figure 5-7 Screenshot of Decision Matrix Module - Results of Estimating Pavement Treatments Service Life (Without Coordination)

Figure 5-7 shows the results obtained from the simulation module for the pavement treatment service life values considering the pipe failure impacts. The queues named “s1”,”s2”, and ”s3” have values of 12, 8, and 6, respectively. These values represent the service life in years for a new full-depth HMA construction type and the application of resurfacing (3R partial standards) twice.

After determining the reduction in pavement treatment service life due to water pipeline M&R intervention, post-treatment average performance is recalculated (utilizing the same procedure explained earlier). A summary of the impact of water pipeline failure on treatments of a candidate scenario is provided in Table 5-5.

Table 5-5 Summary of the Impact of Alternative Treatments of a Candidate Scenario (Considering Pipe Failure Impact – Without Coordination).

Treatment Type	Service life (tsi) (year)	PI_{trigg} (IRI in/mi)	PJ After Intervention (IRI in/mi)	Post-Treatment Average PI (IRI in/mi)
New Full-Depth HMA Construction	12	127	-	89.25
Resurfacing (3R partial standards) rehabilitation	8	127	46.32	95.19
Resurfacing (3R partial standards) rehabilitation	6	127	46.32	95.37

5.5 Coordinating Module - Results

The coordination module determines whether or not a pipe failure has occurred after a sufficient time from the start of the pavement treatment service life to warrant pavement replacement. If so, the subsequent treatment will be carried out concurrently with repairing the broken pipe (i.e., at the time of pipe failure). Figure 5-8 shows a graphical illustration of the coordination of a pipe failure that occurs during the first pavement treatment service life. If the time of first pipe break is greater than the product of the first pavement treatment's service life and the allowable percentage (%), then the subsequent treatment would be applied just after fixing the pipe. In the considered scenario, tp1 =11 years, ts2 =12, and the allowable percentage was taken to be 80%. Therefore, ts2 would be carried out when fixing the first pipe failure (tp1) and ts1 becomes equal to tp1. The simulation model results for treatment service life when considering the coordination between both assets are shown in Figure 5-9.

When considering the coordination between the two assets, ts1 becomes equal to tp1 (i.e., 11 years). Therefore, the time for applying the subsequent treatment has to be adjusted accordingly. The second pipe failure occurred during the third pavement treatment service life. Thus, ts2 remains unchanged (i.e., 8 years) and ts3 becomes equal to 7 years. After determining the reduction in pavement treatment service life due to water pipeline M&R interventions, the average post-treatment performance is calculated for each treatment (presented in Table 5-6), utilizing the same procedure explained earlier.

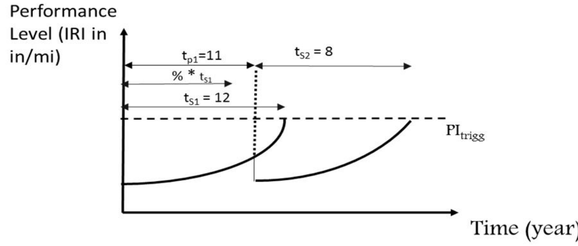


Figure 5-8 Graphical Illustration of the Coordination Concept of First Pipe Failure with Second Pavement Treatment Service Life

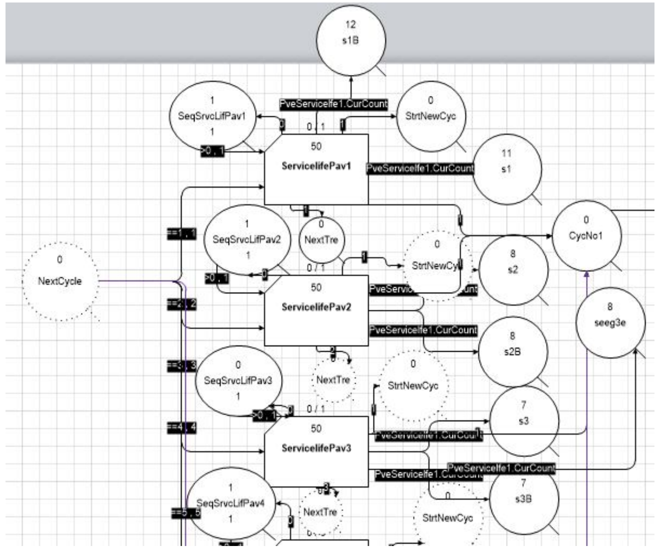


Figure 5-9 Screenshot of Decision Matrix Module - Results of Estimating Pavement Treatments Service Life (With Coordination).

Table 5-6 Summary of the Impact of Alternative Treatments of a Candidate Scenario (Considering Pipe Failure Impact – With Coordination)

Treatment Type	Service life (tsi) (year)	PI_{trigg} (IRI in/mi)	PJ After Intervention (IRI in/mi)	Post-Treatment Average PI (IRI in/mi)
New Full-Depth HMA Construction	11	127	-	89.25
Resurfacing (3R partial standards) rehabilitation	8	127	46.32	95.19
Resurfacing (3R partial standards) rehabilitation	7	127	46.32	93.9

From Table 5-6, while the reduction in the service life of the new full-depth HMA construction due to the coordination has no impact on the PIAvg, the gain in the service life of the third treatment application has a positive impact on the PIAvg compared to the no coordination scenario (Table 5-4).

5.6 Estimating Pavement Treatment Effectiveness - Results

As explained earlier, the pavement treatment effectiveness can be measured using two sub-modules (monetized sub-module and non-monetized sub-module). For the non-monetized sub-module, the estimated treatment service lives (i.e., ts1, ts2m and ts3) represent the effectiveness of the treatments. In the monetized sub-module, the effectiveness of the treatment is represented by the savings in annual maintenance cost (MCSi) and VOC (VOCSi) due to the treatment application. Taking the first treatment (new full-depth HMA construction) as an example to estimate the MCS, the pre-treatment and the average post-treatment performance are 127 (in/mi) and 89.25 (in/mi). Converting these values from IRI to PSI values using Equation (3.11), the PSIpre and the PSIpost are 2.963 and 4.123, respectively. The traffic volume was assumed to be high. Therefore, the annual maintenance expenditure before and after applying the treatment are estimated as follows:

AMC = $10^{4.0283 - 0.462 * (2.963)}$ = 456.45 ($/lane-mail) ($1994)

AMC = $10^{4.0283 - 0.462 * (4.123)}$ = 132.88 ($/lane-mail) ($1994)

These costs are then brought to the year 2013 using an escalation factor.

$$Escalation\ factor = \frac{CPI\ (current\ year)}{CPI(Base\ year)} = \frac{CPI\ (2013)}{CPI\ (1994)} = \frac{233.78}{147.96} = 1.58$$

CPI = Consumer Price Index (Bureau of Labor Statistics 2013).

The savings in annual maintenance cost due to the treatment application is as follows:

MCS=456.45 –132.88 = 323.56 ($/lane-mail) ($1994)

MCS = 511.22 ($/lane-mail) ($2013)

Figure 5-10 shows the simulation results for estimating the annual maintenance cost of new full-depth HMA construction.

The annual savings in the vehicle operating cost (VOCS) due to treatment application is calculated by computing the difference between the annual VOC savinga before and after applying the treatment using Equation (3.13). A study in New Zealand (Opus 1999) developed plots between the pavement performance in terms of IRI (in/mi) and VOC (cents per vehicle-mile) (see Figure 3-15). For the purpose of this thesis, the annual savings in VOC before and after applying the treatment are estimated using these plots.

For PIpre= 127 (IRI in in/mi), the corresponding cost is 0.4135 (cent per vehicle-mile)

For PIpost= 89.25 (IRI in in/mi), the corresponding cost is 0.40 (cent per vehicle-mile)

To estimate the overall VOC ($/lane-mile), the volume of traffic (AADT = 22,831) estimated by Irfan (2009) was employed while assuming a lane distribution factor of 0.5 and a directional distribution factor of 0.5. Therefore:

VOC Before = 0.4135 * 365 * 22831 * 0.5 *0.5 = 861,456 ($/lane-mile) ($1999)

VOC After = 0.40 * 365 * 22831 * 0.5 *0.5 = 833,331 ($/lane-mile) ($1999)

These costs are in 1999 dollars value, therefore an escalation factor (i.e., 1.41) was used to update the costs to 2013 dollars.

The savinga in annual VOC due to treatment application is as follows:

VOCS = 1,214,652 – 1,174,996 = 39,655 ($/lane-mail) ($1999)

The results of the simulation model for estimating the annual maintenance cost of new full-depth HMA construction type is presented in Figure 5-11.

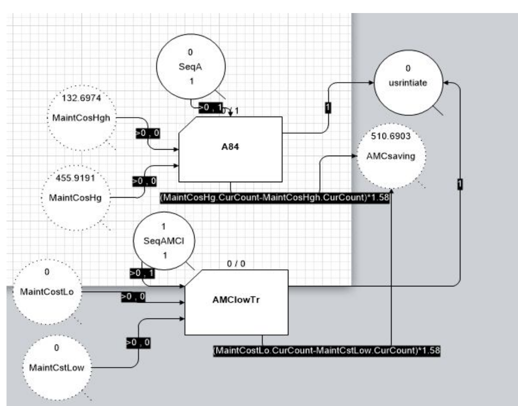


Figure 5-10 Screenshot of Annual Maintenance Cost Saving Sub-Sub-Module - Results

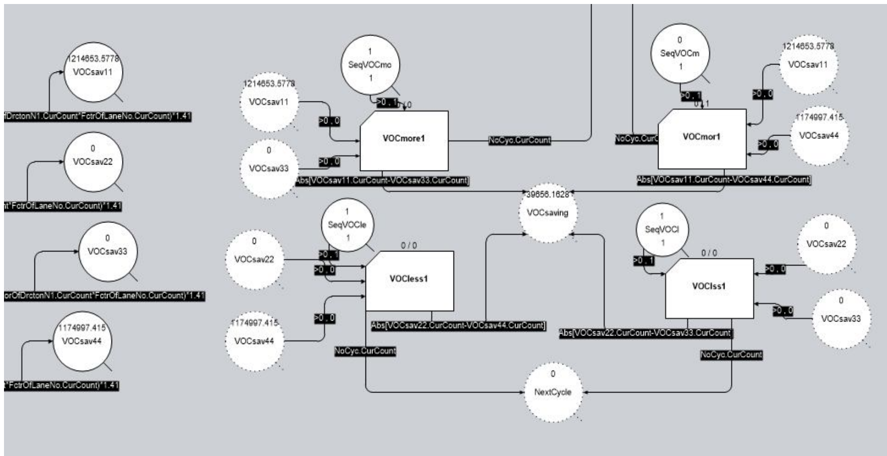


Figure 5-11 Screenshot of Vehicle Operation Cost Saving Sub Sub-Module - Results

A summary of the savings in maintenance costs and VOC for each treatment of the candidate scenario with and without coordination are presented in Tables 5-7 and 5-8. The costs associated with the second and third treatment applications, projected to be applied in years 2025 and 2033, respectively, are forecasted using CPI. The average increase in the CPI values for the last ten years (i.e., about 2.1%) was employed to forecast changes in the CPI over the evaluation period (Bureau of Labor Statistics 2013).

$$Escalation\ factor = \frac{CPI\ (Future\ year)}{CPI(Base\ year)} = \frac{CPI\ (2025)}{CPI\ (2013)} = \frac{293.78}{233.78} = 1.256$$

$$Escalation\ factor = \frac{CPI\ (Future\ year)}{CPI(Base\ year)} = \frac{CPI\ (2033)}{CPI\ (2013)} = \frac{333.78}{233.78} = 1.428$$

Table 5-7 Summary of Estimated Pavement Treatments Effectiveness of A Candidate Scenario – With No Coordination

Treatment Type	[1]Service life (tsi) (year)	PI_{trigg} (IRI in/mi)	Post-Treatment Average PI (IRI in/mi)	MCS ($/lane-mail) ($2013)	VOCS ($/lane-mail) ($2013)
New Full-Depth HMA Construction	12	127	89.25	511.22	39,655
Resurfacing (3R partial standards) rehabilitation	8	127	95.19	458.39 [2](575.74)	39,655 [2](49,806)
Resurfacing (3R partial standards) rehabilitation	6	127	95.37	456.7 [3](652.167)	39,655 [3](56,627)

1Measuer of treatment effectiveness in non-monetized term.
2Projected costs in 2025 year
3Projected costs in 2033 year

Table 5-8 Summary of Estimated Pavement Treatments Effectiveness of A Candidate Scenario – With Coordination

Treatment Type	1Service life (tsi) (year)	PI_{trigg} (IRI in/mi)	Post-Treatment Average PI (IRI in/mi)	MCS ($/lane-mail) ($2013)	VOCS ($/lane-mail) ($2013)
New Full-Depth HMA Construction	11	127	89.25	511.22	39,655
Resurfacing (3R partial standards) rehabilitation	8	127	95.19	458.39 [2](566.2)	39,655 [2](48,985)
Resurfacing (3R partial standards) rehabilitation	7	127	93.9	470.4 [3](661.6)	39,655 [3](55,771)

1Measuer of treatment effectiveness in non-monetized term.
2Projected costs in 2024 year
3Projected costs in 2032 year

5.7 Estimating Pavement Treatments Cost - Results

The costs associated with treatment applications can be estimated using two sub-modules (agency cost sub-module and user cost sub-module).

The agency sub-module is estimated utilizing Equation (3.18), which was used to estimate the cost of maintenance and rehabilitation treatments since it represents the best fit among other forms evaluated by Irfan (2009). The estimated parameters for each treatment type are presented in Appendix C. For the new full-depth HMA construction, the average cost of $484,123 /lane-mile in 2013 dollars was used. Therefore, assuming one lane of one mile length is to be treated, the overall cost of the work is $484,123. The cost of applying the resurfacing (3R partial standards) treatment to one lane of one mile in length is as follows:

$T_{AC} = 0.098 * (1)^{0.690} * (1)^{0.458} *[\ln (127)]^{4.867}$ = $211.932 ($/lane-mile)($2007)

An escalation factor of 1.13 is used to update the costs.

T_{AC} = 239.483 ($/lane-mile) ($2013)

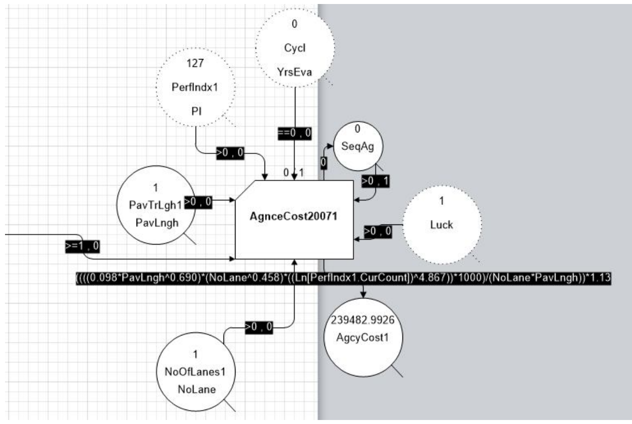


Figure 5-12 Screenshot of Agency Cost Sub-Module - Results

Figure 5-12 shows a screenshot of the agency cost sub-module for estimating the cost of the resurfacing (3R partial standards) treatment. The pavement length and the number of lanes to be maintained are modeled as input variables. The treatment performance indicator is taken as the prior treatment performance threshold (i.e., IRI = 127 in/mi).

The user cost sub-module consists of two sub sub-modules: the work zone travel delay cost (WZttd) and the work zone VOC (WZvoc) sub-sub-modules (see Section 3.8.2). First, the work zone project duration models developed by Irfan (2009) were employed as shown using Equations (5.2, 5.3, and 5.4). These models are a function of the project cost (total agency cost in millions of dollars) and the contract type (0 indicates that available days for project completion were specified, and 1 indicates that a deadline date was fixed).

Road Maintenance Projects: $y = e^{4.87 + 0.299*COST + 0.268*CONTRACT\_TYPE}$ (5.2)

Road Resurfacing Project: $y = e^{4.60 + 0.340*COST + 0.253*CONTRACT\_TYPE}$ (5.3)

Road Construction Projects: $y = e^{4.70 + 0.307*COST + 0.237*CONTRACT\_TYPE}$ (5.4)

The work zone duration was estimated as 65% of the project duration (Lamptey et al 2004). The work zone duration for the new full-depth HMA construction was estimated by Equation

5.4 to be 105 days, assuming the deadline date was fixed for the project. Having determined the project duration, then WZttd is estimated using Equation (3.22). To estimate the $UC_{ttd,}$ the following assumptions were made:

- AADT = 22,831.
- Percentage of traffic share = 0.7 and 0.3 for passenger cars and trucks, respectively.
- Lane distribution factor and directional distribution factor are 0.5 for both.
- Road section: two lanes with one lane closed for the construction.
- Speed limits are 50 and 30 mph at non-work zone and at work zone section, respectively.
- Travel time values = $17.55 and $29.26 (2013 dollars) for passenger car and single-unit truck/combination-truck, respectively. These values were estimated in a study by the FHWA in 1996 (FHWA 1996), and the CPI was used to bring the values to year 2013 (CPI = 1.49).

UC_{ttd} (passenger car) = 105 * 22831 * 0.5 *0.5 * 0.7 * (1/30 – 1/50) * 17.55 = 98,167 ($/lane-mile) ($2013)

UC_{ttd} (truck) = 105 * 22831 * 0.5 *0.5 * 0.3 * (1/30 – 1/50) * 29.26 = 70,143 ($/lane-mile) ($2013)

UC_{ttd} (total) = 98,167 + 70,143 = 168,310 ($/lane-mile) ($2013)

Then WZvoc is estimated using Equation (3.22). To estimate the $UC_{voc,}$ the following assumptions were made:

- AADT = 22,831.
- Percentage of traffic share = 0.7 and 0.3 for passenger cars and trucks, respectively.
- Lane distribution factor and directional distribution factor are 0.5 for both.
- Road section has two lanes with one lane closed for the construction.
- Speed limits are 50 and 30 mph at non-work zone and at work zone section, respectively.

- Fuel price = $2 and $4 per gallon for passenger cars and trucks, respectively.
- Fuel consumption = 0.034 gals/min and 0.345 gals/min for passenger cars and trucks, respectively. (AASHTO 2003; Sinha and Labi 2007)

UC_{voc} (passenger car) = 105 * 22831 * 0.5 *0.5 * 0.7 * (1/30 – 1/50) * 2.04 * 2 = 22,821 ($/lane-mile) ($2013)

UC_{ttd} (truck) = 105 * 22831 * 0.5 *0.5 * 0.3 * (1/30 – 1/50) * 20.73 * 4 = 198,780 ($/lane-mile) ($2013)

UC_{ttd} (total) = 22,821 + 198,780 = 221,601 ($/lane-mile) ($2013)

Figure 5-13 shows a screenshot of the work zone costs sub-sub-modules that estimates the cost of travel time delay (i.e., 168,487 ($/lane-mile) as shown in the queue named “UCttdely1”and VOC (221,797 $/lane-mile as shown in queue named “UCvoc1”) incurred due to the application of the new full-depth HMA construction. The difference between the hand calculation values and the simulation model results is due to the approximation made in the hand calculations. A summary of the agency costs and the user costs for each treatment of the candidate scenario with and without coordination are presented in Tables 5-9 and 5-10.

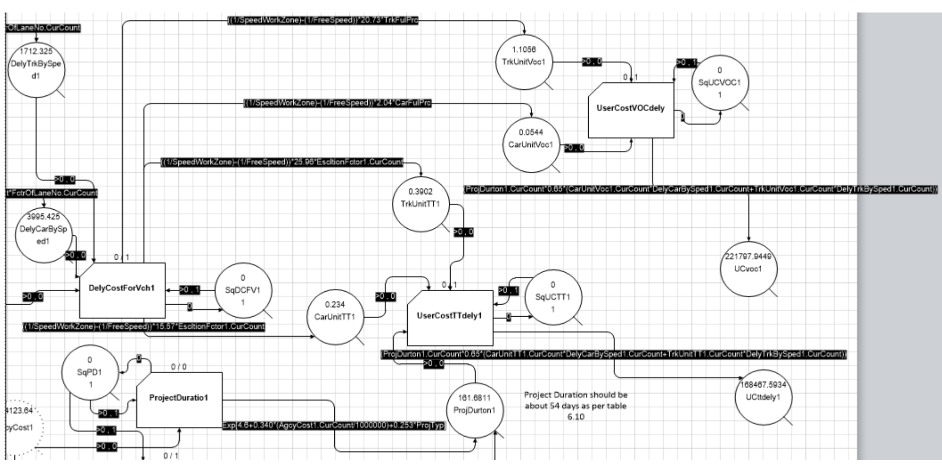


Figure 5-13 Screenshot of Work Zone Costs Sub Sub-Modules – Results

Table 5-9 Summary of Estimated Pavement Treatment Agency and User Costs of A Candidate Scenario – With No Coordination

Treatment Type	Project Duration (day)	1Work Zone Duration (day)	Agency Cost ($/lane-mile) ($2013)	User Cost ($/lane-mile) ($2013)	
				UCttd	UCvoc
New Full-Depth HMA Construction	161	105	484,123	168,310	221,601
Resurfacing (3R partial standards) rehabilitation	139	90	239.483 2(300,791)	144,827 2(181902)	190,674 2(239486)
Resurfacing (3R partial standards) rehabilitation	139	90	239,483 3(341,981)	144,827 3(206812)	190,674 3(272,282)

1Work zone duration is taken as %65 of the project duration
2Projected costs in 2025 year
3Projected costs in 2033 year

Table 5-10 Summary of Estimated Pavement Treatment Agency and User Costs of A Candidate Scenario – With Coordination

Treatment Type	Project Duration (day)	1Work Zone Duration (day)	Agency Cost ($/lane-mile) ($2013)	User Cost ($/lane-mile) ($2013)	
				UCttd	UCvoc
New Full-Depth HMA Construction	161	105	484,123	168,310	221,601
Resurfacing (3R partial standards) rehabilitation	139	90	239.483 2(295,824)	144,827 2(178,899)	190,674 2(235,532)
Resurfacing (3R partial standards) rehabilitation	139	90	239,483 3(336,800)	144,827 3(203,679)	190,674 3(268,157)

1Work zone duration is taken as %65 of the project duration
2Projected costs in 2024 year
3Projected costs in 2032 year

5.8 Estimating Water Pipeline Treatment Effectiveness - Results

Similarly, the water pipeline M&R effectiveness can be measured using two sub-modules: the monetized sub-module and the non-monetized sub-module. For the non-monetized sub-module, the estimated M&R service life (i.e., tp1, tp2, and tp3) represent the treatment effectiveness. In the monetized sub-module, the effectiveness of the M&R is estimated using Equation (3.16). The M&R original cost ($M\&R_{OC}$) is estimated using the pipe agency cost sub-modules (see Section 5.9). The total agency cost is estimated to be $856,230 (2013 dollars). The valuation of the M&R is estimated using Equation (3.15). The historical cost (HC) is equal to the original cost (i.e., $856,216). The scale of the pipe condition ranges from 5, which represents the best pipe condition, to 1, which represents the worst pipe condition. The expected pipe condition at the time of failure is estimated using the model developed by Opila and Attoh-Okine (2011). The proposed method is based on the economic concept of discounting the pipe value using a rate of return, where the mean time to failure (MTTF) of the pipe is used to determine the condition. The MTTF is estimated from the pipe failure module. The general form of the proposed model is presented in Equation (3.17). From the pipe failure module, the first break was estimated to occur at the 11th year; therefore, its condition is calculated as follows:

$S = \frac{5}{(1+0.04)^{11}} = 3.25$ (Assuming 0.04 discounted rate).

The effectiveness measure of the first second and third pipe replacements are estimated using Equation (3.16).

Effectiveness (p1) = 856,216 - 856,216* ($\frac{3.25-1}{5-1}$) = \$374,594 (\$2013)

Since the second and third pipeline failures are projected to be in years 2024 and 2035, respectively, an escalation factor was used to update the costs to their values in these years. The average increase in the CPI values for the last ten years (i.e., about 2.1%) was employed to forecast changes in the CPI (Bureau of Labor Statistics 2013).

$$Escalation\ factor = \frac{CPI\ (Future\ year)}{CPI(Base\ year)} = \frac{CPI\ (2024)}{CPI\ (2013)} = \frac{288.78}{233.78} = 1.235$$

$$Escalation\ factor = \frac{CPI\ (Future\ year)}{CPI(Base\ year)} = \frac{CPI\ (2035)}{CPI\ (2013)} = \frac{343.78}{233.78} = 1.47$$

Effectiveness (p2) = 856,216 * (1.235) - 856,216 * (1.235) * ($\frac{3.25-1}{5-1}$) = \$462,624 (\$2013)

Since the failure of the third pipe replacement is not occurring during the analysis period (i.e., determined by the pavement treatment service life, which in this case is 26 years), then it is assumed that the useful life of that pipe ends at the end of the analysis period.

Effectiveness (p3) = 856,216 * (1.47) – 856,216 * (1.47) * ($\frac{4.27-1}{5-1}$) = \$229,701 (\$2013)

A summary of the agency costs and user costs for the water pipeline replacement scenarios are presented in Table 5-11.

Table 5-11 Summary of Estimated Water Pipeline Replacement Effectiveness of A Candidate Scenario

Pipe Replacement Order	Time Since Last Break (tpi) (year)	Pipe Condition			$M\&R_{Benefits}$ ($2013)
		Best	Worst	[1]Expected	
First	11	1	5	1.75	374,594
Second	11	1	5	1.75	462,624
Third	-	1	5	-	229,701

1Expected condition is estimated at pipe failure time

5.9 Water Pipeline Cost Modules - Results

Similar to the pavement asset, the costs (i.e., agency and user costs) of pipe M&R would be estimated at the beginning of their time of application. These times can be obtained from the pipe failure prediction module and they are, in this case, tp1 = 11 and tp2 = 11. The costs associated with the M&R activities can be measured using two sub-modules: the agency cost sub-module and the user cost sub-module.

The agency sub-module uses Equation (3.25) and consists (as explained earlier) of several sub-sub-modules including the excavation cost module, embedment cost module, pipe materials cost module, dewatering cost module, sheeting and shoring cost module, backfilling and compacting cost module, pavement repair and replacement cost module, and traffic control cost module. Several assumptions, for the purpose of this example, were made to calculate the agency costs and they are presented in Table 5-12.

The agency costs models developed by Clark et al (2002) are employed in the present framework and are presented in Appendix D. The costs of the aforementioned assumptions and their associated parameters are presented in Table 5-13.

Table 5-12 Considered Assumptions of Estimating Water Pipeline Agency Costs

Category	Brief Description	Considered Assumption
Soil	Type of soil to be encountered during pipe installation	Sandy gravel soil with 1:1 side slop
Pipe material	The type of pipe material to be chosen	Ductile Iron pipe (class 52), with mechanical joint
Pipe depth	The depth of the pipe to be installed from the ground surface	12 ft.
Pipe diameter	The outside diameter size of the pipe to be installed	25 in
Pipe length	The length of the pipe to be installed	2570 ft.
Embedment	The type of embedment to be considered	Concrete arch
Dewatering	The condition of dewatering	Moderate dewatering condition
Sheeting and Shoring	The condition of sheeting and shoring	Moderate ground water
Backfilling	The type of soil to be used for backfilling	Sandy native soil with 1:1 side slope
Compacting	The percentage of compacting after backfilling	%90
Pavement	The type of pavement to be removed and replaced	Asphaltic concrete
Traffic	The condition of the traffic to be controlled during the installation period.	Moderate traffic condition

The total agency cost is the product of the sum of the aforementioned costs and the pipe length. Therefore, the total agency cost in 2002 dollars is $658,639. This cost is then updated using an escalation factor of 1.3, which yields a total agency cost of $856,216 in 2013 dollars. The results of the water pipeline agency costs sub-sub-modules are presented in Figure 5-14.

Table 5-13 Summary of Water Pipeline Agency Cost Estimations

Item	Parameters	Unit Cost ($/ft)($2007)
Base Installed pipe	Y= -36+0.62*Pipe Diameter^1.54+2.04*Class^0.78	96.62
Excavation	Y= 2.9+0.0018*Pipe Diameter ^1.9+0.13*Depth^1.77	14.286
Embedment	Y= 7.1+0.26*Pipe Diameter ^1.46	35.67
Dewatering	Y= 1.6+0.032*Pipe Diameter ^1.2	3.12
Sheeting and Shoring	Y= 59	59
Backfilling	Y= -0.094-0.062*Pipe Diameter ^0.73+0.18*Depth^2.03+0.02*Depth*Pipe Diameter	33.18
Pavement	Y= -3+0.23*Pipe Diameter ^0.93+10.7*1^1+0.08*1*Pipe Diameter	14.29
Traffic control	Y= 0.088+0.0022*Pipe Diameter ^0.71	0.1096

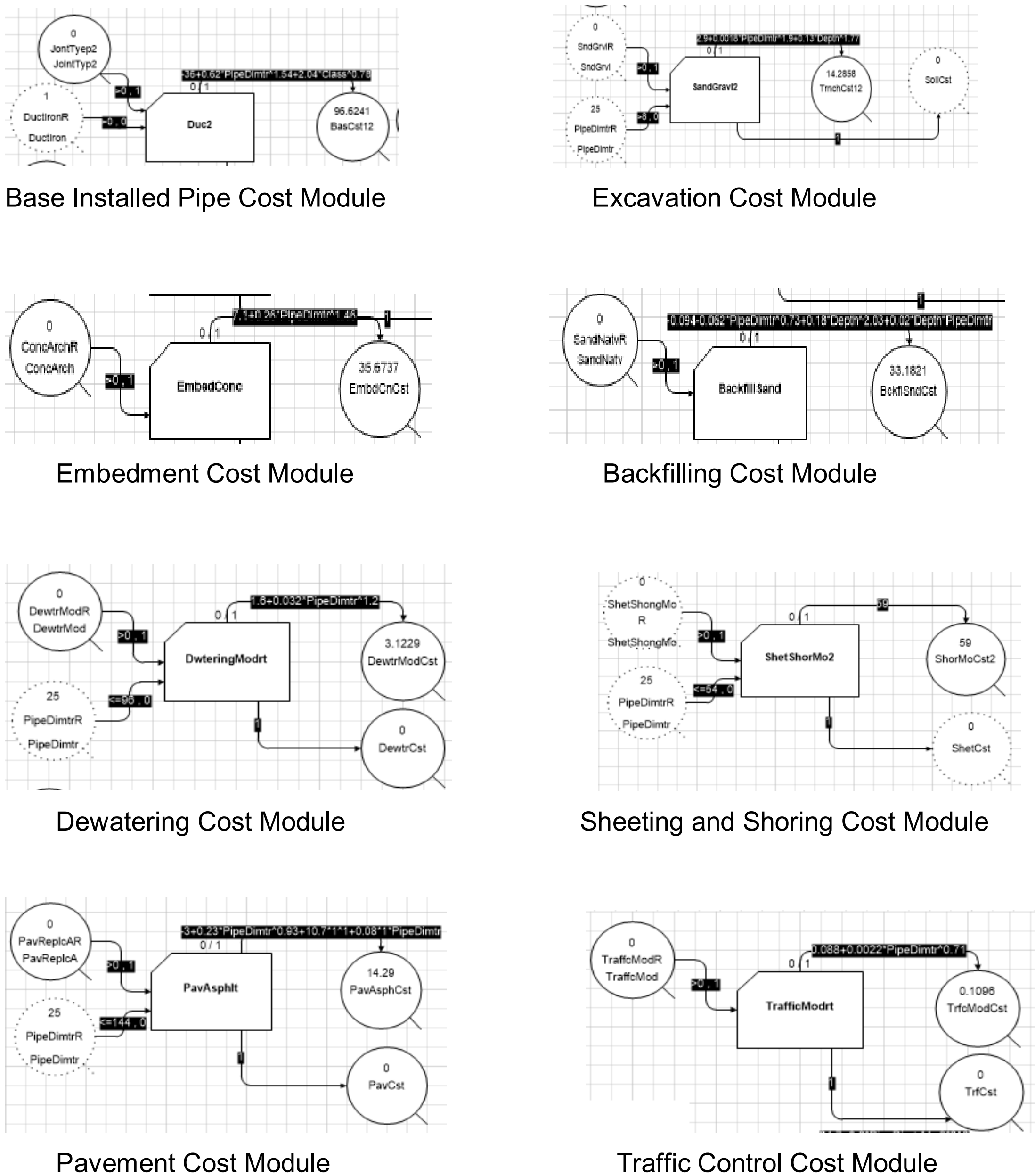


Figure 5-14 Results of Water Pipeline Agency Costs Sub Sub-Modules

The user cost sub-module is similar to the pavement user cost module. However, the work zone project duration models are assumed to be different. A study published by Jung and Sinha (2007) was used as a guideline for determining a reasonable project duration. The study presented six different types of projects. Which are summarized in Table 5-14. It is important to mention that the project duration of water pipeline replacement is influenced by several factors (e.g., weather conditions, site location, soil types, etc.) which vary across different projects. For the purpose of this thesis, the work zone duration was assumed to be 90 days. An illustration of the wok zone assumed to be employed for replacing a water pipeline is depicted in Figure 5-15.

Table 5-14 Summary of General Information of Water Pipeline M&R Projects (Jung and Sinha 2007)

Project Number	Length (m)	Depth (m)	Pipe Size (cm)	Job Duration (day)
4A-2000	144	1.8-2.4	20	55
4B-2000	390	1.8-2.4	20	60
17-2000	81	2.4-3.6	20, 30	45
11-2001	1,828	2.4-3.6	46, 61, 92	120
13-2000	380	1.8-3.0	20	60
11-2002	155	2.4-3.6	20	60

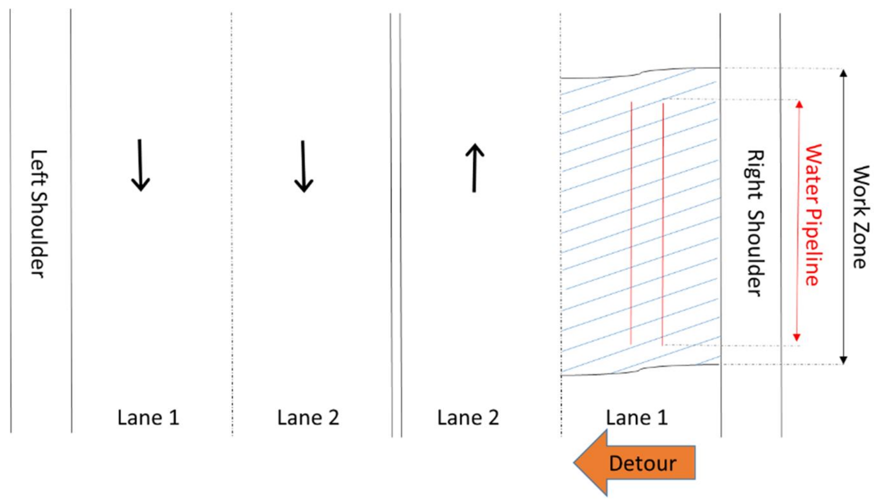


Figure 5-15 Sketch Illustration of Work Zone Area Employed for Water Pipeline Replacement

While the length of the pipe is assumed to be 2,570 ft., the work zone length is 2,740 ft. (i.e., 0.5 mile) to allow for equipment to move. The closure of one lane is assumed while fixing the pipe. The same assumptions considered in estimating the work zone costs incurred by pavement treatments applications are taken.

Having determined the work zone duration, then WZttd is estimated using Equation (3.22).

UC_{ttd} (passenger car) = 90 * 22831 * 0.5 *0.5 * 0.7 * (1/30 – 1/50) * 17.55 = 84,143 ($/lane-mile) ($2013)

UC_{ttd} (truck) = 90 * 22831 * 0.5 *0.5 * 0.3 * (1/30 – 1/50) * 29.26 = 60,123 ($/lane-mile) ($2013)

UC_{ttd} (total) = 84,143 + 60,123 = 144,266 ($/lane-mile) ($2013)

UC_{ttd} (total) = 144,266/2 = $72,133 ($2013)

Then WZvoc is estimated using Equation (3.22)

UC_{voc} (passenger car) = 90 * 22831 * 0.5 *0.5 * 0.7 * (1/30 – 1/50) * 2.04 * 2 = 19,561 ($/lane-mile) ($2013)

UC_{ttd} (truck) = 90 * 22831 * 0.5 *0.5 * 0.3 * (1/30 – 1/50) * 20.73 * 4 = 170,383 ($/lane-mile) ($2013)

UC_{ttd} (total) = 19,561+ 170,383 = 189,944 ($/lane-mile) ($2013)

UC_{ttd} (total) = 189,944/2 = $94,972 ($2013)

The total user cost of closing one lane of 0.5 mile length is $167,105 in 2013 dollars. A summary of the agency costs and the user costs for a water pipeline replacement scenario with and without coordination is presented in Tables 5-15 and 5-16.

Table 5-15 Summary of Estimated Water Pipeline Replacement Agency and User Costs of A Candidate Scenario – With No Coordination

Pipe Replacement Order	Work Zone Duration (day)	Agency Cost ($/lane-mile) ($2013)	User Cost ($/lane-mile) ($2013)	
			UCttd	UCvoc
First	90	856,216	94,972	72,133
Second	90	856,216 [1](1,057,426)	94,972 [1](117,290)	72,133 [1](89,084)
Third	90	856,216 [2](1,258,637)	94,972 [2](139,608)	72,133 [2](106,035)

1Projected costs in 2024 year
2Projected costs in 2035 year

Table 5-16 Summary of Estimated Pavement Treatment Agency and User Costs of A Candidate Scenario – With Coordination

Pipe Replacement Order	Work Zone Duration (day)	Agency Cost ($/lane-mile) ($2013)	User Cost ($/lane-mile) ($2013)	
			UCttd	UCvoc
First	90	856,216	94,972	72,133
Second	[4]72	856,216 [1,3](996,620)	94,972 [1](93,832)	72,133 [1](71,238)
Third	90	856,216 [2](1,258,637)	94,972 [2](139,608)	72,133 [2](106,035)

1Projected costs in 2024 year
2Projected costs in 2035 year
3No costs of pavement cut and patching when coordinating
4(%80 of the work zone assumed when coordinating)

5.10 The Overall Costs and Benefits Module - Results

The main task of the overall costs and benefits module is to perform cost-effectiveness analysis using Equations (3.30) and (3.31). Having the outcomes of estimating all the costs and benefits of both assets (i.e., water pipeline and pavement) using the aforementioned modules, the cost benefit ratio then can be calculated. All the costs and benefits of the M&R activities for both assets are first discounted to the beginning of the analysis period using the present worth factor (PWF) and then annualized using the EUAC. The cost-effectiveness of the considered scenario is presented in Tables 5-17 and 5-18 for the no-coordination and coordination scenarios. A discount rate of 0.04 was employed, and a reduction of 20% of the total work zone duration is assumed in the case of coordination.

Table 5-17 Cost-Effectiveness of a Candidate's M&R Activities – With No Coordination

Treatment Type	PWC ($/lane)	PWB ($/lane)	EUAC ($/lane)	EUAB ($/lane)	Cost-Effectiveness (B/C)
New Full-Depth HMA Construction	437,017	-	27,343	20,083	0.734
Resurfacing (3R partial standards)	225,535	-	14,111	25,191	1.785
Resurfacing (3R partial standards)	187,364	-	11,722	28,640	2.443
First Pipe Replacement	1,023,311	243,329	64,026	15,225	0.238
Second Pipe Replacement	820,917	195,207	51,362	12,214	0.238
Third Pipe Replacement	634,739	81,769	39,714	5,116	0.129
Overall	3,328,883	520,305	208,279.5	106,467.6	0.511

Table 5-18 Cost-Effectiveness of a Candidate's M&R Activities – With Coordination

Treatment Type	PWC ($/lane)	PWB ($/lane)	EUAC ($/lane)	EUAB ($/lane)	Cost-Effectiveness (B/C)
New Full-Depth HMA Construction	437,017	-	27,353	20,083	0.734
Resurfacing (3R partial standards)	230,684	-	14,433	24,775	1.717
Resurfacing (3R partial standards)	191,906	-	12,007	28,216	2.352
First Pipe Replacement	1,023,325	243,329	64,026	15,225	0.238
Second Pipe Replacement	754,632	195,206	47,215	12,214	0.259
Third Pipe Replacement	634,747	817,68	39,714	5,116	0.129
Overall	3,328,883	520,305	204,730	105,628	0.516

Figures 5-16 and 5-17 present screenshots of the simulation model results for the estimated cost-effectiveness of the candidate scenario, considering no coordination and coordination.

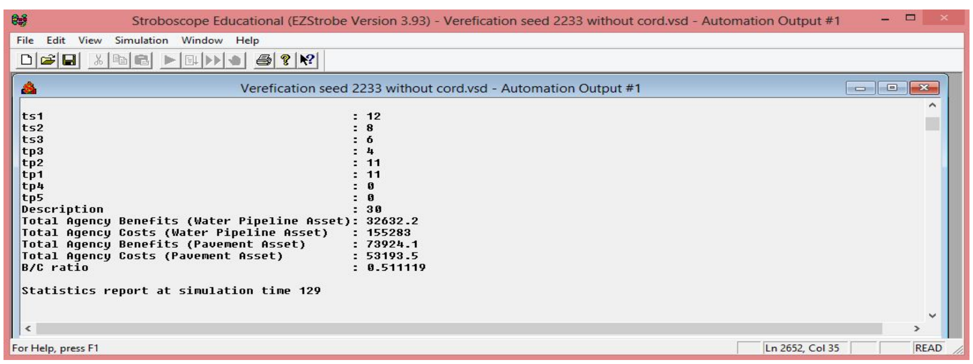


Figure 5-16 Screenshot of the Simulation Model Results – Cost-Effectiveness-With No Coordination

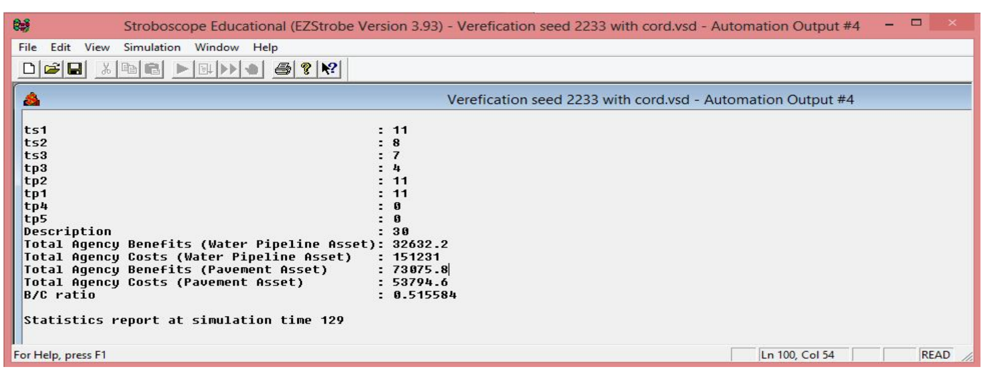


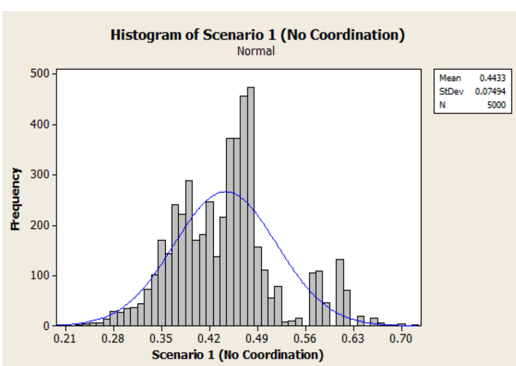
Figure 5-17 Screenshot of the Simulation Model Results – Cost-Effectiveness-With Coordination

5.11 Maintenance and Rehabilitation Scenarios - Results

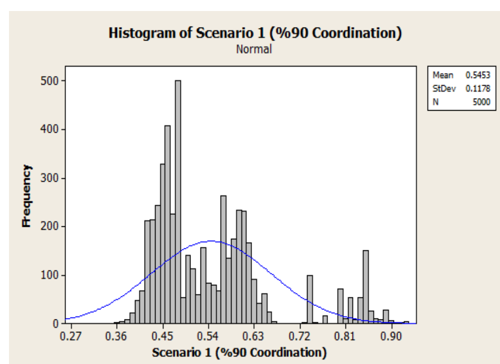
The results of each considered scenario are presented in the ensuing sections along with discussion regarding these results.

5.11.1 Scenario with Preventive Maintenance Only and Water Pipeline Replacement Only

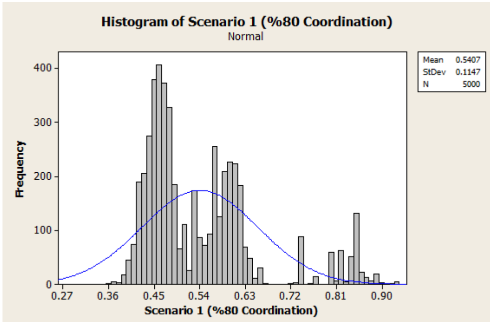
A scenario where a new-full depth HMA construction followed by the application of a thin HMA overlay twice is considered for the pavement assets while only considering replacement for the water pipelines. Figure 5-18 presents the probability distribution of the estimated benefit-cost ratio for this scenario considering coordination and no-coordination scenarios. For the coordination scenario, when the pavement treatment service life reaches a specific percentage (i.e. 70%, 80%, and 90%) of its service life, the coordination is investigated to decide whether or not to carry it out. The results indicate that the coordination, at 70%, 80%, and 90%, scenarios lead to the highest cost-effectiveness with little variations among them. The no-coordination scenario has a lower mean value (0.4433) compared to the coordination scenarios (0.545, 0.541, and 0.549 for 90%, 80%, and 70% respectively). The highest cost benefit ratio among the coordination scenarios is the 70% scenario.



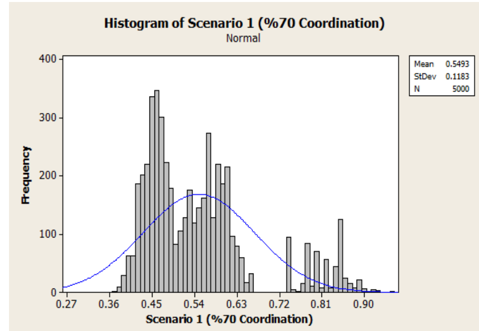
Probability Distribution Plot – Scenario 1 (No Coordination)



Probability Distribution Plot – Scenario 1 (%90 Coordination)



Probability Distribution Plot – Scenario 1 (%80 Coordination)

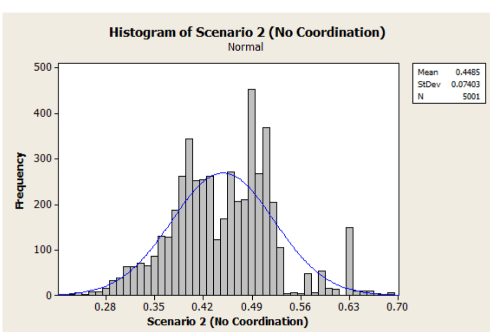


Probability Distribution Plot – Scenario 1 (%70 Coordination)

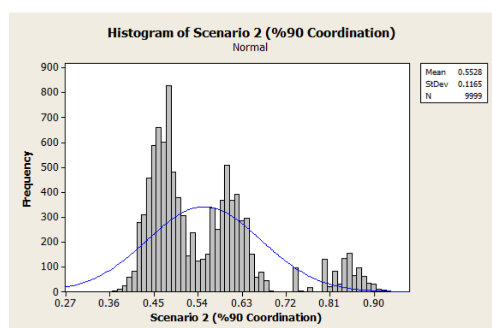
Figure 5-18 Probability Distribution Plots of Scenario 1

5.11.2 Scenario with Rehabilitation Only and Water Pipeline Replacement Only

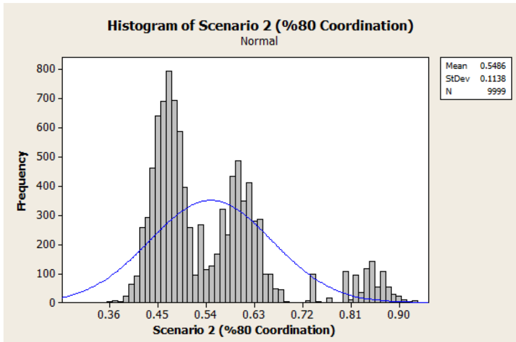
A new-full depth HMA construction followed by applying resurfacing (3R partial standards) twice is considered for pavement assets while only considering replacement for the water pipelines. Figure 5-19 shows a probability distribution of the estimated benefit-cost ratio for this scenario considering coordination and no-coordination scenarios. Similarly, the coordination scenario has the highest cost-effectiveness, with the 70% scenario being the desirable strategy (0.558). The no-coordination scenario has a lower mean value (0.449) compared to the coordination scenarios. The variations in the cost-effectiveness values between the coordination scenarios (i.e. 70%, 80%, and 90%) was small and thus considered to be not significant.



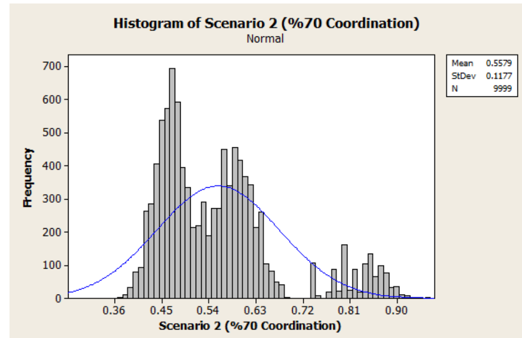
Probability Distribution Plot – Scenario 2 (No Coordination)



Probability Distribution Plot – Scenario 2 (%90 Coordination)



Probability Distribution Plot – Scenario 2 (%80 Coordination)

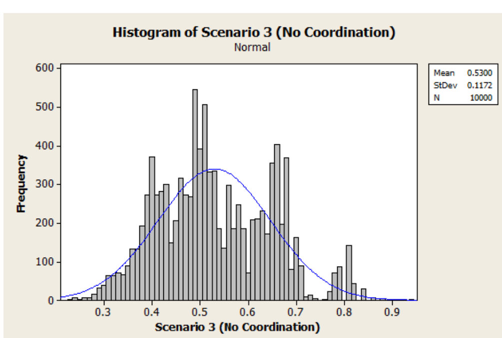


Probability Distribution Plot – Scenario 2 (%70 Coordination)

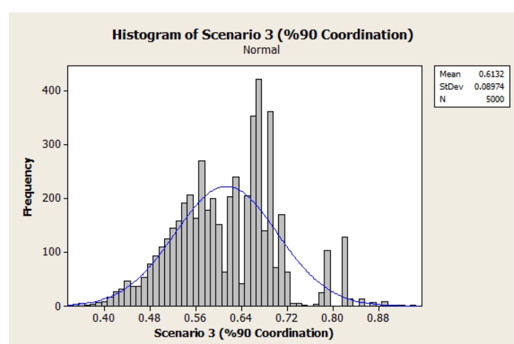
Figure 5-19 Probability Distribution Plots of Scenario 2

5.11.3 Scenario with Preventive Maintenance, Rehabilitation, and Water Pipeline Replacement Only

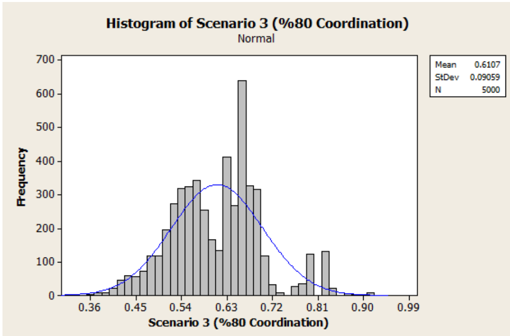
A new-full depth HMA construction followed by applying resurfacing (3R partial standards) and thin HMA overlay maintenance are considered for pavement assets while only considering replacement for water pipelines. The results (as shown in Figure 5-20) indicate that this scenario leads to the most cost-effective scenario compared to the other scenarios 1 and 2. Similarly, the coordination scenarios have the highest cost-benefits. The no-coordination scenario has the lower mean value (0.53) compared to the coordination scenarios (0.613, 0.611 and 0.61 for 90%, 80%, and 70% being the desirable one, respectively).



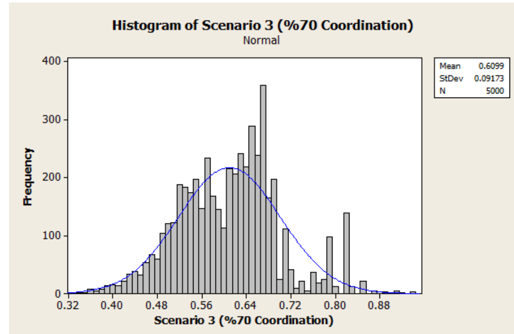
Probability Distribution Plot – Scenario 3 (No Coordination)



Probability Distribution Plot – Scenario 3 (%90 Coordination)



Probability Distribution Plot – Scenario 3 (%80 Coordination)



Probability Distribution Plot – Scenario 3 (%70 Coordination)

Figure 5-20 Probability Distribution Plots of Scenario 3

5.12 Sensitivity Analysis

A sensitivity analysis is a common and robust method of quantifying the uncertainties in the model. Sensitivity analysis is conducted to test how sensitive a model is to the variations in the input values of the model to variations in its outputs. Sensitivity analysis increases the robustness of the model by testing the uncertainty that often exists in the model parameters. The main purpose of the test in this thesis is to investigate the degree of variation in the benefit-cost ratio to changes in the input variables of the framework. The sensitivity of the benefit-cost ratio was investigated with respect to interest rate, percentage of reduction in pavement service life due to pipe failure impact, and agency cost vs. user cost. The sensitivity of these resulting output variables can be explored by keeping all input variables fixed while varying a variable of interest.

5.12.1 Design of Sensitivity Analysis Tests

The sensitivity of the resulting output can be investigated by all input variables being fixed while an input variable of interest (as shown in Table 5-19) are tested independently. The input variables of interest are the interest rates, the percentages reduction in pavement service life due to pipe failure impact, and the changes in agency cost vs. user cost. The output variables include water pipeline total cost, water pipeline total benefits, pavement infrastructure total cost, pavement infrastructure total benefits, and total benefit-cost ratio (these costs and benefits are in terms of their EAUC.

Table 5-19 Assigned Values of the Variables of Interest

Input Variables of Interest	Case 1	Case 2	Base	Case 3	Case 4
Interest Rate (%)	2%	3%	4%	5%	6%
Reduction in Pavement Service Life (%)	50%	40%	30%	20%	10%
Agency Cost ($)	-20%	-10%	0%	10%	20%
User Cost ($)	-20%	-10%	0%	10%	20%

5.12.2 Sensitivity Analysis Results

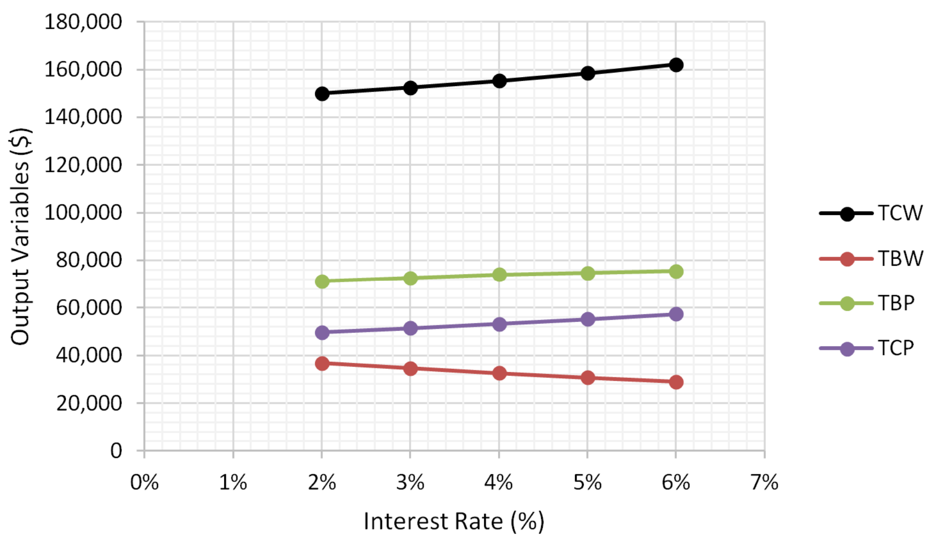
The sensitivity of each of the aforementioned outputs of the proposed framework is evaluated with respect to the changes in the input variables of interest. Table 5-20 to Table 5-23, presents the results of the sensitivity analysis and also depicted in Figure 5-21 to Figure 5-24.

Figure 5-21 (a & b) illustrate the sensitivity of the output variables to the changes in the interest rates. The total benefits associated with the water pipeline assets (TBW) decrease when the interest rates increasing due to the reduction in the benefits of the first pipe application, which is highly impacted by the value of the interest rates. The other outputs have a positive correlation with the interest rate values. The results also show that the total cost of the water pipeline is most sensitive to the changes in the interest rate values, which can be due to their higher values compared to other input values. The overall cost-benefit effectiveness has a negative correlation due to the impact of the total benefits of the water pipeline asset.

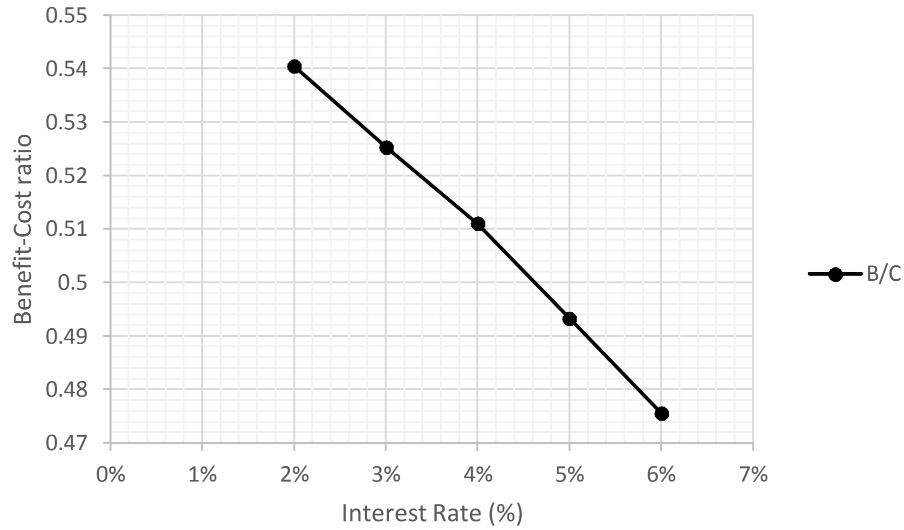
Figure 5-22 illustrates the sensitivity of the output variables to the changes in the percentage of pavement service life reduction. The output variables are less sensitive with small percentage reductions (i.e., 10% to 20%) in the pavement service life. The overall Benefit Cost difference (i.e. 10% - 50%) is small. However, it is clear that the reduction in pavement service life has a negative impact on the overall benefit cost ratio.

Table 5-20 Sensitivity of the Output Values to Changes in Interest Rate

	Case 1	Case 2	Base	Case 3	Case 4
Interest Rate (%)	2%	3%	4%	5%	6%
TCW ($)	149,963	152,434	155,282	158,516	162,132
TBW ($)	36,672	34,609	32,608	30,743	28,945
TBP ($)	71,188	72,445	73,924	74,663	75,402
TCP ($)	49,616	51,343	53,193	55,169	57,272
B/C (ratio)	0.5404	0.5253	0.5110	0.4932	0.4755



(a)

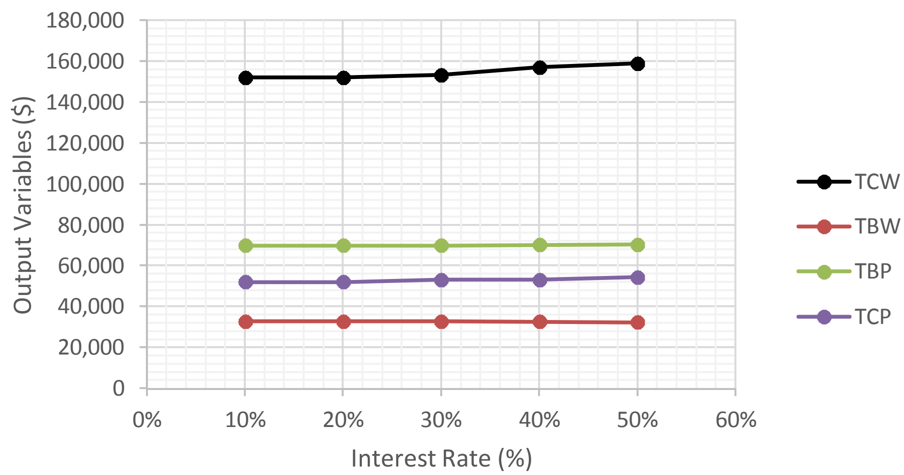


(b)

Figure 5-21 Sensitivity of Output Variables to Changes in the Interest Rates

Table 5-21 Sensitivity of the Output Values to Changes in the Reduction of Pavement Service Life

	Case 1	Case 2	Base	Case 3	Case 4
Reduction in pavement service life	50%	40%	30%	20%	10%
TCW ($)	158,868	156,983	153,282	151,985	151,985
TBW ($)	32,304	32,632	32,844	32,844	32,844
TBP ($)	70,341	70,258	69,924	69,877	69,864
TCP ($)	54,421	53,193	53,193	52,063	52,063
B/C (ratio)	0.481248	0.489542	0.497726	0.503416	0.503352



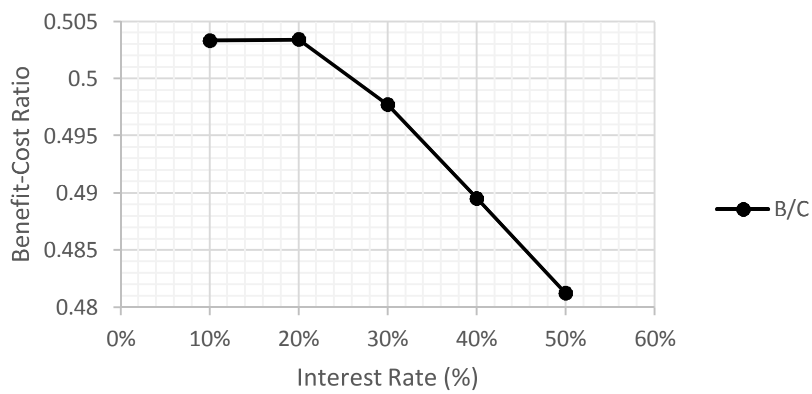
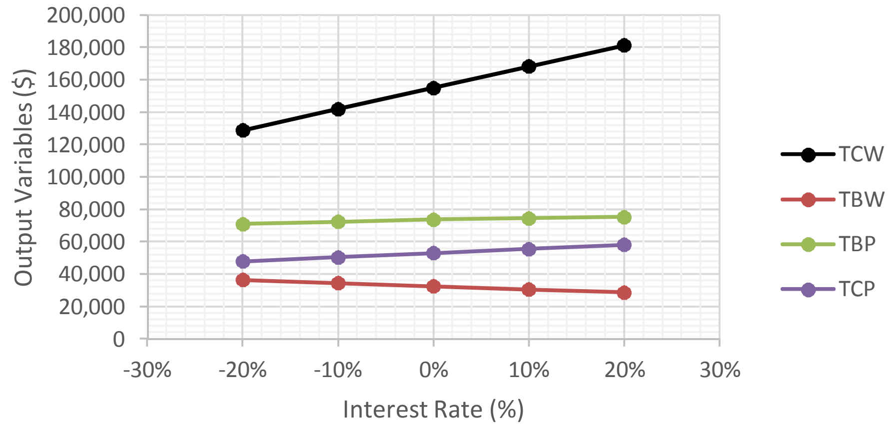


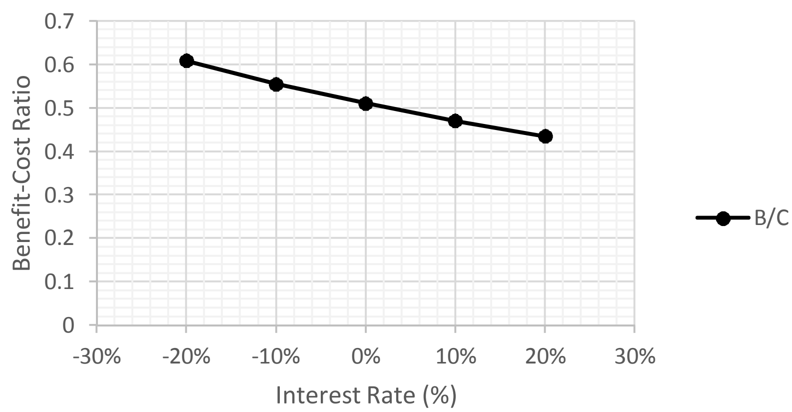
Figure 5-22 Sensitivity of Output Variables to Changes in the Reduction of Pavement Service Life

Table 5-22 Sensitivity of the Output Values to Changes in Agency Costs

	Case 1	Case 2	Base	Case 3	Case 4
Agency Costs	-20%	-10%	0%	10%	20%
TCW ($)	129,072	142,177	155,282	168,389	181,494
TBW ($)	36,672	34,609	32,608	30,743	28,945
TBP ($)	71,188	72,445	73,924	74,663	75,402
TCP ($)	48,012	50,602	53,193	55,784	58,375
B/C (ratio)	0.609089	0.55532	0.511006	0.470199	0.435017



(a)

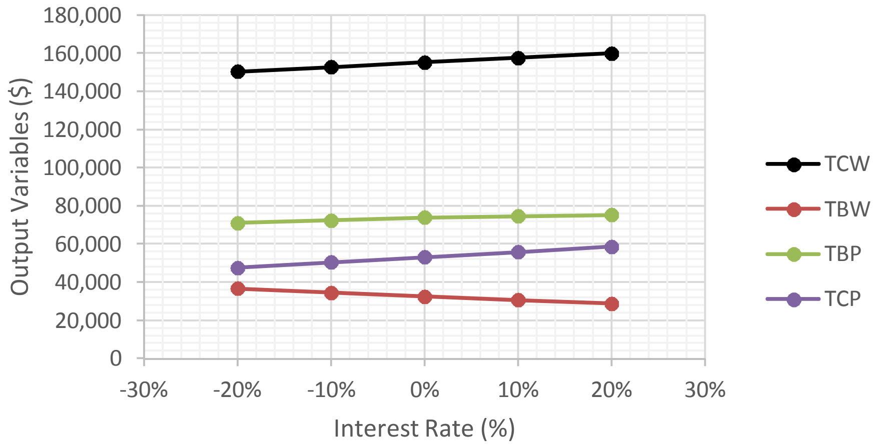


(b)

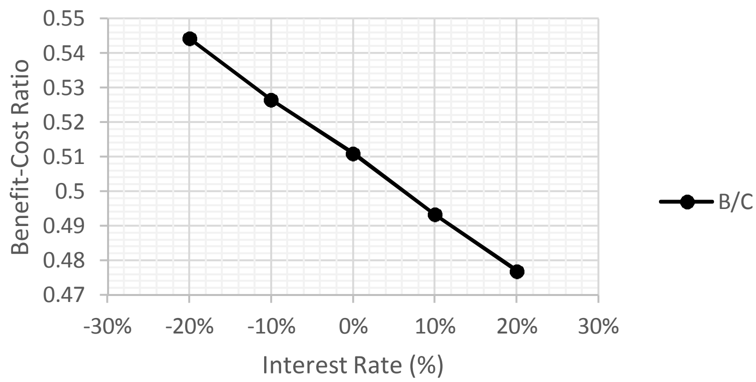
Figure 5-23 Sensitivity of Output Variables to Changes in Agency Costs

Table 5-23 Sensitivity of the Output Values to Changes in User Costs

	Case 1	Case 2	Base	Case 3	Case 4
User Costs	-20%	-10%	0%	10%	20%
TCW ($)	150,437	152,860	155,282	157,706	160,128
TBW ($)	36,672	34,609	32,608	30,743	28,945
TBP ($)	71,188	72,445	73,924	74,663	75,402
TCP ($)	47,736	50,464	53,193	55,922	58,650
B/C (ratio)	0.544272	0.526519	0.511006	0.493409	0.476954



(a)



(b)

Figure 5-24 Sensitivity of Output Variables to Changes in User Costs

Figure 5-23 and Figure 5-24 illustrate the sensitivity of the output variables to the changes in the agency cost and user cost, respectively. While the changes in the user cost have large impacts on the overall benefit-cost ratio, the changes in the agency cost have less impact on the overall benefit-cost ratio (as shown in Table 5-24). This difference is due to the fact that the total user cost values are greater than the total agency cost values and therefore the user costs have a greater impact on the benefit-cost ratio than the agency cost. In both cases, the overall benefits associated with water pipeline asset are less sensitive to the changes in the agency and user costs because only the benefits associated with the agency are considered. These results and analyses are presented for the purpose of testing the validity of the model and therefore increase the robustness of the developed model.

Table 5-24 Benefit Cost Ratio Comparison between Agency and User Costs

	Case 1	Case 2	Base	Case 3	Case 4
	-20%	-10%	0%	10%	20%
Agency Costs (B/C ratio)	0.609089	0.55532	0.511006	0.470199	0.435017
User Costs (B/C ratio)	0.544272	0.526519	0.511006	0.493409	0.476954

5.13 <u>Chapter Summary</u>

In this chapter, three candidate scenarios (i.e., preventive treatments only, rehabilitation treatments only, and a combination of the two) were analyzed to demonstrate how the thesis framework can determine the cost-effectiveness of these scenarios. The results of the simulation were presented and then verified using detailed hand calculations. The above three scenarios were investigated and the associated results were presented and discussed for pavement treatments while only one scenario (replacement only) for water pipeline M&R was considered. The results of these scenarios show that coordinating pavement and water pipeline M&R activities have a considerably positive impact on the overall cost-benefit ratio. These results illustrate that the developed framework creates a methodology.

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Research Summary

This thesis developed a framework for coordinating the M&R activities of pavement infrastructure and water distribution systems based on LCCA. The impact of water pipeline failure on pavement service life was considered, which is an impact that has not been fully addressed in past studies. The developed framework addresses three main aspects of asset management for water distribution systems and the pavement Infrastructure: (1) how to assess the impact of water pipeline M&R activities on pavement infrastructure using LCCA; (2) how to coordinate water pipeline and pavement M&R practices; and (3) how to assess the effects of coordinating these two systems on the LCCA. For each candidate scenario, which was composed of alternative treatments, the agency and user costs were estimated and, furthermore, the effectiveness corresponding to those treatments were considered in monetized and non-monetized terms. A demonstration of the framework was then carried out using three scenarios for pavement treatments (maintenance only, rehabilitation only, and a combination of both) while considering only one scenario (replacement) for water pipeline assets. These scenarios were evaluated using EZStrobe discrete event simulation software.

On the basis of the conducted literature review regarding pavement management systems and water pipeline asset management, several techniques used in past studies were employed directly and indirectly to formulate a comprehensive framework for coordinating these two different types of assets managed by different entities. The costs of the treatments constitute the agency costs (construction and maintenance costs) and the user costs included travel time delay costs and vehicle operation costs incurred due to and during work zone activities. The effectiveness of applying a candidate treatment was measured using monetized and non-monetized approaches. The pavement treatment service life and water pipeline useful life represent the treatment effectiveness in non-monetized terms while the savings in annual maintenance costs and vehicle operation costs due to the applied treatment are considered an effectiveness measure in monetized terms for pavement assets. The asset valuation method was demonstrated to measure the monetized effectiveness of water pipeline replacement.

The impact of water pipeline failure on pavement treatment service life was explicitly considered in this research for the coordination and the no-coordination scenarios. For each scenario a comparative analysis was also carried out between the coordination and no-coordination strategies of the M&R of both assets. The coordination scenario was investigated further on the basis of when to carry out the coordination. The comparison between these scenarios was conducted based on a cost-effectiveness analysis. First, the costs and benefits were projected using an escalation factor based on the consumer price index (CPI). Second, these costs and benefits were discounted using an interest rate of 4% and then the equivalent uniform annual cost was estimated.

A demonstration of the framework was implemented using a discrete event simulation model in EZStrobe simulation software. A Monte-Carlo simulation technique was used to carry out the sensitivity analysis. The results of the considered scenarios indicate that the coordination scenarios had desirable outcomes in all cases (i.e., 90%, 80% and 70%) compared to the no-coordination scenarios. This is intuitive since the coordination leads to a reduction in the user costs, which can have a great impact on the overall results (as explained in Section 5.12).

6.2 Research Conclusions

This research established a theoretical framework for coordinating the M&R strategies of water pipeline and pavement assets based on LCCA. The framework considers explicitly the impact of water pipeline failures on the pavement condition assuming these two assets are co-located. The costs to the agency and user associated with each candidate M&R profile, which are composed of several treatment alternatives, are evaluated. The effectiveness of these treatments are also measured in both monetized and non-monetized terms. A cost-effectiveness analysis was carried out allowing for unbiased comparisons among the different scenarios. The feasibility of the application of the framework was demonstrated using a discrete event simulation technique. EZStrobe simulation software was employed to implement the theoretical framework and demonstrate its applicability. After conducting a Monte-Carlo simulation, the obtained outcomes were in favor of the coordination concept.

6.3 Contributions of the Research

A typical urban right-of-way usually includes more than one infrastructure system, which are typically owned and operated by different entities. Given the fact that these infrastructure assets are treated based on many available treatment alternatives that have different service lives, deterioration tendencies, and application times, these assets are preserved based on in-vacu decisions by a responsible party. In this thesis, a theoretical framework was developed to demonstrate the visibility of temporal coordination of the maintenance and rehabilitation of two unique co-located infrastructure assets (pavement and water pipeline assets) which have distinctive service lives and deterioration mechanisms and, most importantly, are owned and managed by two different entities. The impact of utility cuts and patching (for repairing a broken water pipeline under a paved road) on the pavement's service life, an impact that has not been fully addressed in past studies, was explicitly considered and assessed through the life cycle of both assets. The costs to the agency (construction and maintenance) and the users (costs of travel time delay and vehicle operation) were estimated for each candidate scenario, and their associated effectiveness was measured in monetized and non-monetized terms. A new effectiveness measure for water pipeline replacement was proposed based on pipe useful life and asset valuation concepts to obtain the non-monetized and monetized benefits, respectively. The thesis framework is composed of several concepts, techniques, and tools combined to create this decision-making tool. It was developed using EZStrobe discrete event simulation system. The framework also incorporated Monte Carlo simulations to help asset managers quickly assess their decisions regarding the coordination of pavement and water pipeline M&R alternatives and thereby identify the most cost-effective scenarios. The framework can be used for other infrastructure assets including, but not limited to, sewer pipeline infrastructure. In conclusion, this thesis provides a logical, intuitive, and innovative methodology through which highway agencies and water utilities can evaluate different M&R scenarios and enhance the robustness of their decision-making processes.

6.4 Limitations of the Research

This research intended to employ accepted concepts, established techniques, and available tools to formulate a comprehensive framework for coordinating pavement infrastructure and water distribution system M&R activities based on life cycle cost analysis. However, a few limitations exist in this research and they include:

- The cumulative annual average daily traffic was assumed to be constant across the life cycle of the assets.
- The interdependence between water pipeline and pavement assets, which is represented by the impact of the pavement treatment application on the water pipeline service life, was not considered.

- Only traffic user costs incurred due to water pipeline M&R interventions were considered. This could be considered a limitation since other social costs, such as disruption to adjacent businesses, might occur.
- The thesis assumed that no budget constraints exist. However, due to the poor conditions of most infrastructure assets, a limitation on the budget might be applicable.

6.5 Recommendations for Future Work

Based on the conducted literature review, almost no studies have focused on coordinating the M&R of dissimilar infrastructure assets, which creates substantial opportunities for improving the robustness of the decision-making process in this area. The extent of the short-term impacts of utility cuts and patching on pavement condition performance and service life have yet to be recognized. Moreover, the long-term impacts of these activities have not been investigated for different types of treatments throughout the life cycle. Similarly, the short and long-term impacts of pavement treatment applications on water pipeline conditions and useful life have not been studied. Optimization techniques could be adopted to evaluate many more candidate scenarios and then select the optimal one. The framework employed specific mathematical models for asset performance and costs, which can be replaced by other appropriate models. This research introduced the necessity of considering the managerial aspects, which is indispensable for the successful implementation of this framework.

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APPENDICES

Appendix A

Estimated Performance Jump and Post Performance Treatment Models' Parameters

Table A.1 Post-performance Models - Non-NHS (Irfan, 2010)

Treatment Type	Model parameters
Thin HMA overlay	$PI = e^{[4.164+0.016*AATA.t+0.105*.ANDX.t]}$
Micro-surfacing	$PI = e^{[4.117+0.016*AATA.t+0.151*.ANDX.t]}$
HMA overly functional	$PI = e^{[4.097+0.093*AATA.t+0.113*.ANDX.t]}$
HMA overlay structural	$PI = e^{[4.148+0.020*AATA.t+0.059*.ANDX.t]}$
Resurfacing (Partial 3R standards)	$PI = e^{[4.183+0.015*AATA.t+0.101*.ANDX.t]}$

Table A.2 Performance Jump Models - Non-NHS (Irfan, 2010)

Treatment Type	Model parameters
Thin HMA overlay	PJ= 67.577ln(PItrig) – 262.178
Micro-surfacing	PJ= 72.386ln(PItrig) – 284.555
HMA overly functional	PJ= 63.988ln(PItrig) – 231.579
HMA overlay structural	PJ= 109.659ln(PItrig) – 451.358
Resurfacing (Partial 3R standards)	PJ= 104.216ln(PItrig) – 424.006

Appendix B

Estimated Models' Parameter for the Exponential and Weibull Functions

Table B.1 Equations for the Different Functions of the Exponential and Weibull Distributions and Estimated Parameters (Mailhot, 2000).

Destitution	Probability Density Function	Survival Function	Hazard Function
Exponential	K exp (- Kt)	exp (- Kt)	K
Weibull	K1p $(Kt)^{p-1}$ exp[-$(kt)^{p}$]	exp[-$(kt)^{p}$]	Kp $(Kt)^{p-1}$

Table B.2 Results of the Weibull-Exponential (W-E) Model for Different Pipe Segment Installation Period (Mailhot, 2000).

Installation period	P	K1	K2
1976-1996	1.157	0.017	0.168
1970-1996	1.262	0.013	0.148
1965-1996	1.394	0.024	0.182
1960-1996	1.474	0.025	0.205
1949-1996	1.241	0.018	0.161
1991-1996	1.053	0.015	0.147

Table B.3 Results of the Weibull-Weibull-Exponential (W-W-E) Model for Different Pipe Segment Installation Period (Mailhot, 2000).

Installation period	P	P2	K1	K2	K3
1976-1996	1.55	0.924	0.017	0.07	0.347
1970-1996	1.20	0.999	0.018	0.077	0.2355
1965-1996	1.38	1.013	0.024	0.080	0.301
1960-1996	1.469	1.43	0.025	0.74	0.352
1949-1996	1.318	0.921	0.20	0.46	0.283
1991-1996	1.23	0.774	0.19	0.03	0.260

Table B.4 Results of the Weibull- Exponential-Exponential (W-E-E) Model for Different Pipe Segment Installation Period (Mailhot, 2000).

Installation period	P	K1	K2	K3
1976-1996	1.155	0.017	0.076	0.331
1970-1996	1.193	0.018	0.078	0.246
1965-1996	1.364	0.024	0.078	0.291
1960-1996	1.461	0.025	0.75	0.342
1949-1996	1.244	0.20	0.48	0.284
1991-1996	1.154	0.018	0.038	0.261

Table B.5 Results of the Weibull-Weibull-Exponential- Exponential (W-W-E-E) Model for Different Pipe Segment Installation Period (Mailhot, 2000).

Installation period	P	P2	K1	K2	K3	K4
1976-1996	1.157	0.922	0.017	0.07	0.166	0.521
1970-1996	1.184	0.991	0.81	0.079	0.130	0.374
1965-1996	1.342	0.993	0.023	0.084	0.140	0.407
1960-1996	1.404	1.008	0.025	0.081	0.119	0.494
1949-1996	1.243	0.955	0.020	0.061	0.071	0.438
1991-1996	1.123	0.917	0.018	0.055	0.049	0.420

Appendix C

Estimated Costs Models' Parameters for Pavement Treatments

Table C.1 Cost Models – Function Form (1) [Cobb – Douglas I] (Irfan, 2010)

Treatment Type	Model parameters
Thin HMA overlay	$T_{AC} = 0.106 * (L)^{0.814} * (N)^{1.334} *[\ln (PI_{trrig})]^{4.261}$
Micro-surfacing	Not Applicable
HMA overly functional	$T_{AC} = 24.446 * (L)^{0.662} * (N)^{0.243} *[\ln (PI_{trrig})]^{1.736}$
HMA overlay structural	$T_{AC} = 0.026 * (L)^{0.624} * (N)^{0.818} *[\ln (PI_{trrig})]^{5.946}$
Resurfacing (Partial 3R standards)	$T_{AC} = 0.098 * (L)^{0.690} * (N)^{0.458} *[\ln (PI_{trrig})]^{4.867}$

Table C.2 Cost Models – Function Form (2) (Irfan, 2010)

Treatment Type	Model parameters
Thin HMA overlay	$T_{AC} = -2.182 + (0.119*L) + (0.415*N) + (0.333*[\ln (PI_{trrig})])$
Micro-surfacing	Not Applicable
HMA overly functional	$T_{AC} = -1.936 + (0.176*L) + (0.468*N) + 0$
HMA overlay structural	$T_{AC} = -11.697 + (0.251*L) + (1.159*N) + (1.856*[\ln (PI_{trrig})])$
Resurfacing (Partial 3R standards)	$T_{AC} = -2.600 + (0.106*L) + (0.187*N) + (0.517*[\ln (PI_{trrig})])$

Table C.3 Cost Models – Function Form (3) [Cobb – Douglas II] (Irfan, 2010)

Treatment Type	Model parameters
Thin HMA overlay	$T_{AC} = 0.112 * (L)^{0.650} * (N)^{1.281}$
Micro-surfacing	$T_{AC} = 0.004 * (L)^{1.072} * (N)^{0.447}$
HMA overly functional	$T_{AC} = 0.180 * (L)^{0.704} * (N)^{1.12}$
HMA overlay structural	$T_{AC} = 0.244 * (L)^{0.628} * (N)^{1.101}$
Resurfacing (Partial 3R standards)	$T_{AC} = 0.619 * (L)^{0.412} * (N)^{0.206}$

Table C.4 Cost Models – Function Form (4) (Irfan, 2010)

Treatment Type	Model parameters
Thin HMA overlay	T_{AC} = -0.381 + (0.112*L) + (0.256*N)
Micro-surfacing	T_{AC} = -0.049 + (0.075*L) + (0.022*N)
HMA overly functional	T_{AC} = -0.469 + (0.223*L) + (0.304*N)
HMA overlay structural	T_{AC} = -1.019 + (0.159*L) + (0.806*N)
Resurfacing (Partial 3R standards)	T_{AC} = -0.620+ (0.111*L) + (0.062*N)

Appendix D

Estimated Costs Models' Paremeters for Water Pipeline

Table D.1 Parameter for Base Installed Cost Equations (Clark et al, 2002)

Type of pipe	Pipe diameter (in)	Parameter Values							
		a	b	c	d	e	f	R^2	n
Ductile iron pipe	(4-36)[a,b]	-44.0	0.33	1.72	2.87	0.74	0.0	0.99	24
	(4-24)[c,b]	-36.0	0.62	1.54	2.04	0.78	0.0	0.99	20
Asbestos-cement pipe	(4-24)[d]	2.6	0.0052	2.86	-0.0001	1.56	0.0048	0.99	19
PVC Pressure pipe	(4-12)[d]	-1.0	0.0008	3.59	0.011	1.00	0.0067	0.99	10
Cement mortar lined and coated steel pipe	(12-42)	14.2	0.19	1.66	0.0	0.0	0.0	0.99	9
Concrete cylinder pipe	(12-54)	11.7	0.51	1.38	0.0	0.0	0.0	0.99	10
Prestressed concrete cylinder pipe	(60-44)	7.9	1.30	1.25	0.0	0.0	0.0	0.99	7

a With push on joint
b Indicatore Variable: 50, 52
c Mechanical joints.
d Indicatore Variable: 150, 200

Table D.2 Parameter for Trenching and Excavation Cost Equations (Clark et al, 2002)

Soil conditions	Pipe diameter (in)	Parameter Values						
		a	b	c	d	E	R	n
Sandy gravel soil with 1:1 side slope	(4-8)	-24.0	0.32	0.67	16.7	0.38	0.99	15
	(8-144)	2.9	0.0018	1.90	0.13	1.77	0.98	90
Sandy gravel soil with vertical walls	(4-8)	-13.1	6.42	0.11	3.31	0.84	0.96	15
	(8-144)	1.5	0.0053	1.72	0.52	1.26	0.96	90
Sandy clay soil with vertical walls	(4-8)	-0.13	0.08	1.431	0.50	1.02	0.99	15
	(8-144)	2.7	0.06	1.17	0.20	1.62	0.94	90
Sandy gravel soil with 3/4:1 side slope	(4-8)	-.41	0.13	1.27	0.63	0.98	0.99	15
	(8-144)	-2.0	0.07	1.18	4.2	0.21	0.85	90

Table D.3 Parameter for Embedment, Backfill, and Compaction Cost Equations (Clark et al, 2002)

Installation conditions	Parameter values							
	a	b	c	d	e	f	R^2	n
Concrete arch[a]	7.1	0.26	1.46	0.0	0.0	0.0	0.99	21
First clas and ordinary[b,d]	1.6	0.0062	1.83	-0.20	1.00	0.07	0.99	42
Sandy native soil with 1:1 side slope[b,d]	-0.094	-0.062	0.73	0.18	2.03	0.02	0.99	105
Sandy native soil with 3/4:1 side slope[b,d]	1.4	-.84	0.42	0.32	1.99	0.0037	0.99	105
Imported soil for vertical trenches[b,d]	-0.65	-0.21	0.73	1.06	1.00	0.064	0.99	105

a Embedment
b Backfill and compaction
c Indicatore varibles = 0 for ordinary and 1 for first class.
d Indicatore Variable = 4,6,8,10 and 12

Table D.4 Parameter for Dewatering, Sheeting and Shoring and Pavement Repair and Replacement Cost Equations (Clark et al, 2002)

Frequency of installation	Installation conditions	Pipe diameter (in)	Parameter values				
			a	b	c	R^2	n
Dewatering	Moderate[b]	(4-96)	1.6	0.032	1.2	0.99	18
	Severe[b]	(60-144)	32.1	0.049	1.3	0.94	7
Sheeting and Shoring	Minimal[b]	(4-60)	8.9	0.0	0.0	0.94	-
	Moderate[b]	(4-20)	41.0	0.0	0.0	0.99	-
	Moderate[b]	(20-54)	59.0	0.0	0.0	0.99	-
	Severe[b]	(4-30)	344.0	0.0	0.0	0.98	-
	Severe[b]	(36-84)	473.0	0.0	0.0	0.99	-
	Severe[b]	(96-144)	684.0	0.0	0.0	0.99	-
Pavement removal and replacement[c,d]	-	(4-144)	-3.0	0.23	0.93	0.99	21

a parameter value for d, e, and f are zero
b indicator value are zero
c Indicator variables are 1 for asphaltic concrete payment and 2 for concrete pavement.
d Value for d= 10.7, e= 1.0 and f= 0.080

Appendix E

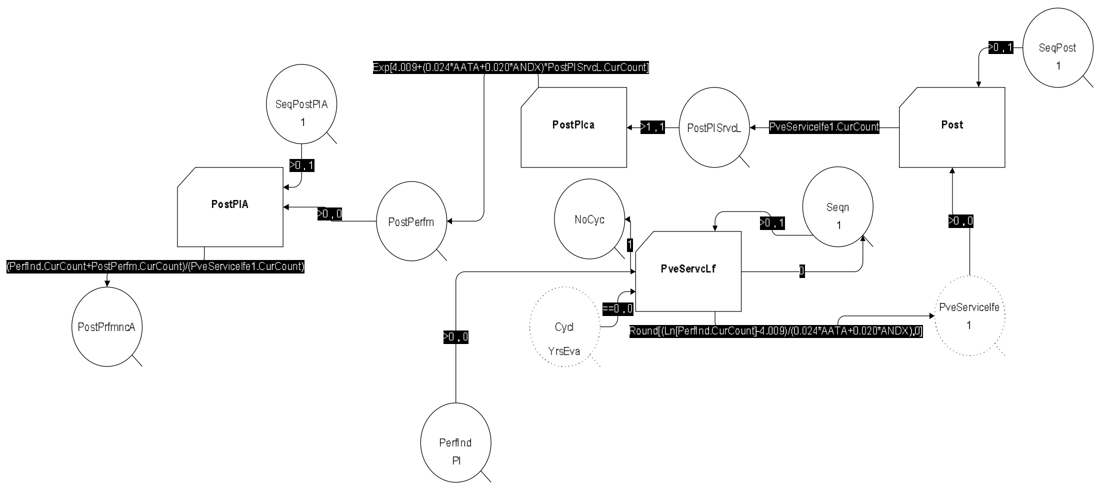
Screenshots of Decision Making Model for Corrdinating Water Pipeline and Pavement M&R Alternatives Utilizing EZStrobe Simulation

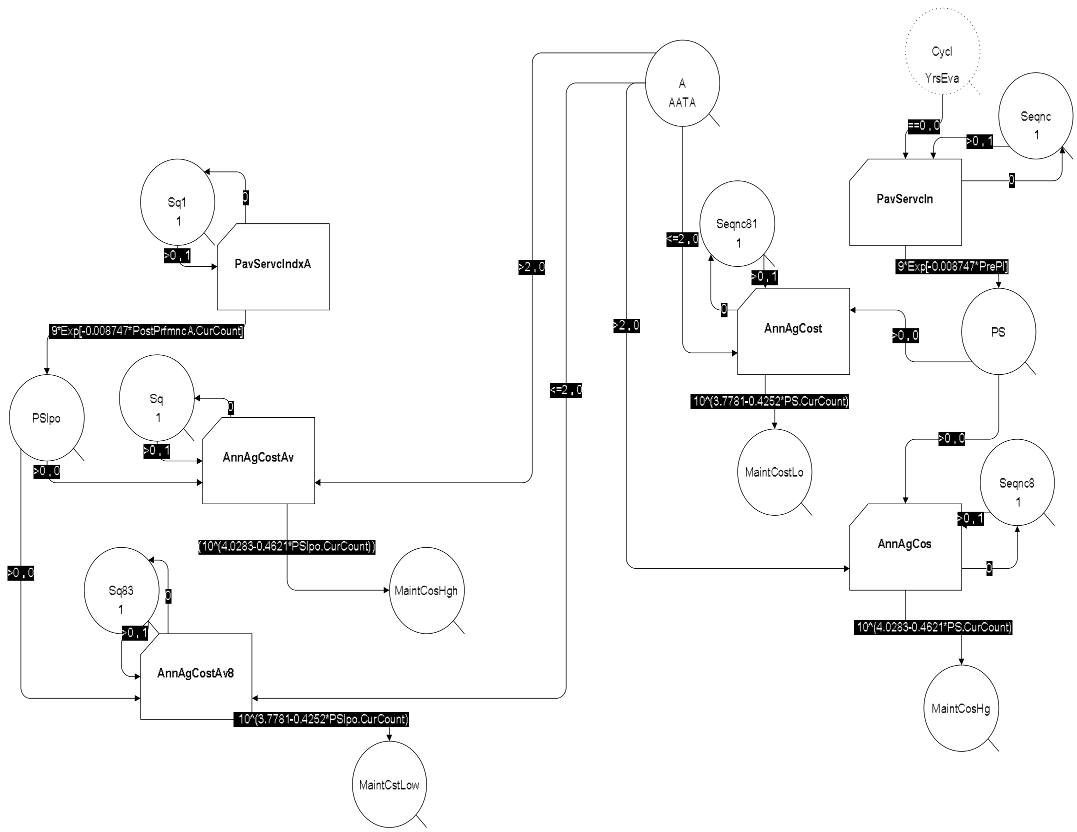
PipeDimtr	Pipe Diameter (in)	12
Depth	Depth of cover of pipe (ft)	10
DuctIron	Insert 1 for Ductile Iron pipe, 0 otherwise	1
AsbtsCmnt	Insert 1 for Asbestos cement pipe, 0 otherwise	0
PVC	Insert 1 for PVC pressure pipe, 0 otherwise	0
CmntMortLnd	Insert 1 for Cement mortar lind and coated steel pipe, 0 otherwise	0
CocrtCyndr	Insert 1 for Concrete Cylinder pipe, 0 otherwise	0
PrsConcCy	Insert 1 for Prestressed concete cylinder pipe, 0 otherwise	0
SndGrvl	Insert 1 for Sandy gravel soil with 1:1 side slope,0 otherwise	1
SndGrvlVer	Insert 1 for Sandy gravel soil with vertical walls,0 otherwise	0
SndCly	Insert 1 for Sandy clay soil with 3/4:1 side slope,0 otherwise	0
SndClyVer	Insert 1 for Sandy clay soil with vertical walls,0 otherwise	0
ConcArch	Insert 1 if the embedment is concrete arch,0 otherwise	1
FirsclsOrdnry	Insert 1 if the embedment is first class and ordinary,0 otherwise	0
SandNatv	Insert 1 if the backfill is Sandy native soil with 1:1 side slope,0 otherwise	1
SandNatvS	Insert 1 if the backfill is Sandy native soil with 3/4:1 side slope,0 otherwise	0
PipConstTim	Pipe Repair Time (Day)	70

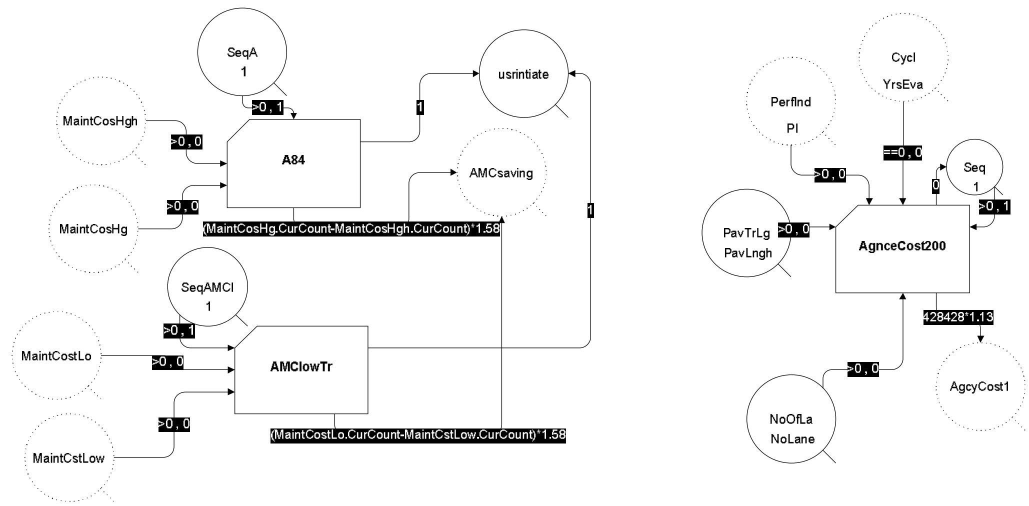
PergIndx	Pavement Physical Performance Threshold (IRI)	117
AATA	Accumulated Annual Truck Traffic Loading	2.5
ANDX	Frezing Index (Thousnds)	0.490
PavLngh	Pavement Length To Be Treated (Mail)	1
NoLane	Number of Lanes To Be treated	1
FreeSpeed	Speed Limit before Intervintion	50
SpeedWorkZone	Speed Limit after Intervintion	30
ClosLane	Number of closed lane due to intervintion	1
LnghOfClosLane	Length of closed lane due to intervintion (mile)	0
IntrstRate	Description	0.04

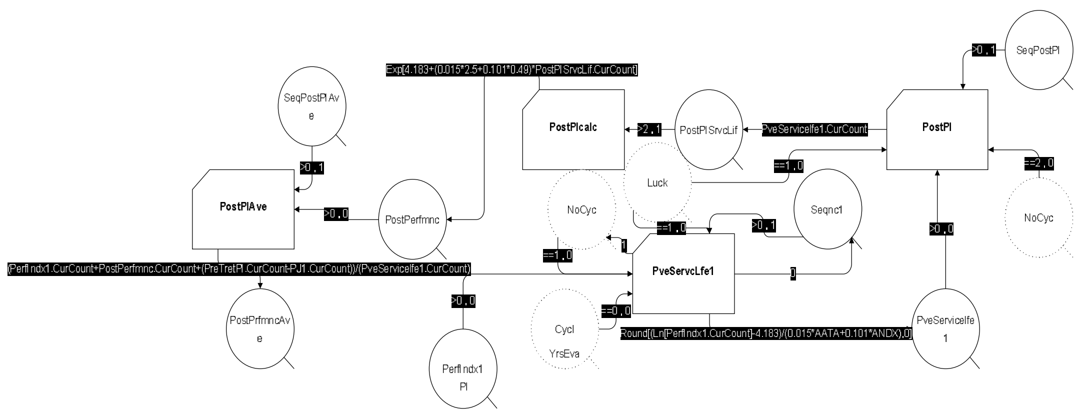
SandImprt	Insert 1 if the backfill is Imported soil for vertical trenches,0 otherwise	0
LowFreqnc	Insert 1 for low frequency of instalation of Valve, Fitting and Hydrant,0 otherwise	0
MedmFreqnc	Insert 1 for medium frequency of instalation of Valve, Fitting and Hydrant,0 otherwise	1
HighFreqnc	Insert 1 for High frequency of instalation of Valve, Fitting and Hydrant,0 otherwise	0
DewtrMod	Insert 1 for moderate dewatering,0 otherwis	1
DewtrSev	Insert 1 for Severe dewatering,0 otherwis	0
ShetShongMi	Insert 1 for Minimal groundwater,0 otherwis	0
ShetShongMo	Insert 1 for Moderate groundwater,0 otherwis	1
ShetShongSv	Insert 1 for Severe groundwater,0 otherwis	0
PavReplcA	Insert 1 when asphaltic concrete pavement are removed and replaced,0 otherwis	1
PavReplcC	Insert 2 when asphaltic concrete pavement are removed and replaced,0 otherwis	0
TraffcMod	Insert 1 for moderate Traffic Condition,0 otherwis	1
TraffcHevy	Insert 1 for Heavy Traffic Condition,0 otherwis	0
JointTyp1	Insert 1 for Ductile Iron with push on joints, 0 otherwise	0
JointTyp2	Insert 1 for Ductile Iron with Mechanical joints, 0 otherwise	1
Class	Thikness Class of Ductile Iron Pipe (50 or 52)	52
Press	Pressure Class of Asbestose Cement and PVC Pipe (150 or 200)	0

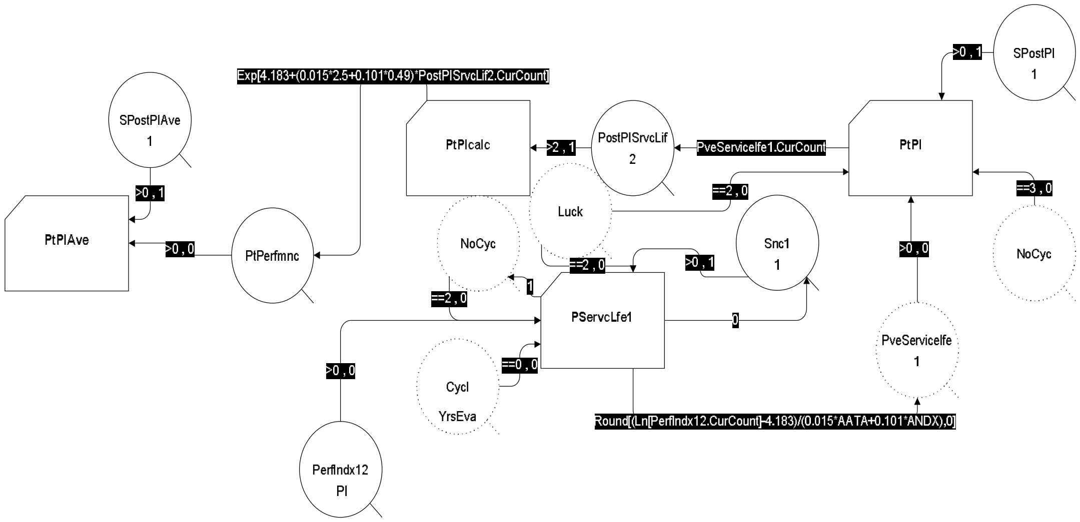
ProjTyp	Zero if the project duration is Fixed Date, 1 if the project duration is available days for the project to be ended	1
CPIcurrent	Consumer Price Index for current Year (2013)	230
AADT	Annual Average Daily Traffic (Thousnds)	22.831
NoOfDircton	Number of road's direction	2
NoOfLane	Number of lane for each direction	2
TrkTrafficShare	Truck traffic Share on the road	0.3
PassCarTrfcShre	Passenger car traffic Share on the road	0.7
CarFulPrc	Fuel Price for Passenger Car ($/gal)	2.2
TrkFulPrc	Fuel Price for Truck ($/ga)	4.5
VehcDelySpeed	Number of Vehicles delayed by the speed changes	AADT*1

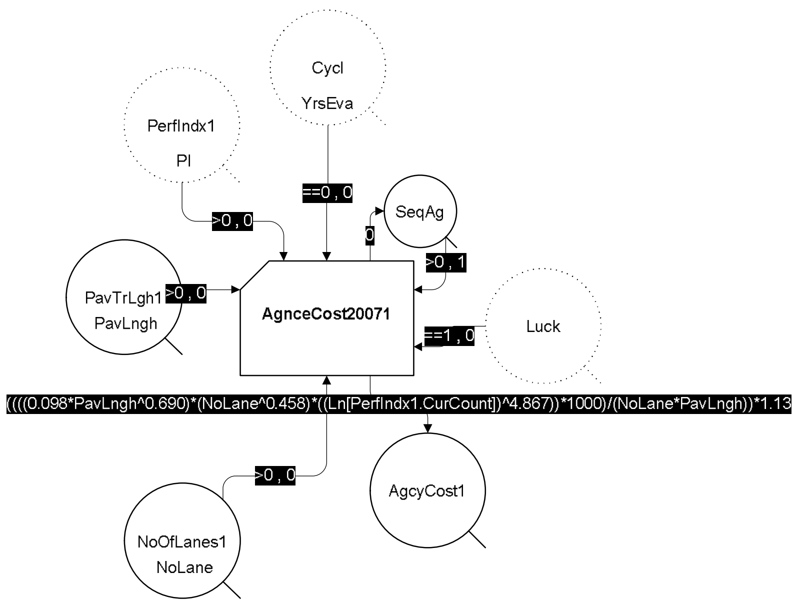

SeqPost
1
Exp[4.009+(0.024*AATA+0.020*ANDX)*PostPISrvcL.CurCount]
SeqPostPIA
1
PostPIca
PostPISrvcL
PveServicelfe1.CurCount
Post
PostPIA
PostPerfm
NoCyc
Seqn
1
PveServcLf
(PerfInd.CurCount+PostPerfm.CurCount)/(PveServicelfe1.CurCount)
PostPrfmncA
Cycl
YrsEva
PveServicelfe
1
Round[(Ln[PerfInd.CurCount]-4.009)/(0.024*AATA+0.020*ANDX),0]
PerfInd
PI

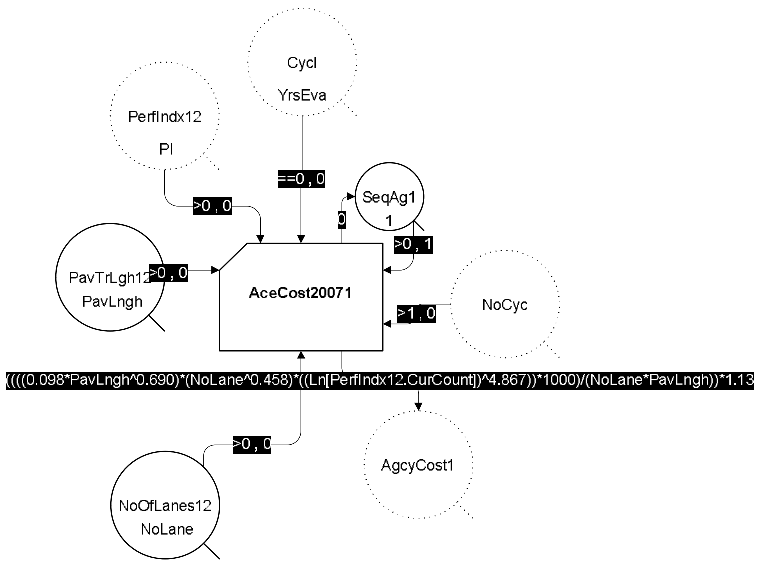

A
AATA
Cycl
YrsEva
Seqnc
1
Sq1
1
PavServcIndxA
PavServcIn
Seqnc81
1
9*Exp[-0.008747*PrePI]
9*Exp[-0.008747*PostPrfmncA.CurCount]
AnnAgCost
PS
PSIpo
Sq
1
AnnAgCostAv
10^(3.7781-0.4252*PS.CurCount)
MaintCostLo
Seqnc8
1
(10^(4.0283-0.4621*PSIpo.CurCount))
MaintCosHgh
AnnAgCos
Sq83
1
10^(4.0283-0.4621*PS.CurCount)
AnnAgCostAv8
MaintCosHg
10^(3.7781-0.4252*PSIpo.CurCount)
MaintCstLow

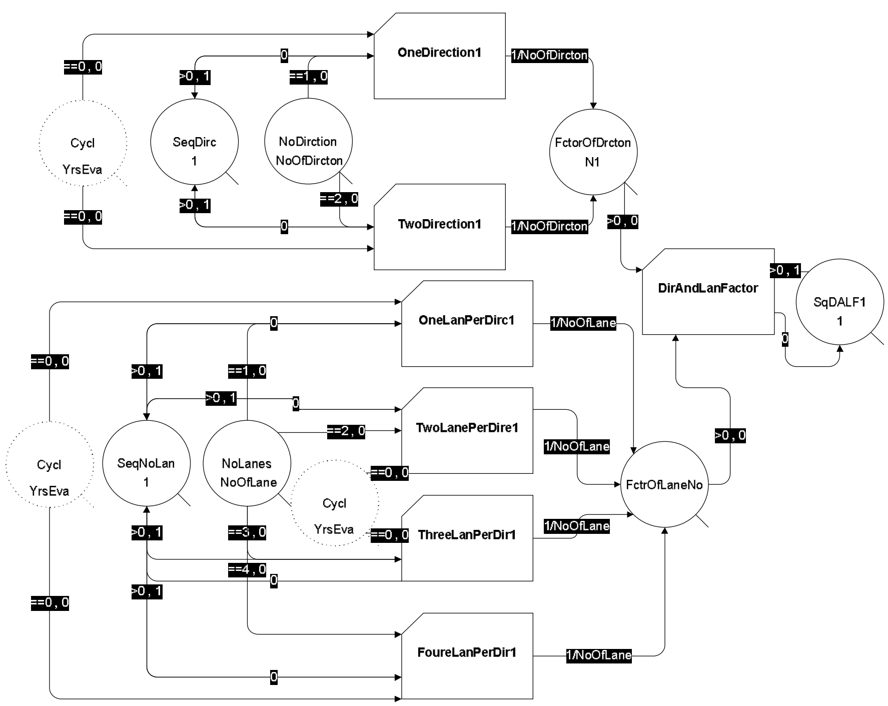

SeqA
1
usrintiate
MaintCosHgh
>0, 1
>0, 0
A84
1
AMCsaving
MaintCosHg
>0, 0
(MaintCosHg.CurCount-MaintCosHgh.CurCount)*1.58
SeqAMCl
1
>0, 1
MaintCostLo
>0, 0
AMClowTr
>0, 0
MaintCstLow
(MaintCostLo.CurCount-MaintCstLow.CurCount)*1.58
Cycl
YrsEva
PerfInd
PI
==0, 0
Seq
1
>0, 0
0
PavTrLg
PavLngh
>0, 0
AgnceCost200
>0, 1
428428*1.13
>0, 0
AgcyCost1
NoOfLa
NoLane

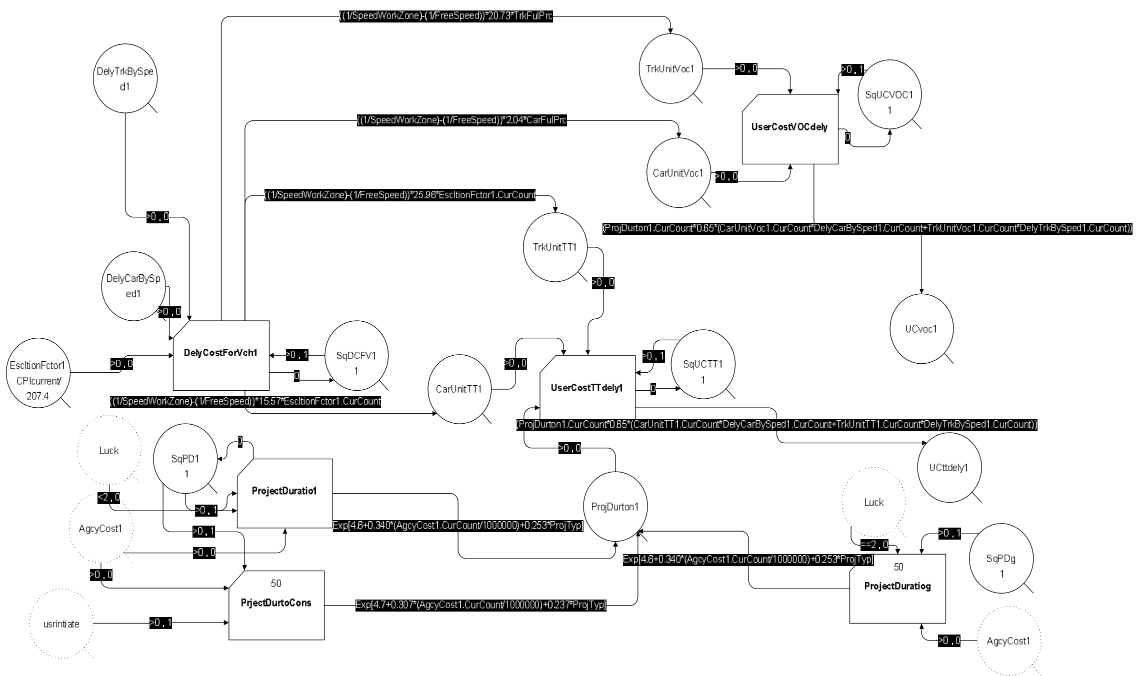

Exp[4.183+(0.015*2.5+0.101*0.49)*PostPlSrvcLif.CurCount]
SeqPostPl
SeqPostPlAv
e
PostPlcalc
>2, 1
PostPlSrvcLif
PveServicelfe1.CurCount
PostPl
==1, 0
==2, 0
Luck
>0, 1
PostPlAve
>0, 0
PostPerfrmnc
NoCyc
Seqnc1
NoCyc
==1, 0
>0, 1
>0, 0
==1, 0
1
PveServcLfe1
(PerfIndx1.CurCount+PostPerfrmnc.CurCount+(PreTretPI.CurCount-PJ1.CurCount))/(PveServicelfe1.CurCount)
>0, 0
==0, 0
PostPrfrmncAv
e
Cycl
YrsEva
Round[(Ln[PerfIndx1.CurCount]-4.183)/(0.015*AATA+0.101*ANDX),0]
PveServicelfe
1
PerfIndx1
PI

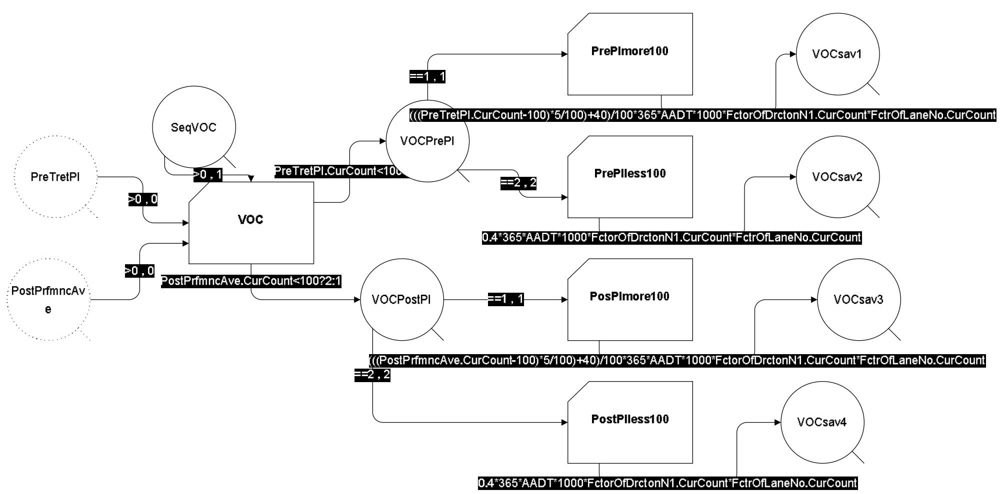

Exp[4.183+(0.015*2.5+0.101*0.49)*PostPISrvcLif2.CurCount]
SPostPIAve
1
>0 , 1
PtPIAve
>0 , 0
PtPerfmnc
PtPIcalc
2 , 1
PostPISrvcLif
2
PveServicelfe1.CurCount
PtPI
>0 , 1
SPostPI
1
Luck
==2 , 0
==3 , 0
NoCyc
Snc1
1
==2 , 0
>0 , 1
>0 , 0
NoCyc
1
==2 , 0
PServcLfe1
0
>0 , 0
Cycl
YrsEva
==0 , 0
PveServicelfe
1
Round[(Ln[Perfindx12.CurCount]-4.183)/(0.015*AATA+0.101*ANDX),0]
Perfindx12
PI

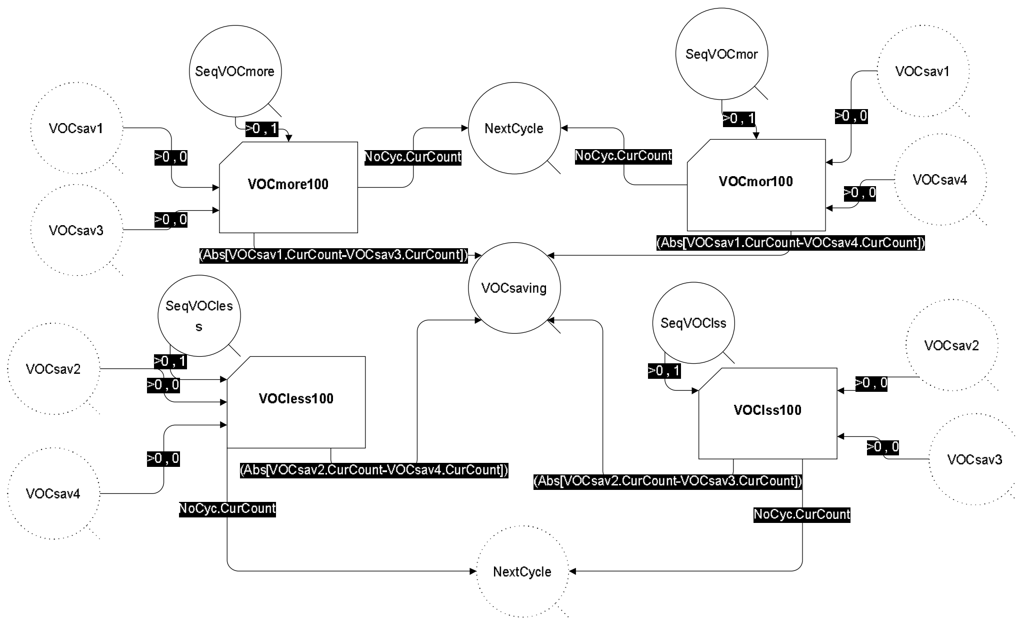

Cycl
YrsEva
PerfIndx1
PI
==0 , 0
SeqAg
>0 , 0
0
>0 , 1
PavTrLgh1
PavLngh
>0 , 0
AgnceCost20071
Luck
==1 , 0
((((0.098*PavLngh^0.690)*(NoLane^0.458)*((Ln[PerfIndx1.CurCount])^4.867))*1000)/(NoLane*PavLngh))*1.13
>0 , 0
AgcyCost1
NoOfLanes1
NoLane

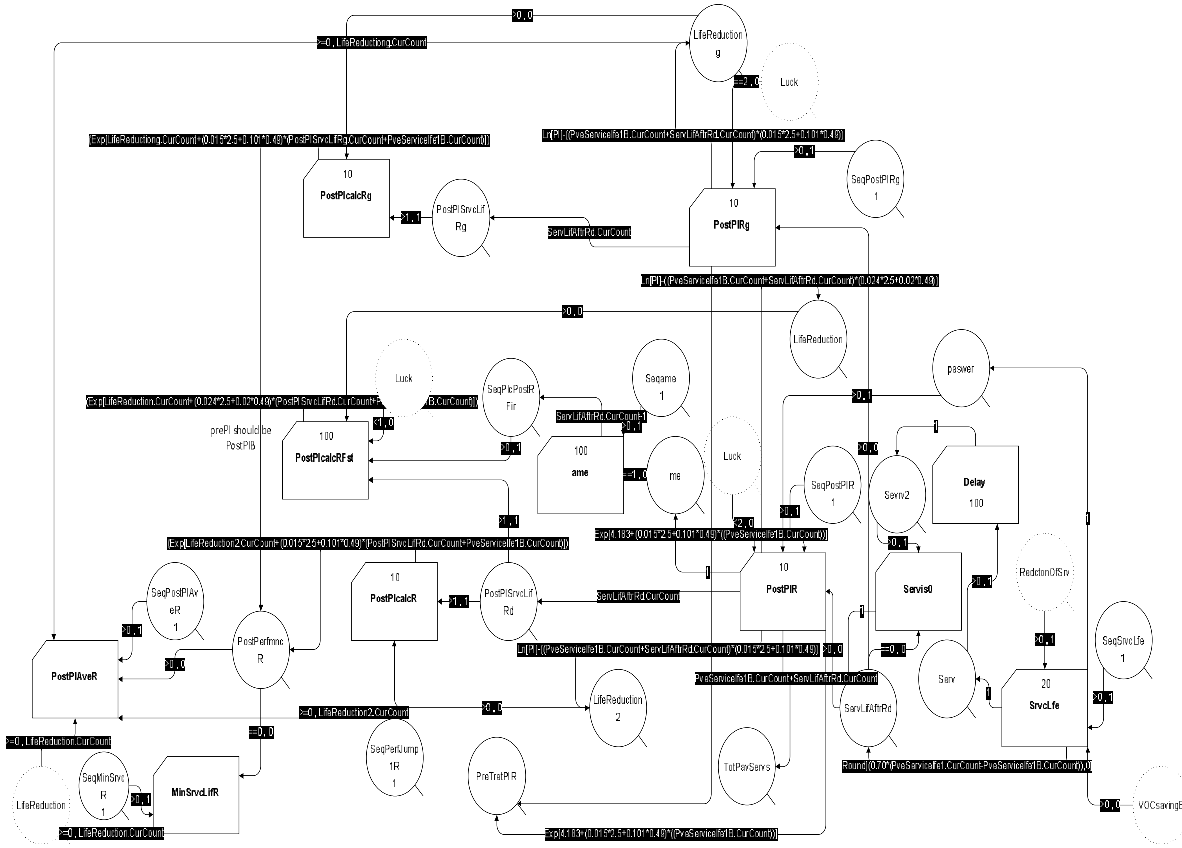

Cycl
YrsEva
PerfIndx12
PI
==0, 0
>0, 0
SeqAg1
1
0
>0, 1
PavTrLgh12
PavLngh
>0, 0
AceCost20071
NoCyc
>1, 0
((((0.098*PavLngh^0.690)*(NoLane^0.458)*((Ln[PerfIndx12.CurCount])^4.867))*1000)/(NoLane*PavLngh))*1.13
>0, 0
AgcyCost1
NoOfLanes12
NoLane

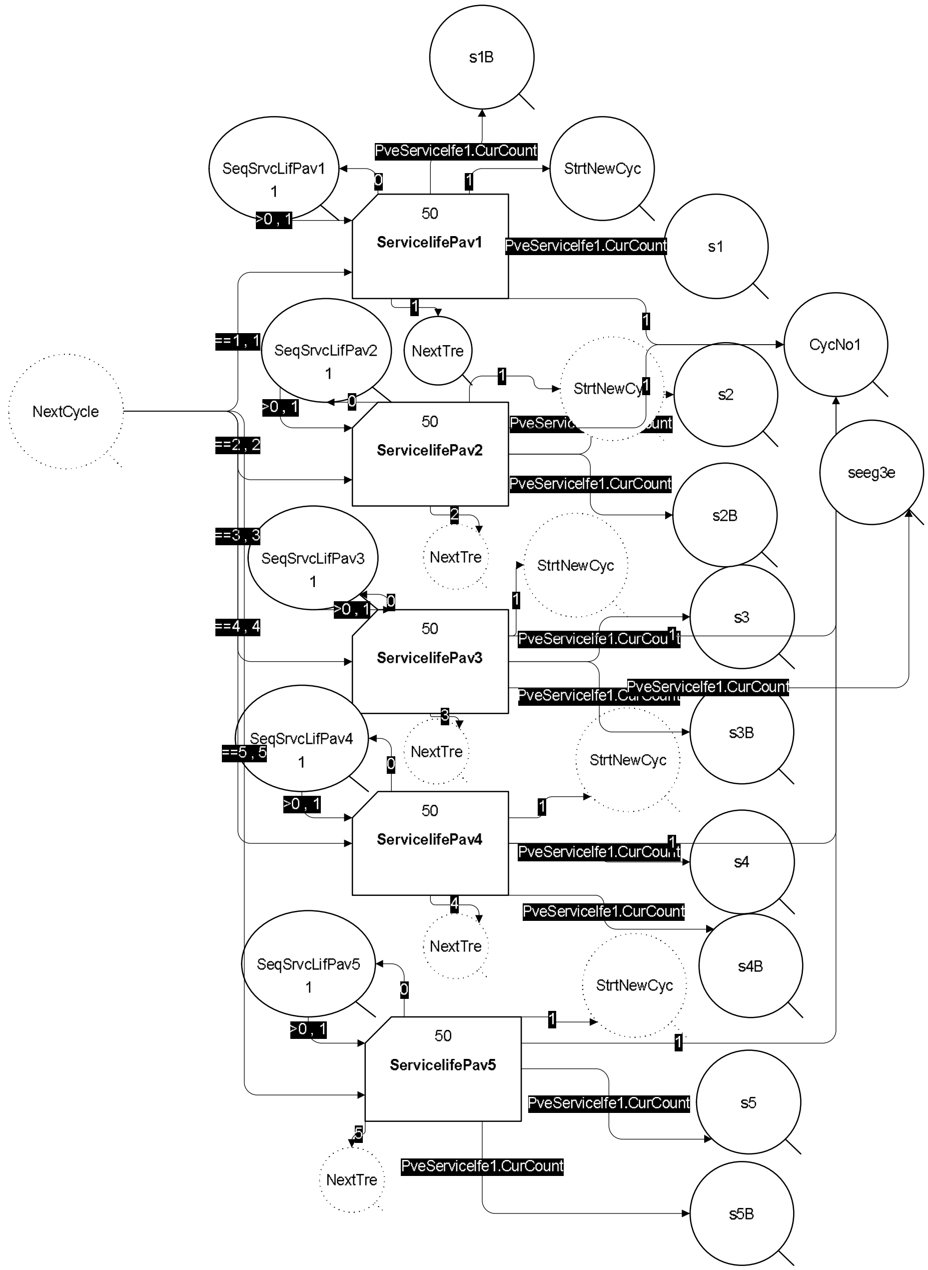

==0, 0
0
>0, 1
==1, 0
OneDirection1
1/NoOfDircton
Cycl
YrsEva
SeqDirc
1
NoDirction
NoOfDircton
FctorOfDrcton
N1
==2, 0
>0, 1
==0, 0
0
TwoDirection1
1/NoOfDircton
>0, 0
DirAndLanFactor
>0, 1
SqDALF1
1
0
OneLanPerDirc1
1/NoOfLane
==0, 0
>0, 1
==1, 0
>0, 1
0
TwoLanePerDire1
==2, 0
1/NoOfLane
>0, 0
Cycl
YrsEva
SeqNoLan
1
NoLanes
NoOfLane
==0, 0
FctrOfLaneNo
Cycl
YrsEva
ThreeLanPerDir1
1/NoOfLane
>0, 1
==3, 0
==0, 0
==4, 0
0
>0, 1
==0, 0
FoureLanPerDir1
1/NoOfLane
0

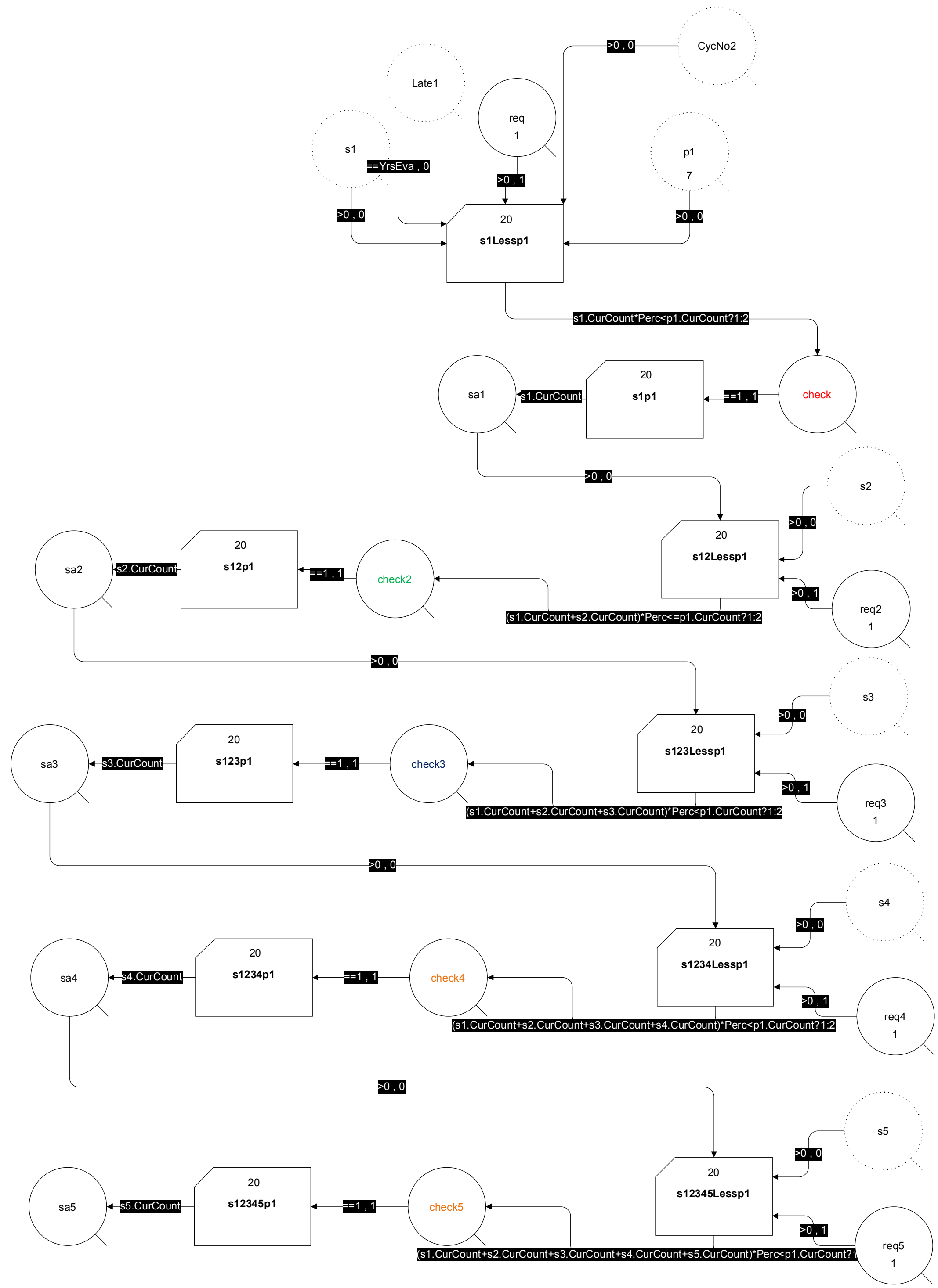

((1/SpeedWorkZone)-(1/FreeSpeed))*20.73*TrkFulPrc
DelyTrkBySped1
TrkUnitVoc1
UserCostVOCdely
SqUCVOC1 1
((1/SpeedWorkZone)-(1/FreeSpeed))*2.04*CarFulPrc
CarUnitVoc1
((1/SpeedWorkZone)-(1/FreeSpeed))*25.86*EscltionFctor1.CurCount
(ProjDurton1.CurCount*0.65*(CarUnitVoc1.CurCount*DelyCarBySped1.CurCount+TrkUnitVoc1.CurCount*DelyTrkBySped1.CurCount))
TrkUnitTT1
DelyCarBySped1
UCvoc1
EscltionFctor1 CPIcurrent/ 207.4
DelyCostForVch1
SqDCFV1 1
CarUnitTT1
UserCostTTdely1
SqUCTT1 1
((1/SpeedWorkZone)-(1/FreeSpeed))*15.57*EscltionFctor1.CurCount
(ProjDurton1.CurCount*0.65*(CarUnitTT1.CurCount*DelyCarBySped1.CurCount+TrkUnitTT1.CurCount*DelyTrkBySped1.CurCount))
Luck
SqPD1 1
ProjectDuratio1
UCttdely1
ProjDurton1
Luck
AgcyCost1
Exp(4.6+0.340*(AgcyCost1.CurCount/1000000)+0.253*ProjTyp)
SqPDg 1
50
Exp(4.6+0.340*(AgcyCost1.CurCount/1000000)+0.253*ProjTyp)
50
PrjectDurtoCons
ProjectDuratiog
usrintiate
Exp(4.7+0.307*(AgcyCost1.CurCount/1000000)+0.237*ProjTyp)
AgcyCost1

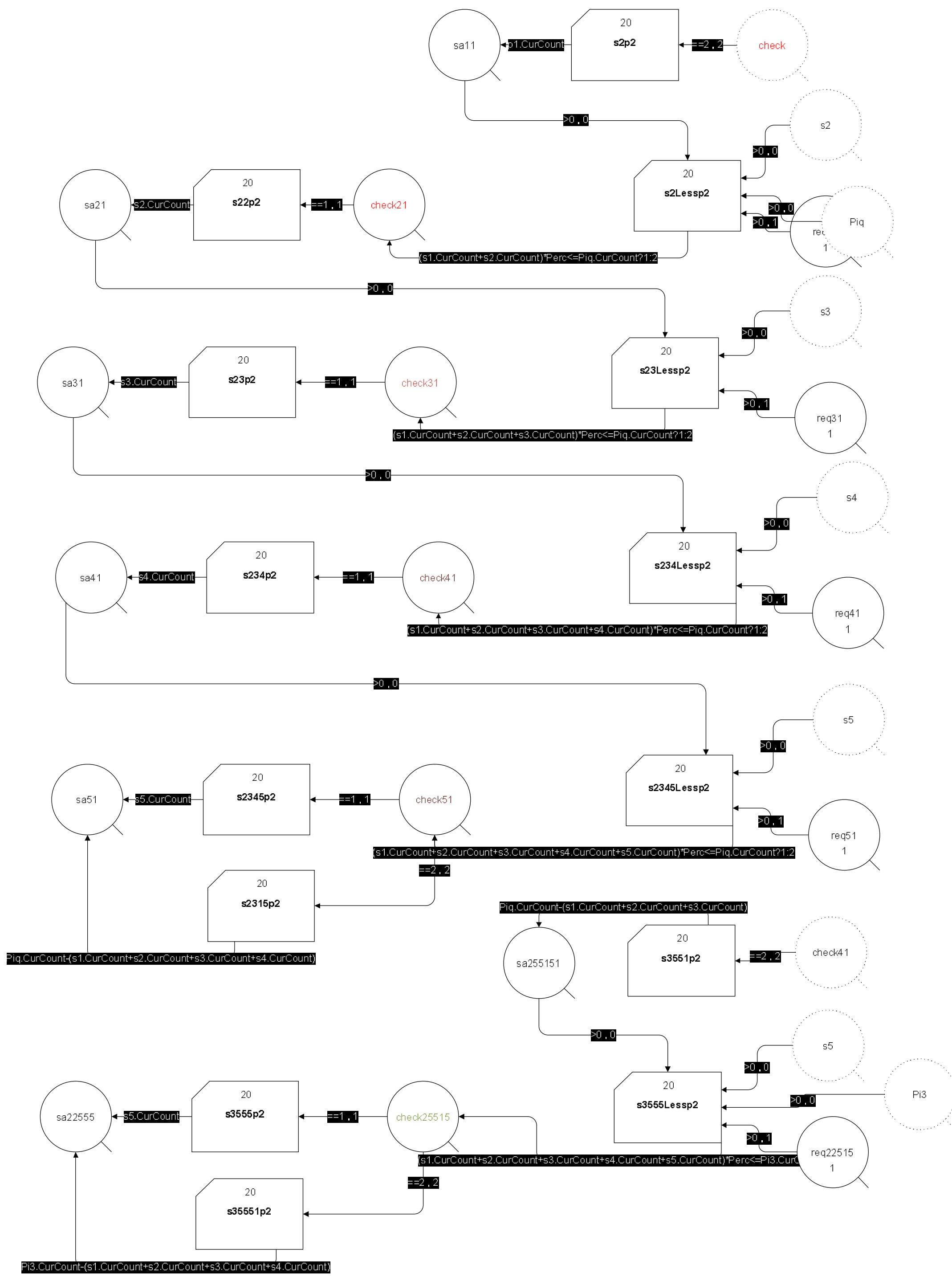

PrePlmore100
VOCsav1
==1,1
SeqVOC
(((PreTretPl.CurCount-100)*5/100)+40)/100*365*AADT*1000*FctorOfDrctonN1.CurCount*FctrOfLaneNo.CurCount
VOCPrePl
PreTretPl
>0,1
PreTretPl.CurCount<100
PrePlless100
VOCsav2
==2,2
>0,0
VOC
0.4*365*AADT*1000*FctorOfDrctonN1.CurCount*FctrOfLaneNo.CurCount
>0,0
PostPrfmncAve
PostPrfmncAve.CurCount<100?2:1
VOCPostPl
==1,1
PosPlmore100
VOCsav3
(((PostPrfmncAve.CurCount-100)*5/100)+40)/100*365*AADT*1000*FctorOfDrctonN1.CurCount*FctrOfLaneNo.CurCount
==2,2
PostPlless100
VOCsav4
0.4*365*AADT*1000*FctorOfDrctonN1.CurCount*FctrOfLaneNo.CurCount

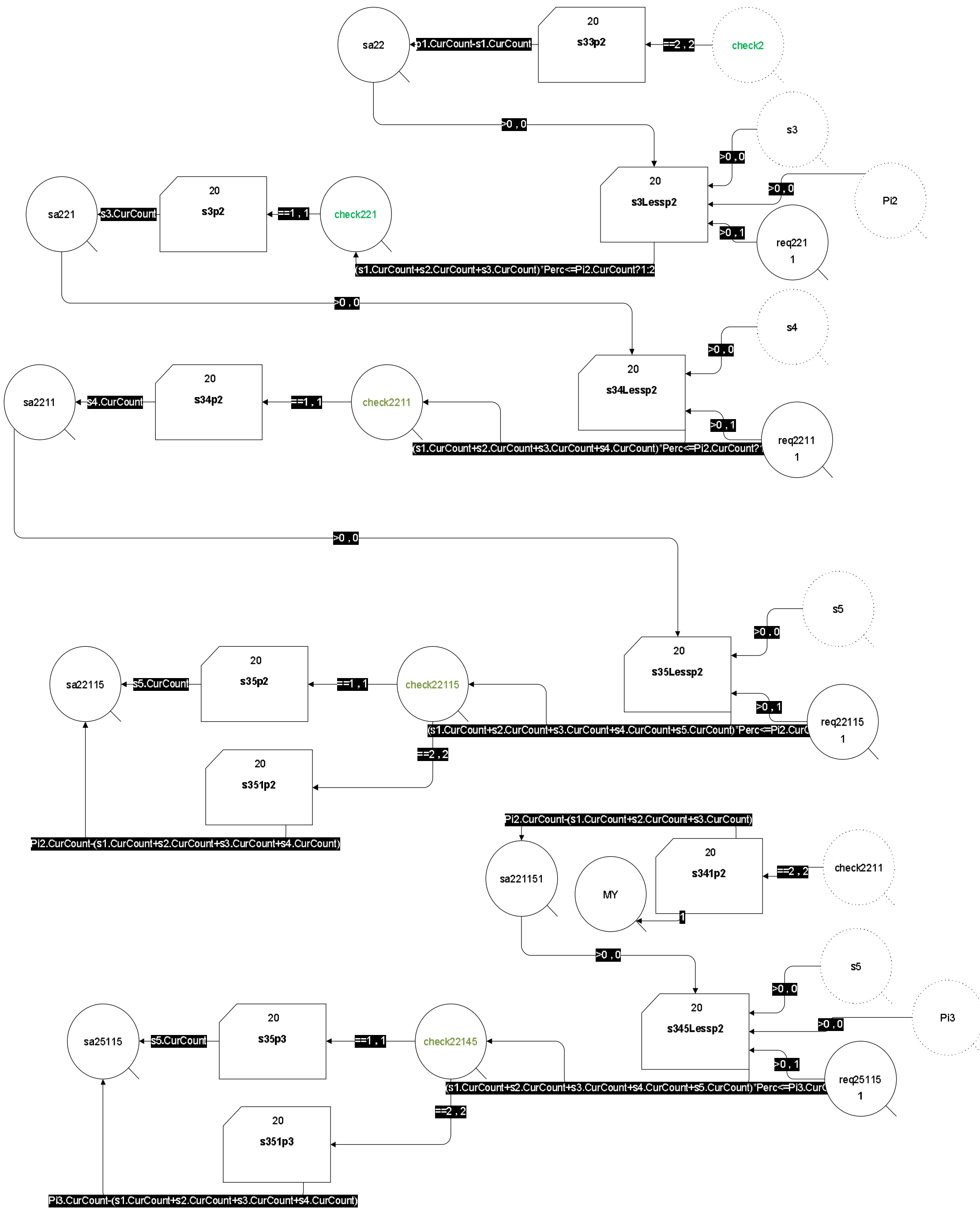

SeqVOCmore
VOCsav1
>0 , 1
>0 , 0
VOCmore100
NoCyc.CurCount
NextCycle
NoCyc.CurCount
SeqVOCmor
>0 , 1
VOCsav1
>0 , 0
VOCmor100
VOCsav4
>0 , 0
VOCsav3
>0 , 0
(Abs[VOCsav1.CurCount-VOCsav3.CurCount])
VOCsaving
(Abs[VOCsav1.CurCount-VOCsav4.CurCount])
SeqVOCless
VOCsav2
>0 , 1
>0 , 0
VOCless100
SeqVOClss
>0 , 1
VOClss100
VOCsav2
>0 , 0
>0 , 0
VOCsav3
VOCsav4
>0 , 0
(Abs[VOCsav2.CurCount-VOCsav4.CurCount])
(Abs[VOCsav2.CurCount-VOCsav3.CurCount])
NoCyc.CurCount
NoCyc.CurCount
NextCycle

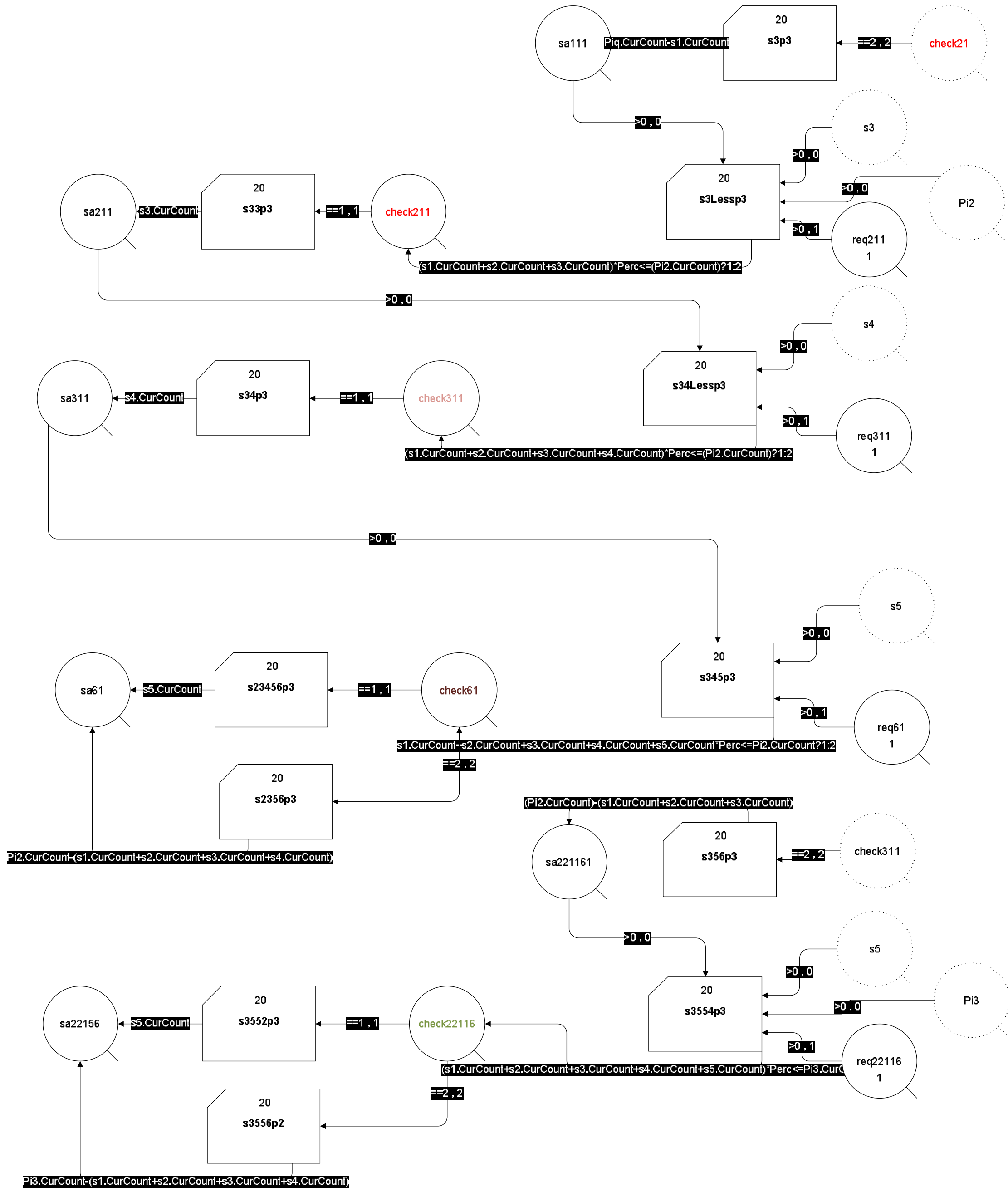

LifeReduction g
Luck
SeqPostPlRg 1
PostPlcalcRg
PostPlSrvcLif Rg
ServLifAftrRd.CurCount
PostPlRg
LifeReduction
paswer
Luck
SeqPlcPostR Fir
Seqame 1
prePl should be PostPlB
PostPlcalcRFst
ame
me
Luck
SeqPostPlR 1
Serv2
Delay
Servis0
PostPlcalcR
PostPlSrvcLif Rd
PostPlR
RedctonOfSrv
SeqPostPlAv eR 1
PostPerfrmnc R
PostPlAveR
LifeReduction 2
ServLifAftrRd
Serv
SeqSrvcLfe 1
SrvcLfe
SeqPerfJump 1R 1
PreTretPlR
TotPavServs
LifeReduction
SeqMinSrvc R 1
MinSrvcLifR
VOCsavingB


s1B
PveServicelfe1.CurCount
SeqSrvcLifPav1
1
StrtNewCyc
0
1
>0 , 1
50
ServicelifePav1
PveServicelfe1.CurCount
s1
1
CycNo1
==1 , 1
SeqSrvcLifPav2
1
NextTre
NextCycle
>0 , 1
0
1
StrtNewCy
s2
50
ServicelifePav2
==2 , 2
PveServicelfe1.CurCount
seeg3e
s2B
2
NextTre
==3 , 3
SeqSrvcLifPav3
1
StrtNewCyc
>0 , 1
0
1
s3
==4 , 4
50
ServicelifePav3
PveServicelfe1.CurCount
PveServicelfe1.CurCount
3
s3B
SeqSrvcLifPav4
1
==5 , 5
NextTre
StrtNewCyc
0
>0 , 1
50
ServicelifePav4
1
PveServicelfe1.CurCount
s4
4
PveServicelfe1.CurCount
NextTre
s4B
SeqSrvcLifPav5
1
StrtNewCyc
0
>0 , 1
50
ServicelifePav5
1
PveServicelfe1.CurCount
s5
5
NextTre
PveServicelfe1.CurCount
s5B

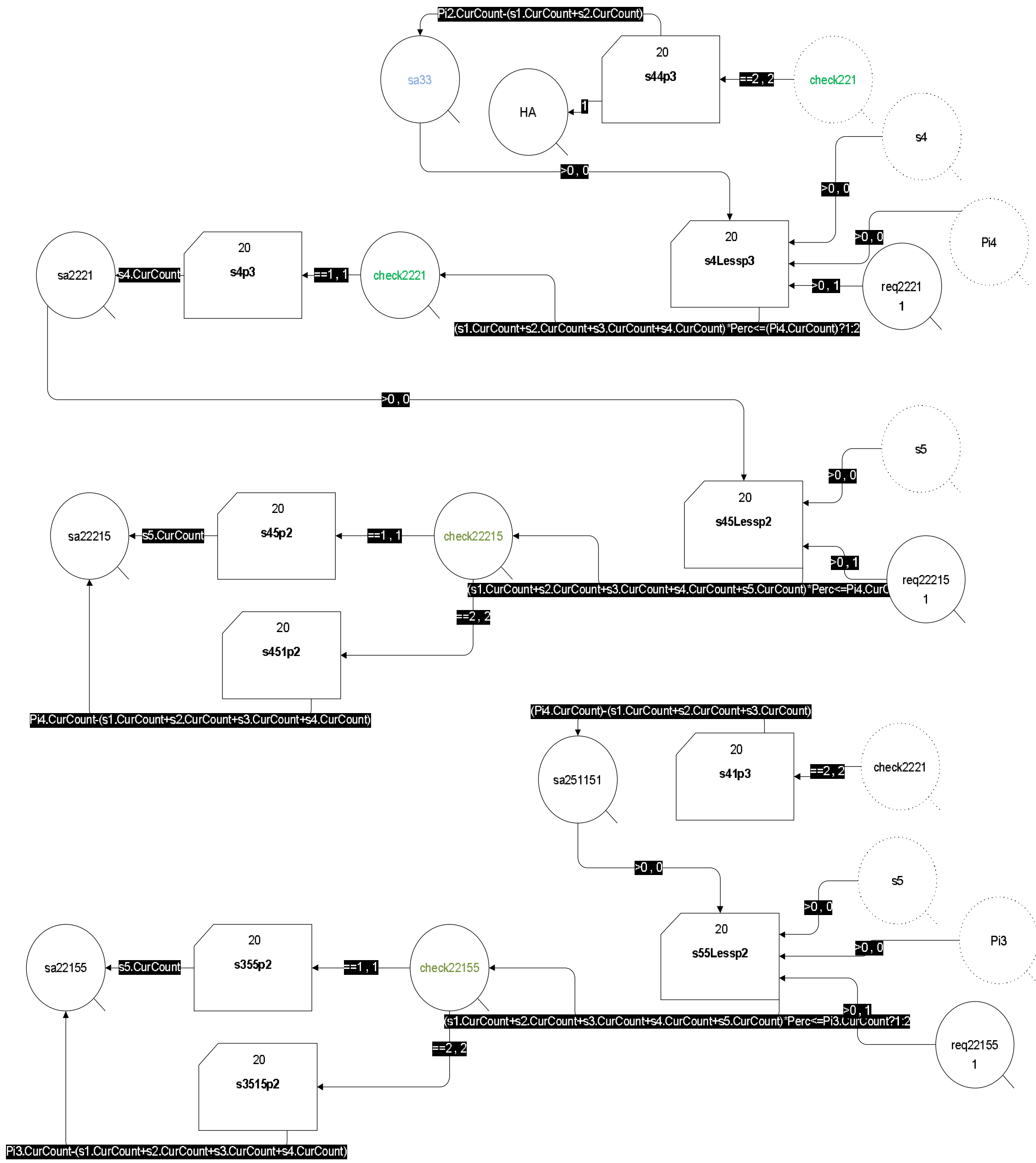

CycNo2
>0 , 0
Late1
req
1
s1
==YrsEva , 0
>0 , 1
p1
7
>0 , 0
>0 , 0
20
s1Lessp1
s1.CurCount*Perc<p1.CurCount?1:2
sa1
s1.CurCount
20
s1p1
==1 , 1
check
>0 , 0
s2
>0 , 0
20
s12Lessp1
>0 , 1
req2
1
sa2
s2.CurCount
20
s12p1
==1 , 1
check2
(s1.CurCount+s2.CurCount)*Perc<=p1.CurCount?1:2
>0 , 0
s3
>0 , 0
20
s123Lessp1
>0 , 1
req3
1
sa3
s3.CurCount
20
s123p1
==1 , 1
check3
(s1.CurCount+s2.CurCount+s3.CurCount)*Perc<p1.CurCount?1:2
>0 , 0
s4
>0 , 0
20
s1234Lessp1
>0 , 1
req4
1
sa4
s4.CurCount
20
s1234p1
==1 , 1
check4
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<p1.CurCount?1:2
>0 , 0
s5
>0 , 0
20
s12345Lessp1
>0 , 1
req5
1
sa5
s5.CurCount
20
s12345p1
==1 , 1
check5
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<p1.CurCount?

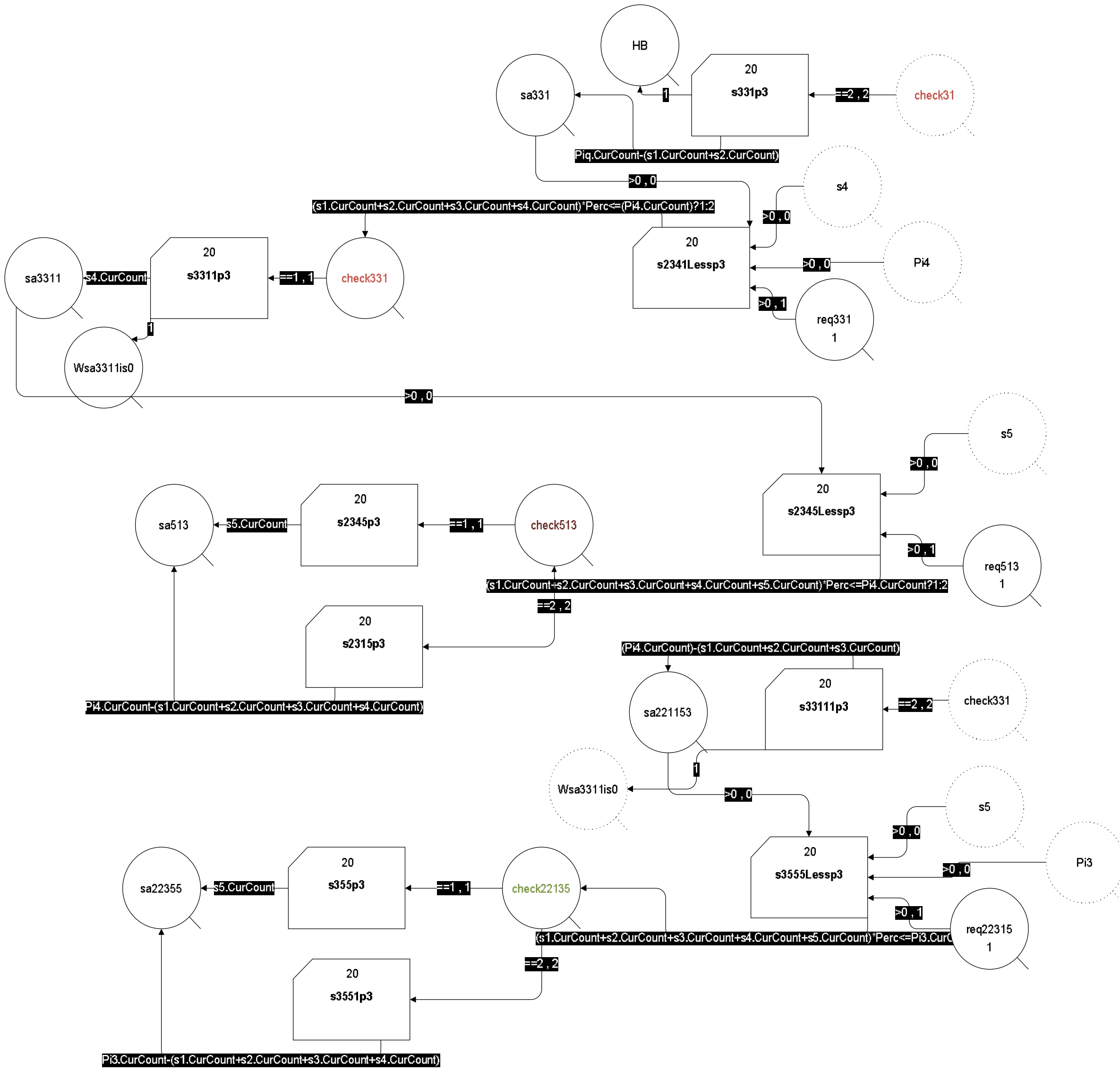

sa11
p1.CurCount
20
s2p2
==2, 2
check
>0, 0
s2
>0, 0
20
s2Lessp2
>0, 0
>0, 1
Piq
sa21
s2.CurCount
20
s22p2
==1, 1
check21
(s1.CurCount+s2.CurCount)*Perc<=Piq.CurCount?1:2
>0, 0
s3
>0, 0
20
s23Lessp2
sa31
s3.CurCount
20
s23p2
==1, 1
check31
>0, 1
req31
1
(s1.CurCount+s2.CurCount+s3.CurCount)*Perc<=Piq.CurCount?1:2
>0, 0
s4
>0, 0
20
s234Lessp2
sa41
s4.CurCount
20
s234p2
==1, 1
check41
>0, 1
req41
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=Piq.CurCount?1:2
>0, 0
s5
>0, 0
20
s2345Lessp2
sa51
s5.CurCount
20
s2345p2
==1, 1
check51
>0, 1
req51
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Piq.CurCount?1:2
==2, 2
20
s2315p2
Piq.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount)
sa255151
20
s3551p2
==2, 2
check41
Piq.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
>0, 0
s5
>0, 0
Pi3
>0, 0
20
s3555Lessp2
sa22555
s5.CurCount
20
s3555p2
==1, 1
check25515
>0, 1
req22515
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.Cur
==2, 2
20
s35551p2
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

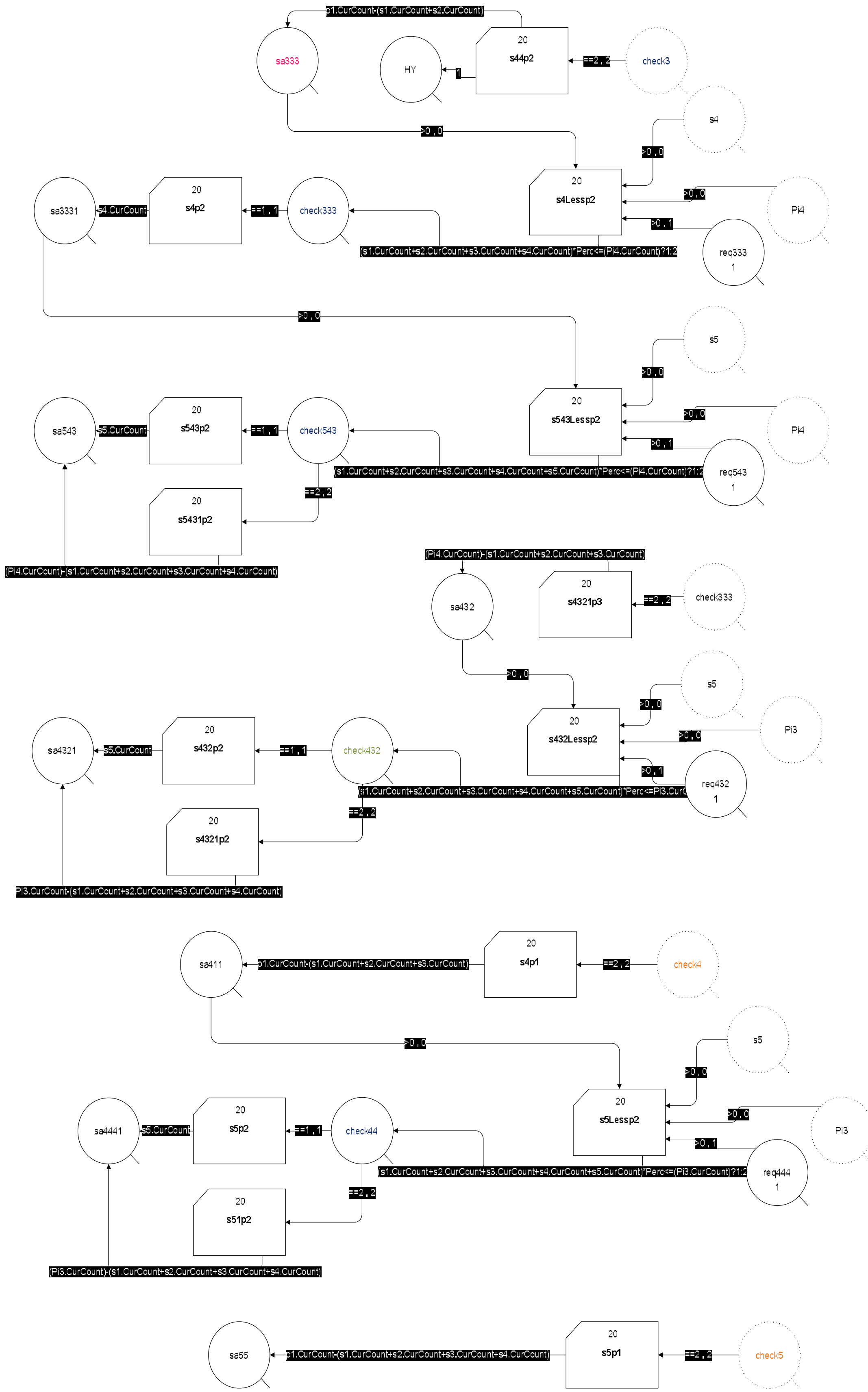

sa22
p1.CurCount-s1.CurCount
20
s33p2
==2 , 2
check2
>0 , 0
s3
20
s3Lessp2
>0 , 0
Pi2
>0 , 1
req221
1
sa221
s3.CurCount
20
s3p2
==1 , 1
check221
(s1.CurCount+s2.CurCount+s3.CurCount)*Perc<=Pi2.CurCount?1:2
>0 , 0
s4
20
s34Lessp2
>0 , 1
req2211
1
sa2211
s4.CurCount
20
s34p2
==1 , 1
check2211
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=Pi2.CurCount?
>0 , 0
s5
20
s35Lessp2
>0 , 1
req22115
1
sa22115
s5.CurCount
20
s35p2
==1 , 1
check22115
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi2.Cur
==2 , 2
20
s351p2
Pi2.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
Pi2.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount)
sa221151
MY
20
s341p2
==2 , 2
check2211
1
>0 , 0
s5
>0 , 0
20
s345Lessp2
>0 , 0
Pi3
>0 , 1
req25115
1
sa25115
s5.CurCount
20
s35p3
==1 , 1
check22145
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.Cur
==2 , 2
20
s351p3
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

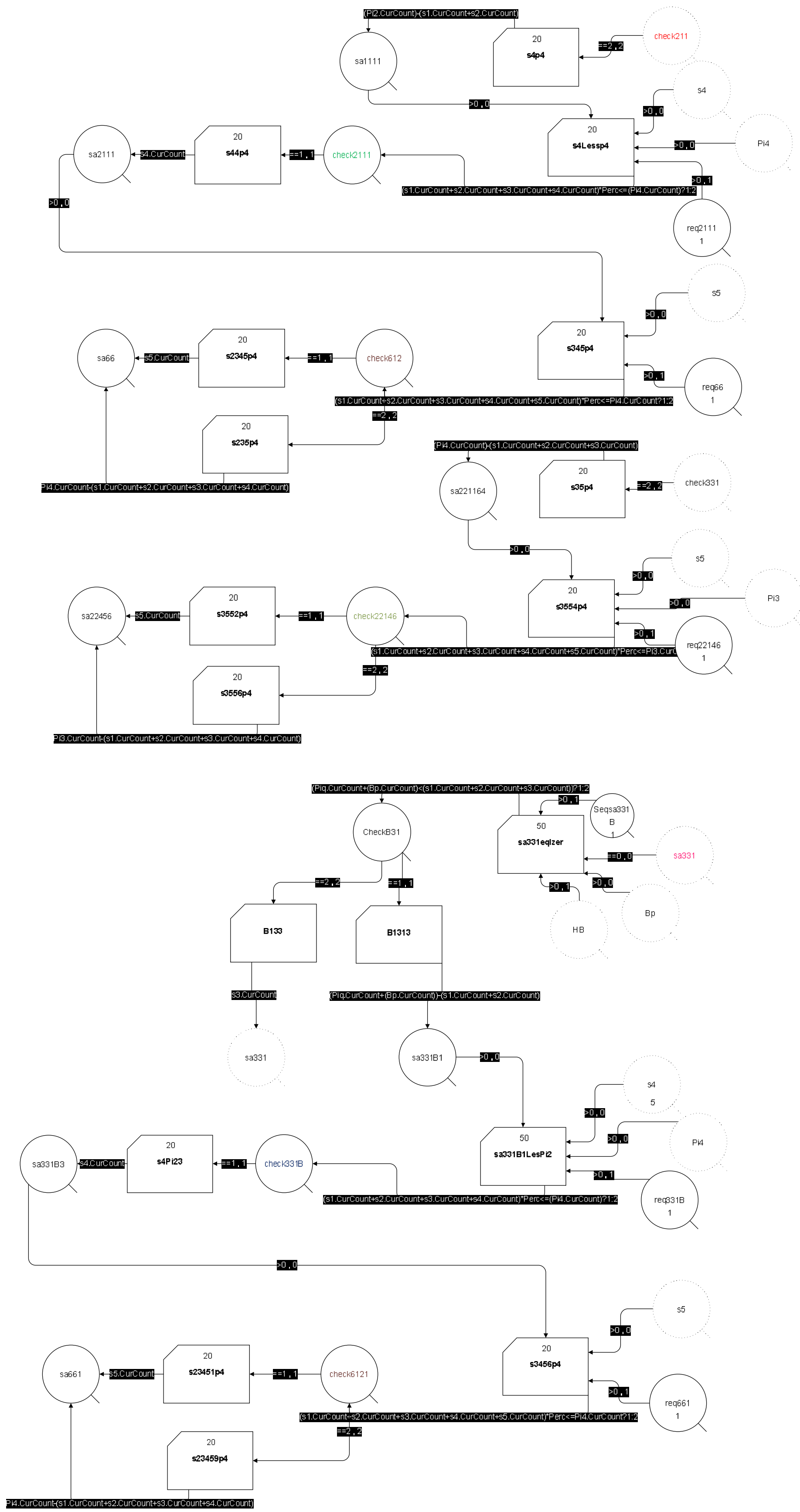


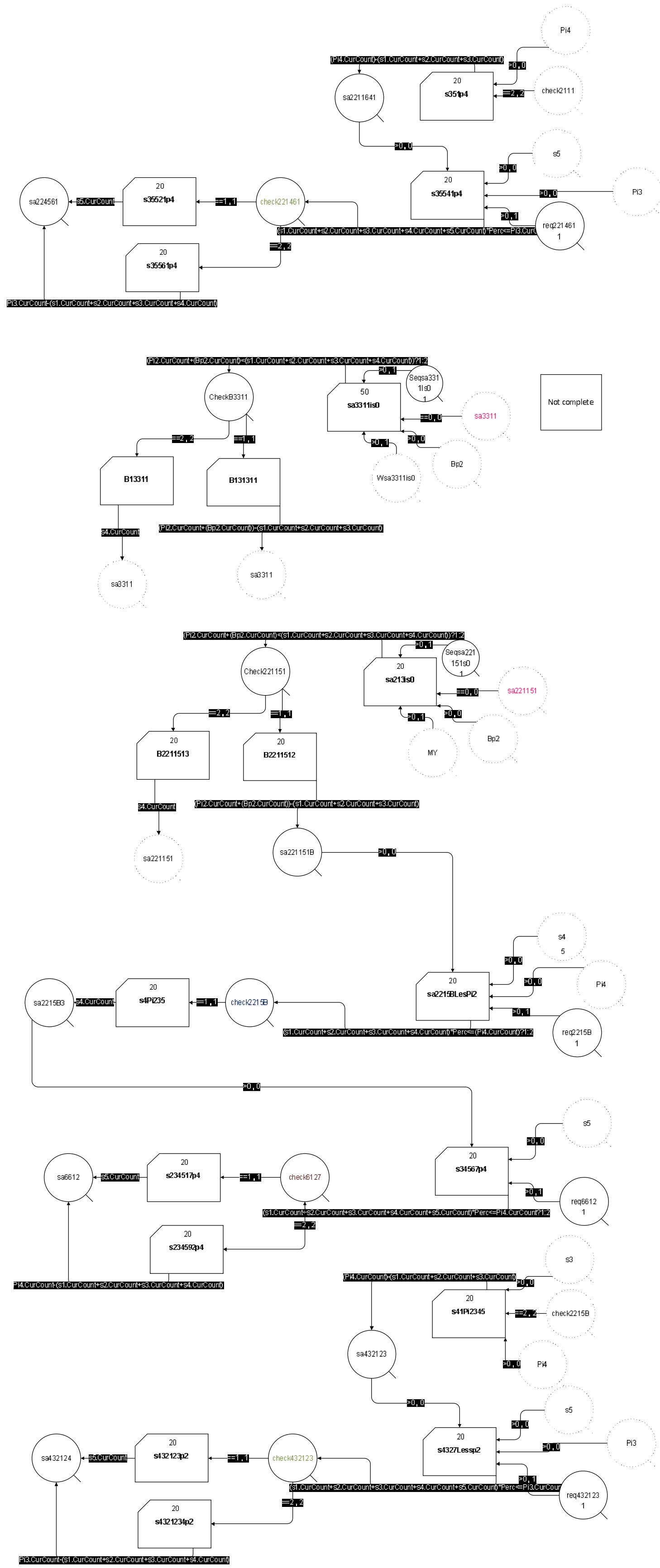
sa111
Piq.CurCount-s1.CurCount
20
s3p3
==2 , 2
check21
>0 , 0
s3
>0 , 0
20
s3Lessp3
>0 , 0
Pi2
>0 , 1
req211
1
sa211
s3.CurCount
20
s33p3
==1 , 1
check211
(s1.CurCount+s2.CurCount+s3.CurCount)*Perc<=(Pi2.CurCount)?1:2
>0 , 0
s4
>0 , 0
20
s34Lessp3
>0 , 1
req311
1
sa311
s4.CurCount
20
s34p3
==1 , 1
check311
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi2.CurCount)?1:2
>0 , 0
s5
>0 , 0
20
s345p3
>0 , 1
req61
1
sa61
s5.CurCount
20
s23456p3
==1 , 1
check61
s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount*Perc<=Pi2.CurCount?1:2
==2 , 2
20
s2356p3
Pi2.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Pi2.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
sa221161
20
s356p3
==2 , 2
check311
>0 , 0
s5
>0 , 0
20
s3554p3
>0 , 0
Pi3
>0 , 1
req22116
1
sa22156
s5.CurCount
20
s3552p3
==1 , 1
check22116
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.Cur
==2 , 2
20
s3556p2
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

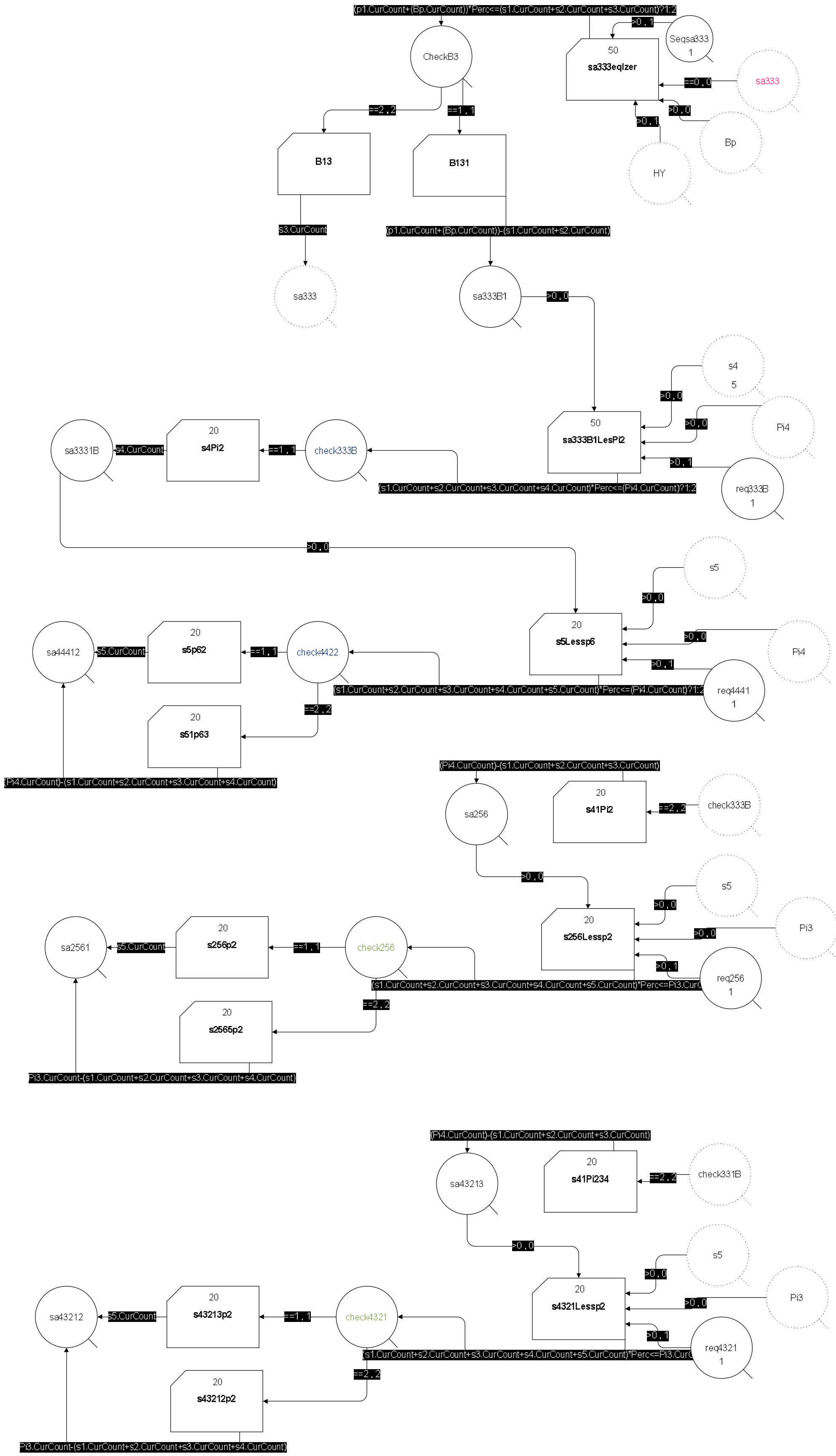

Pi2.CurCount-(s1.CurCount+s2.CurCount)
sa33
HA
1
20
s44p3
==2, 2
check221
s4
>0, 0
>0, 0
Pi4
>0, 0
20
s4Lessp3
>0, 1
req2221
1
sa2221
s4.CurCount
20
s4p3
==1, 1
check2221
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi4.CurCount)?1:2
>0, 0
s5
>0, 0
20
s45Lessp2
>0, 1
sa22215
s5.CurCount
20
s45p2
==1, 1
check22215
req22215
1
==2, 2
20
s451p2
Pi4.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
sa251151
20
s41p3
==2, 2
check2221
>0, 0
s5
>0, 0
Pi3
>0, 0
20
s55Lessp2
>0, 1
sa22155
s5.CurCount
20
s355p2
==1, 1
check22155
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.CurCount?1:2
req22155
1
==2, 2
20
s3515p2
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

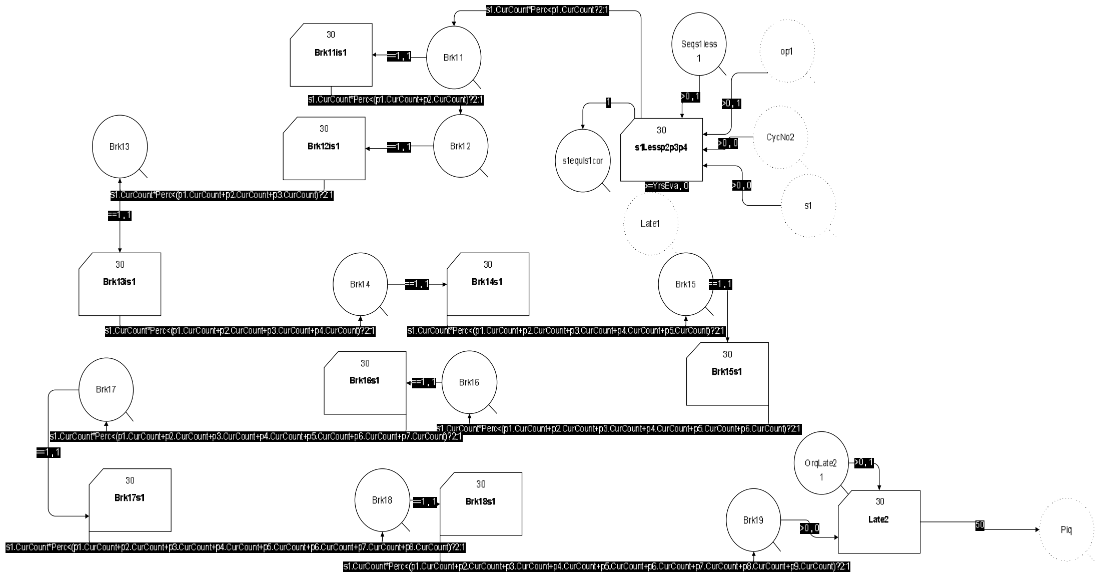

HB
sa331
20
s331p3
==2 , 2
check31
1
Piq.CurCount-(s1.CurCount+s2.CurCount)
>0 , 0
s4
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi4.CurCount)?1:2
>0 , 0
20
s2341Lessp3
>0 , 0
Pi4
sa3311
s4.CurCount
20
s3311p3
==1 , 1
check331
>0 , 1
req331
1
1
Wsa3311is0
>0 , 0
s5
>0 , 0
20
s2345Lessp3
sa513
s5.CurCount
20
s2345p3
==1 , 1
check513
>0 , 1
req513
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi4.CurCount?1:2
==2 , 2
20
s2315p3
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
20
s33111p3
==2 , 2
check331
sa221153
Pi4.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
1
Wsa3311is0
>0 , 0
s5
>0 , 0
20
s3555Lessp3
>0 , 0
Pi3
sa22355
s5.CurCount
20
s355p3
==1 , 1
check22135
>0 , 1
req22315
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.CurC
==2 , 2
20
s3551p3
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

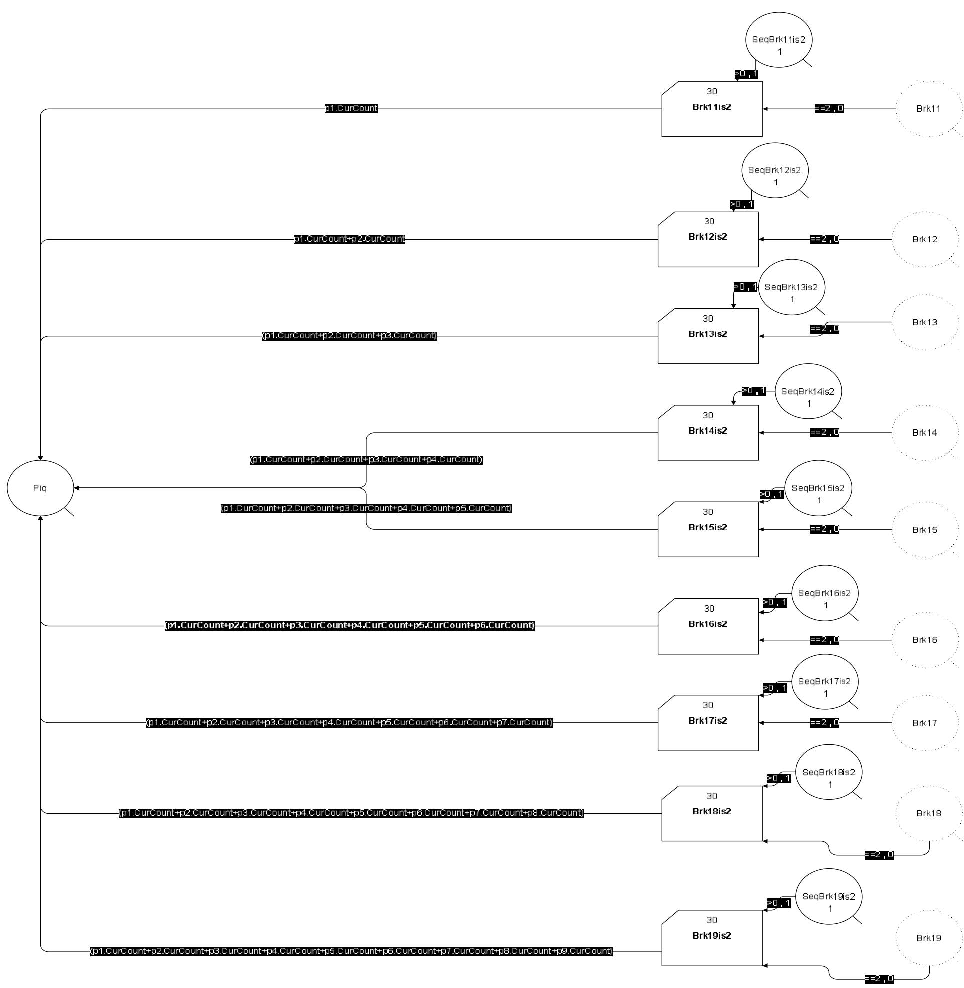

p1.CurCount-(s1.CurCount+s2.CurCount)
sa333
HY
1
20
s44p2
==2 , 2
check3
s4
>0 , 0
>0 , 0
20
s4Lessp2
>0 , 0
Pi4
>0 , 1
sa3331
s4.CurCount
20
s4p2
==1 , 1
check333
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi4.CurCount)?1:2
req333
1
>0 , 0
s5
>0 , 0
20
s543Lessp2
>0 , 0
Pi4
>0 , 1
sa543
s5.CurCount
20
s543p2
==1 , 1
check543
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=(Pi4.CurCount)?1:2
req543
1
==2 , 2
20
s5431p2
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
sa432
20
s4321p3
==2 , 2
check333
>0 , 0
s5
>0 , 0
20
s432Lessp2
>0 , 0
Pi3
>0 , 1
sa4321
s5.CurCount
20
s432p2
==1 , 1
check432
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.Cur
req432
1
==2 , 2
20
s4321p2
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
sa411
p1.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount)
20
s4p1
==2 , 2
check4
>0 , 0
s5
>0 , 0
20
s5Lessp2
>0 , 0
Pi3
>0 , 1
sa4441
s5.CurCount
20
s5p2
==1 , 1
check44
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=(Pi3.CurCount)?1:2
req444
1
==2 , 2
20
s51p2
(Pi3.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
sa55
p1.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
20
s5p1
==2 , 2
check5

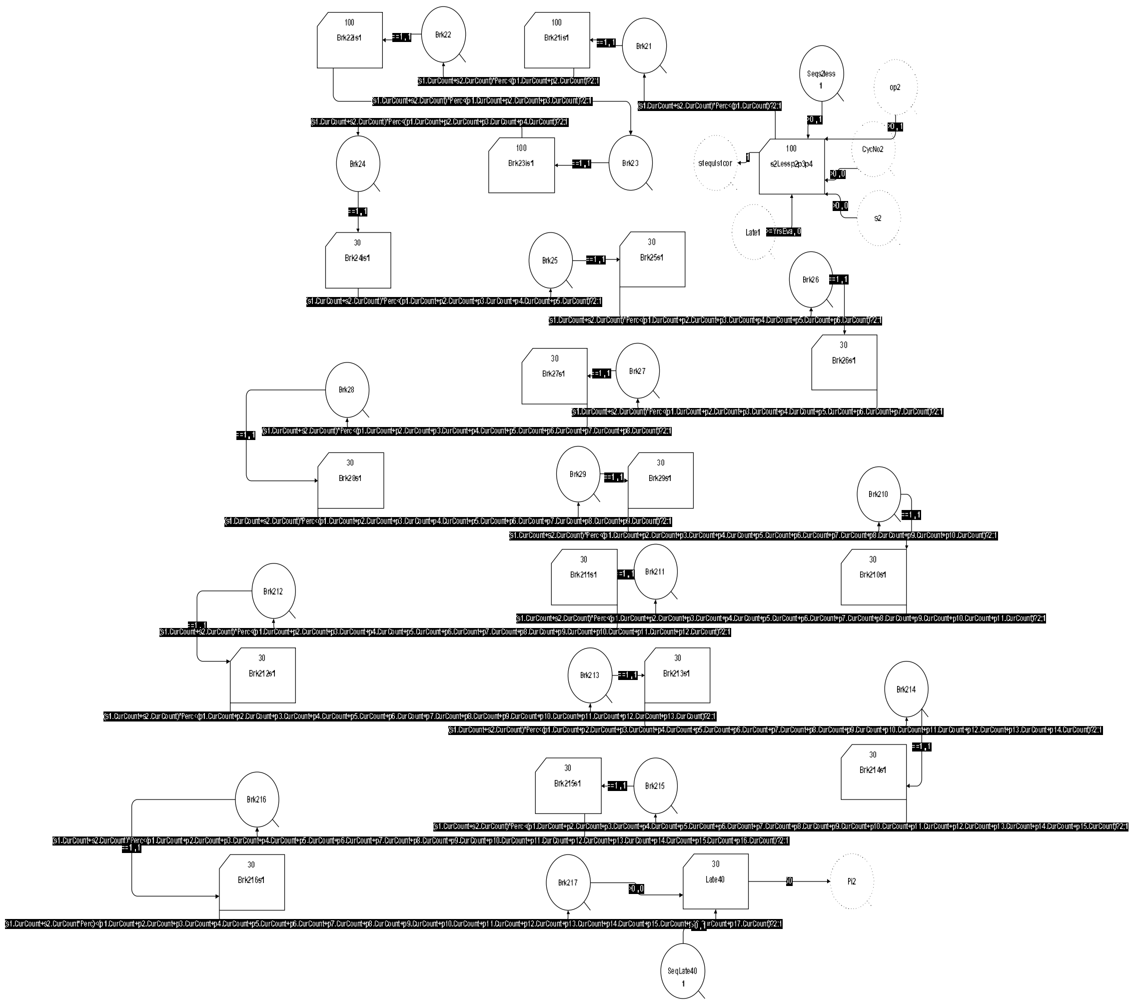

(Pi2.CurCount)-(s1.CurCount+s2.CurCount)
sa1111
20
s4p4
==2,2
check211
s4
>0,0
>0,0
20
s4Lessp4
>0,0
Pi4
>0,1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi4.CurCount)?1:2
req2111
1
sa2111
s4.CurCount
20
s44p4
==1,1
check2111
>0,0
s5
>0,0
20
s345p4
>0,1
req66
1
sa66
s5.CurCount
20
s2345p4
==1,1
check612
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi4.CurCount?1:2
==2,2
20
s235p4
Pi4.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
sa221164
20
s35p4
==2,2
check331
>0,0
s5
>0,0
20
s3554p4
>0,0
Pi3
>0,1
req22146
1
sa22456
s5.CurCount
20
s3552p4
==1,1
check22146
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.Cur
==2,2
20
s3556p4
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Piq.CurCount+(Bp.CurCount)<(s1.CurCount+s2.CurCount+s3.CurCount))?1:2
>0,1
Seqsa331
B
1
CheckB31
50
sa331eqlzer
==0,0
sa331
>0,1
>0,0
Bp
HB
==2,2
==1,1
B133
B1313
s3.CurCount
(Piq.CurCount+(Bp.CurCount))-(s1.CurCount+s2.CurCount)
sa331
sa331B1
>0,0
s4
5
>0,0
>0,0
Pi4
50
sa331B1LesPi2
>0,1
req331B
1
sa331B3
s4.CurCount
20
s4Pi23
==1,1
check331B
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi4.CurCount)?1:2
>0,0
s5
>0,0
20
s3456p4
>0,1
req661
1
sa661
s5.CurCount
20
s23451p4
==1,1
check6121
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi4.CurCount?1:2
==2,2
20
s23459p4
Pi4.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

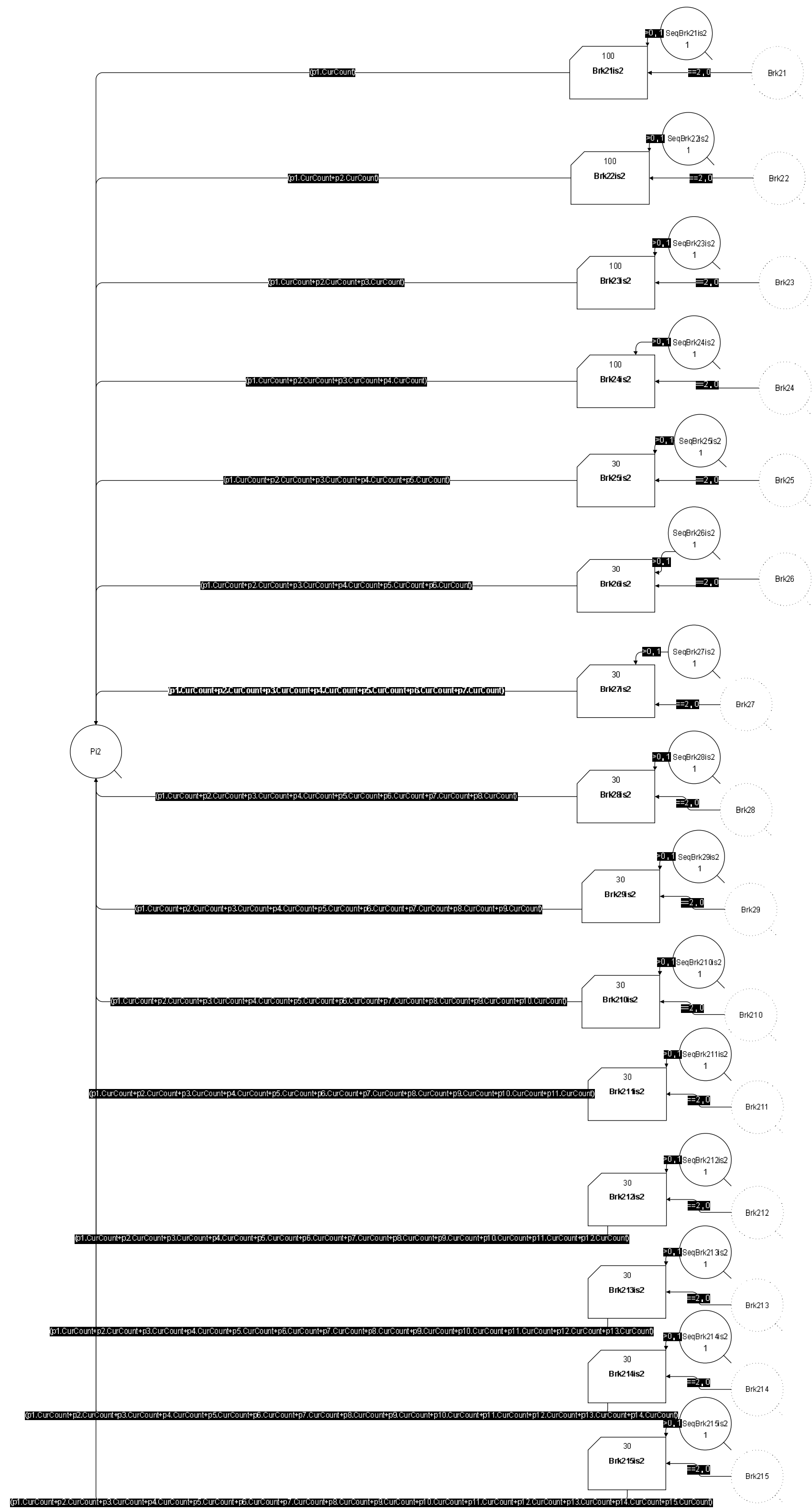

Pi4
check2111
sa2211641
s351p4
s5
Pi3
s35541p4
req221461
sa224561
s35521p4
check221461
s35561p4
CheckB3311
Seqsa3311is0
sa3311is0
sa3311
Bp2
Wsa3311is0
Not complete
B13311
B131311
Check221151
Seqsa221151s0
sa213is0
sa221151
MY
B2211513
B2211512
sa221151B
s4
Pi4
sa2215BLesPi2
req2215B
sa2215B3
s4Pi235
check2215B
s34567p4
req6612
sa6612
s234517p4
check6127
s234592p4
s3
s41Pi2345
check2215B
sa432123
s4327Lessp2
req432123
sa432124
s432123p2
check432123
s4321234p2


(p1.CurCount+(Bp.CurCount))*Perc<=(s1.CurCount+s2.CurCount+s3.CurCount)?1:2
>0,1
Seqsa333
1
CheckB3
50
sa333eqlzer
==0,0
sa333
==2,2
==1,1
>0,0
>0,1
Bp
B13
B131
HY
s3.CurCount
(p1.CurCount+(Bp.CurCount))-(s1.CurCount+s2.CurCount)
sa333
sa333B1
>0,0
s4
5
>0,0
>0,0
Pi4
50
sa333B1LesPi2
20
s4Pi2
sa3331B
s4.CurCount
==1,1
check333B
>0,1
req333B
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)*Perc<=(Pi4.CurCount)?1:2
>0,0
s5
>0,0
20
s5Lessp6
>0,0
Pi4
20
s5p62
sa44412
s5.CurCount
==1,1
check4422
>0,1
req4441
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=(Pi4.CurCount)?1:2
==2,2
20
s51p63
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
20
s41Pi2
==2,2
check333B
sa256
>0,0
s5
>0,0
20
s256Lessp2
>0,0
Pi3
20
s256p2
sa2561
s5.CurCount
==1,1
check256
>0,1
req256
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.CurC
==2,2
20
s2565p2
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)
(Pi4.CurCount)-(s1.CurCount+s2.CurCount+s3.CurCount)
20
s41Pi234
==2,2
check331B
sa43213
>0,0
s5
>0,0
20
s4321Lessp2
>0,0
Pi3
20
s43213p2
sa43212
s5.CurCount
==1,1
check4321
>0,1
req4321
1
(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount)*Perc<=Pi3.CurC
==2,2
20
s43212p2
Pi3.CurCount-(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount)

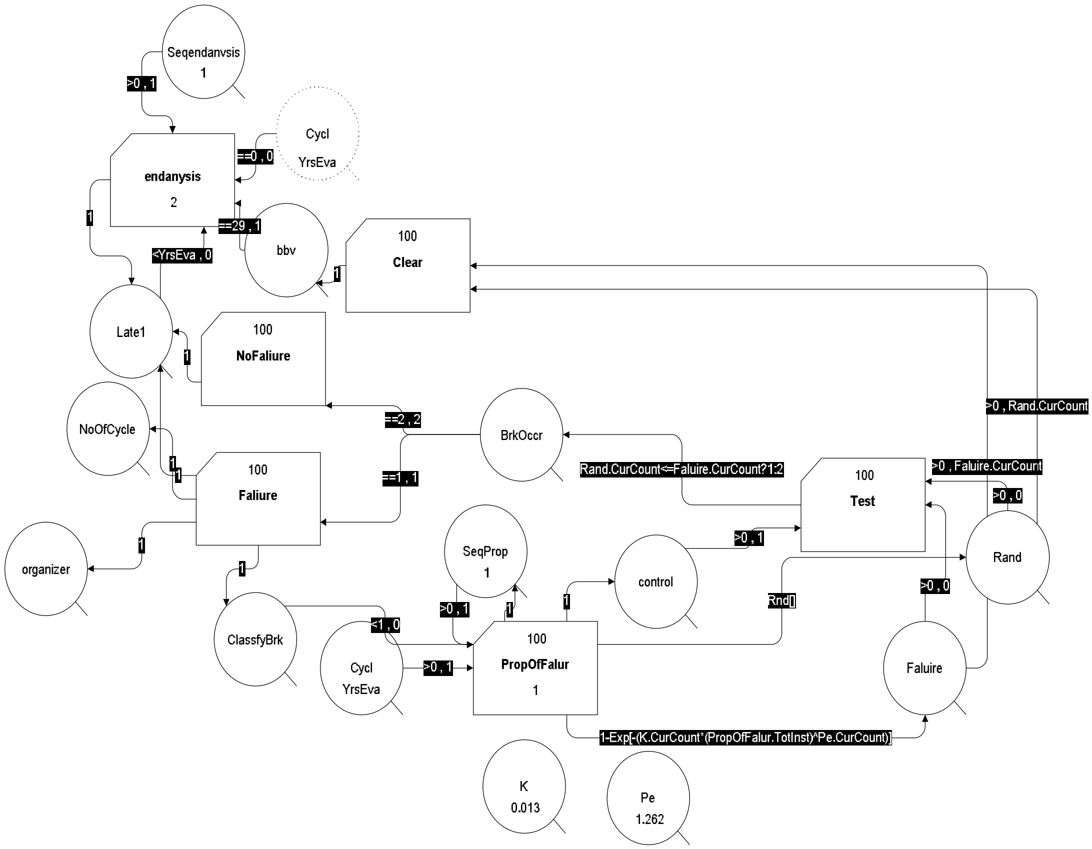

s1.CurCount*Perc<p1.CurCount?2:1
30
Brk11is1
==1,1
Brk11
Seqs1less
1
op1
>0,1
>0,1
s1.CurCount*Perc<(p1.CurCount+p2.CurCount)?2:1
1
30
s1Lessp2p3p4
CycNo2
>0,0
stequls1cor
30
Brk12is1
==1,1
Brk12
Brk13
>=YrsEva,0
>0,0
s1
Late1
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount)?2:1
==1,1
30
Brk13is1
Brk14
==1,1
30
Brk14s1
Brk15
==1,1
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount)?2:1
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount)?2:1
30
Brk15s1
Brk17
30
Brk16s1
==1,1
Brk16
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount)?2:1
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount+p7.CurCount)?2:1
==1,1
OrgLate2
1
>0,1
30
Brk17s1
Brk18
==1,1
30
Brk18s1
Brk19
>0,0
30
Late2
>0
Piq
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount+p7.CurCount+p8.CurCount)?2:1
s1.CurCount*Perc<(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount+p7.CurCount+p8.CurCount+p9.CurCount)?2:1

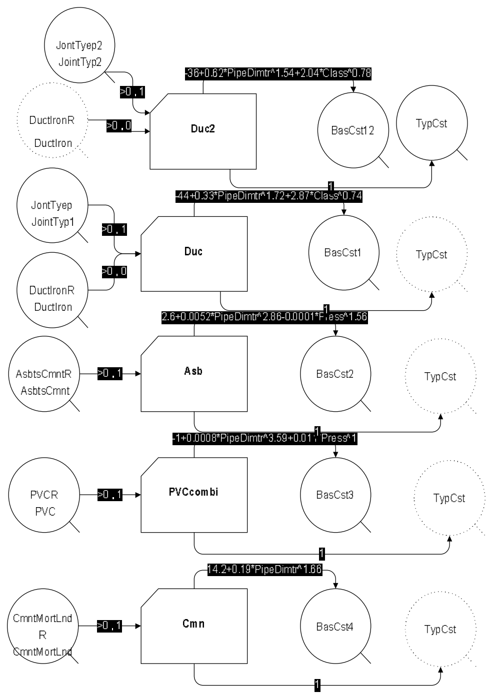

SeqBrk11is2
1
>0,1
30
Brk11is2
p1.CurCount
==2,0
Brk11
SeqBrk12is2
1
>0,1
30
Brk12is2
p1.CurCount+p2.CurCount
==2,0
Brk12
>0,1
SeqBrk13is2
1
30
Brk13is2
(p1.CurCount+p2.CurCount+p3.CurCount)
==2,0
Brk13
>0,1
SeqBrk14is2
1
30
Brk14is2
==2,0
Brk14
(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount)
Piq
SeqBrk15is2
1
>0,1
(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount)
30
Brk15is2
==2,0
Brk15
SeqBrk16is2
1
>0,1
30
Brk16is2
(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount)
==2,0
Brk16
SeqBrk17is2
1
>0,1
30
Brk17is2
(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount+p7.CurCount)
==2,0
Brk17
SeqBrk18is2
1
>0,1
30
Brk18is2
(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount+p7.CurCount+p8.CurCount)
Brk18
==2,0
SeqBrk19is2
1
>0,1
30
Brk19is2
(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount+p5.CurCount+p6.CurCount+p7.CurCount+p8.CurCount+p9.CurCount)
Brk19
==2,0



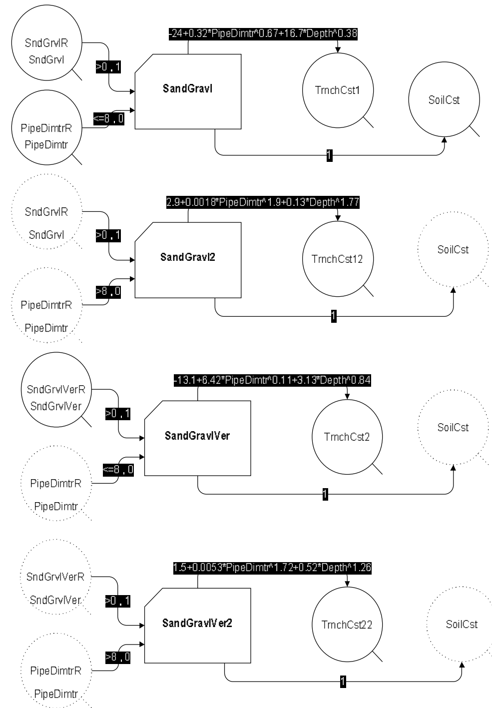


Pi2
Brk21is2
Brk22is2
Brk23is2
Brk24is2
Brk25is2
Brk26is2
Brk27is2
Brk28is2
Brk29is2
Brk210is2
Brk211is2
Brk212is2
Brk213is2
Brk214is2
Brk215is2
Brk21
Brk22
Brk23
Brk24
Brk25
Brk26
Brk27
Brk28
Brk29
Brk210
Brk211
Brk212
Brk213
Brk214
Brk215
SeqBrk21is2
(p1.CurCount)
(p1.CurCount+p2.CurCount)

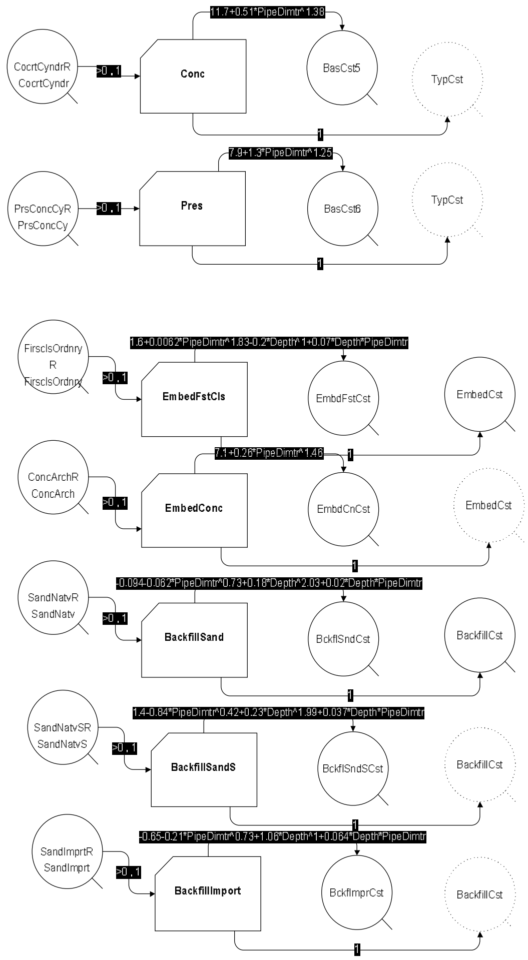

Seqendanvsis
1
>0 , 1
Cycl
YrsEva
==0 , 0
endanysis
2
==29 , 1
bbv
100
Clear
<YrsEva , 0
Late1
100
NoFaliure
NoOfCycle
BrkOccr
==2 , 2
>0 , Rand.CurCount
100
Faliure
==1 , 1
Rand.CurCount<=Faliure.CurCount?1:2
100
Test
>0 , Faliure.CurCount
>0 , 0
organizer
SeqProp
1
control
>0 , 1
Rand
Rnd[]
>0 , 0
ClassfyBrk
<1 , 0
>0 , 1
100
PropOfFalur
1
Cycl
YrsEva
>0 , 1
Faluire
1-Exp[-(K.CurCount*(PropOfFalur.TotInst)^Pe.CurCount)]
K
0.013
Pe
1.262

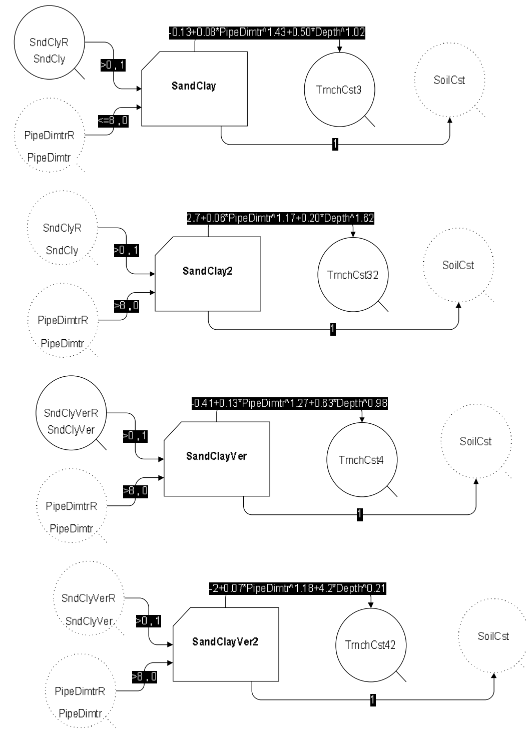


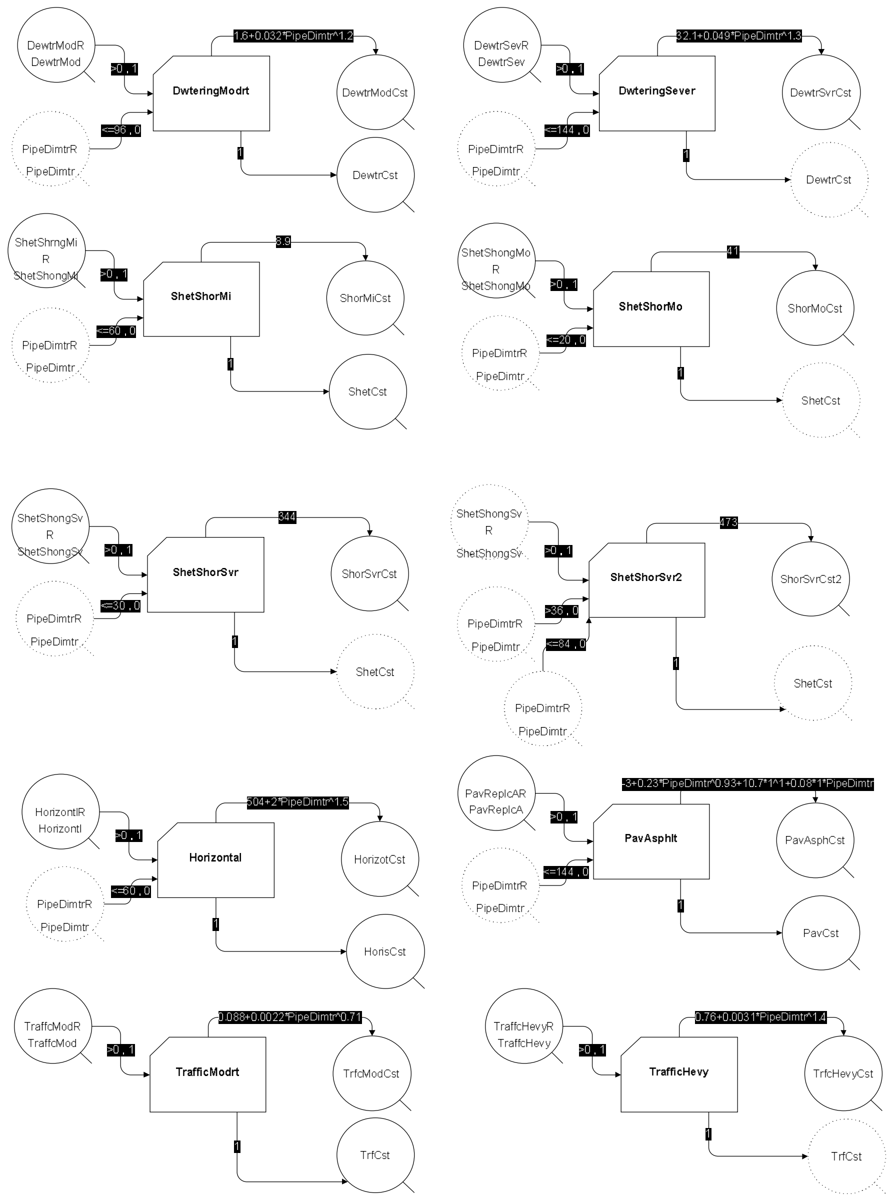
JontTyep2
JointTyp2
>0 , 1
DuctIronR
DuctIron
>0 , 0
-36+0.62*PipeDimtr^1.54+2.04*Class^0.78
Duc2
BasCst12
TypCst
1
JontTyep
JointTyp1
>0 , 1
DuctIronR
DuctIron
>0 , 0
-44+0.33*PipeDimtr^1.72+2.87*Class^0.74
Duc
BasCst1
TypCst
1
AsbtsCmntR
AsbtsCmnt
>0 , 1
2.6+0.0052*PipeDimtr^2.86-0.0001*Press^1.56
Asb
BasCst2
TypCst
1
PVCR
PVC
>0 , 1
-1+0.0008*PipeDimtr^3.59+0.01*Press^1
PVCcombi
BasCst3
TypCst
1
CmntMortLnd
R
CmntMortLnd
>0 , 1
14.2+0.19*PipeDimtr^1.66
Cmn
BasCst4
TypCst
1

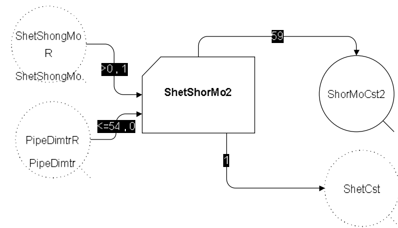


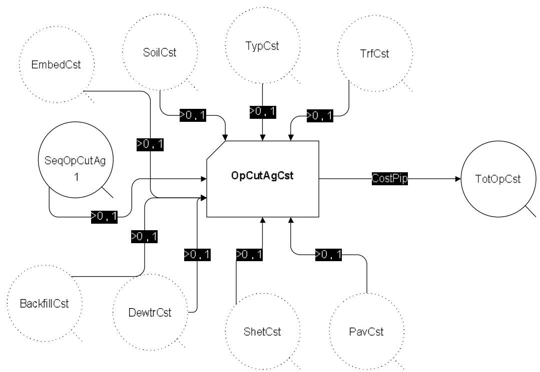
SndGrvlR
SndGrvl
>0 , 1
PipeDimtrR
PipeDimtr
<=8 , 0
-24+0.32*PipeDimtr^0.67+16.7*Depth^0.38
SandGravl
TrnchCst1
SoilCst
1
SndGrvlR
SndGrvl
>0 , 1
PipeDimtrR
PipeDimtr
>8 , 0
2.9+0.0018*PipeDimtr^1.9+0.13*Depth^1.77
SandGravl2
TrnchCst12
SoilCst
1
SndGrvlVerR
SndGrvlVer
>0 , 1
PipeDimtrR
PipeDimtr
<=8 , 0
-13.1+6.42*PipeDimtr^0.11+3.13*Depth^0.84
SandGravlVer
TrnchCst2
SoilCst
1
SndGrvlVerR
SndGrvlVer
>0 , 1
PipeDimtrR
PipeDimtr
>8 , 0
1.5+0.0053*PipeDimtr^1.72+0.52*Depth^1.26
SandGravlVer2
TrnchCst22
SoilCst
1

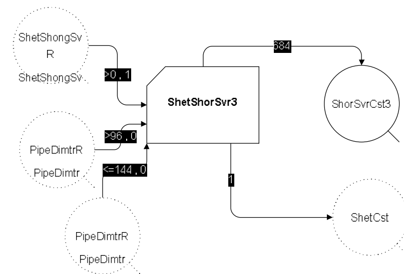

CocrtCyndrR
CocrtCyndr
>0 , 1
Conc
11.7+0.51*PipeDimtr^1.38
BasCst5
TypCst
1
PrsConcCyR
PrsConcCy
>0 , 1
Pres
7.9+1.3*PipeDimtr^1.25
BasCst6
TypCst
1
FirsclsOrdnry
R
FirsclsOrdnry
>0 , 1
EmbedFstCls
1.6+0.0062*PipeDimtr^1.83-0.2*Depth^1+0.07*Depth*PipeDimtr
EmbdFstCst
EmbedCst
1
ConcArchR
ConcArch
>0 , 1
EmbedConc
7.1+0.26*PipeDimtr^1.46
EmbdCnCst
EmbedCst
1
SandNatvR
SandNatv
>0 , 1
BackfillSand
-0.094-0.062*PipeDimtr^0.73+0.18*Depth^2.03+0.02*Depth*PipeDimtr
BckflSndCst
BackfillCst
1
SandNatvSR
SandNatvS
>0 , 1
BackfillSandS
1.4-0.84*PipeDimtr^0.42+0.23*Depth^1.99+0.037*Depth*PipeDimtr
BckflSndSCst
BackfillCst
1
SandImprtR
SandImprt
>0 , 1
BackfillImport
-0.65-0.21*PipeDimtr^0.73+1.06*Depth^1+0.064*Depth*PipeDimtr
BckflmprCst
BackfillCst
1

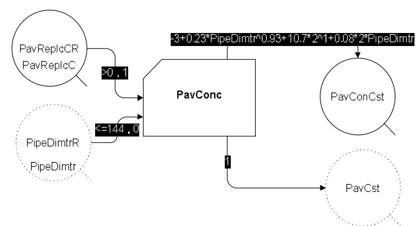

SndClyR
SndCly
>0 , 1
PipeDimtrR
PipeDimtr
<=8 , 0
SandClay
-0.13+0.08*PipeDimtr^1.43+0.50*Depth^1.02
TrnchCst3
SoilCst
1
SndClyR
SndCly
>0 , 1
PipeDimtrR
PipeDimtr
>8 , 0
SandClay2
2.7+0.06*PipeDimtr^1.17+0.20*Depth^1.62
TrnchCst32
SoilCst
1
SndClyVerR
SndClyVer
>0 , 1
PipeDimtrR
PipeDimtr
>8 , 0
SandClayVer
-0.41+0.13*PipeDimtr^1.27+0.63*Depth^0.98
TrnchCst4
SoilCst
1
SndClyVerR
SndClyVer
>0 , 1
PipeDimtrR
PipeDimtr
>8 , 0
SandClayVer2
-2+0.07*PipeDimtr^1.18+4.2*Depth^0.21
TrnchCst42
SoilCst
1

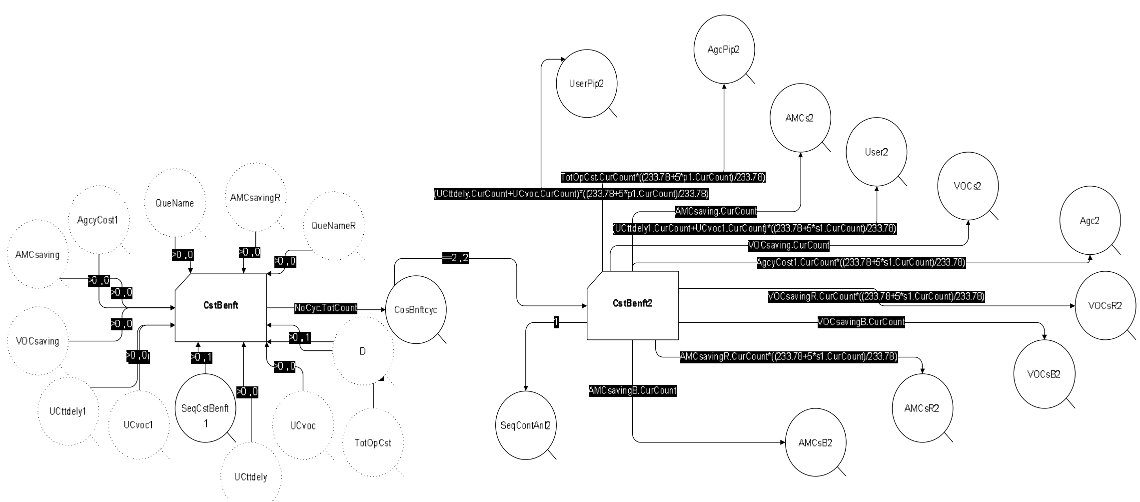

DewtrModR
DewtrMod
>0 , 1
PipeDimtrR
PipeDimtr
<=96 , 0
DwteringModrt
1.6+0.032*PipeDimtr^1.2
DewtrModCst
1
DewtrCst
DewtrSevR
DewtrSev
>0 , 1
PipeDimtrR
PipeDimtr
<=144 , 0
DwteringSever
32.1+0.049*PipeDimtr^1.3
DewtrSvrCst
1
DewtrCst
ShetShrngMi
R
ShetShongMi
>0 , 1
PipeDimtrR
PipeDimtr
<=60 , 0
ShetShorMi
8.9
ShorMiCst
1
ShetCst
ShetShongMo
R
ShetShongMo
>0 , 1
PipeDimtrR
PipeDimtr
<=20 , 0
ShetShorMo
41
ShorMoCst
1
ShetCst
ShetShongSv
R
ShetShongSv
>0 , 1
PipeDimtrR
PipeDimtr
<=30 , 0
ShetShorSvr
344
ShorSvrCst
1
ShetCst
ShetShongSv
R
ShetShongSv
>0 , 1
PipeDimtrR
PipeDimtr
>36 , 0
PipeDimtrR
PipeDimtr
<=84 , 0
ShetShorSvr2
473
ShorSvrCst2
1
ShetCst
HorizontlR
Horizontl
>0 , 1
PipeDimtrR
PipeDimtr
<=60 , 0
Horizontal
504+2*PipeDimtr^1.5
HorizotCst
1
HorisCst
PavReplcAR
PavReplcA
>0 , 1
PipeDimtrR
PipeDimtr
<=144 , 0
PavAsphlt
-3+0.23*PipeDimtr^0.93+10.7*1^1+0.08*1*PipeDimtr
PavAsphCst
1
PavCst
TraffcModR
TraffcMod
>0 , 1
TrafficModrt
0.088+0.0022*PipeDimtr^0.71
TrfcModCst
1
TrfCst
TraffcHevyR
TraffcHevy
>0 , 1
TrafficHevy
0.76+0.0031*PipeDimtr^1.4
TrfcHevyCst
1
TrfCst


ShetShongMo R
ShetShongMo.
>0, 1
PipeDimtrR
PipeDimtr
<=54, 0
ShetShorMo2
59
ShorMoCst2
1
ShetCst


EmbedCst
SoilCst
TypCst
TrfCst
>0, 1
>0, 1
>0, 1
>0, 1
SeqOpCutAg 1
>0, 1
OpCutAgCst
CostPip
TotOpCst
>0, 1
>0, 1
>0, 1
>0, 1
BackfillCst
DewtrCst
ShetCst
PavCst


ShetShongSv R
ShetShongSv
>0, 1
ShetShorSvr3
584
ShorSvrCst3
PipeDimtrR
PipeDimtr
>96, 0
<=144, 0
1
ShetCst
PipeDimtrR
PipeDimtr


PavReplcCR
PavReplcC
-3+0.23*PipeDimtr^0.93+10.7*2^1+0.08*2*PipeDimtr
>0, 1
PavConc
PavConCst
PipeDimtrR
PipeDimtr
<=144, 0
1
PavCst


UserPip2
AgcPip2
AMCs2
User2
VOCs2
Agc2
TotOpCst.CurCount*((233.78+5*p1.CurCount)/233.78)
(UCttdely.CurCount+UCvoc.CurCount)*((233.78+5*p1.CurCount)/233.78)
AMCsaving.CurCount
(UCttdely1.CurCount+UCvoc1.CurCount)*((233.78+5*s1.CurCount)/233.78)
VOCsaving.CurCount
AgcyCost1.CurCount*((233.78+5*s1.CurCount)/233.78)
VOCsavingR.CurCount*((233.78+5*s1.CurCount)/233.78)
VOCsavingB.CurCount
AMCsavingR.CurCount*((233.78+5*s1.CurCount)/233.78)
AMCsavingB.CurCount
AMCsaving
AgcyCost1
QueName
AMCsavingR
QueNameR
VOCsaving
>0, 0
>0, 0
>0, 0
>0, 0
>0, 0
>0, 0
>0, 0
CstBenft
NoCycTotCount
CosBnftcyc
==2, 2
CstBenft2
1
>0, 1
>0, 1
>0, 0
>0, 0
D
UCttdely1
UCvoc1
SeqCstBenft 1
UCvoc
TotOpCst
UCttdely
SeqContAnt2
AMCsB2
AMCsR2
VOCsB2
VOCsR2

Cpav	Cost Of Pavement	((Agc.CurCount+User.CurCount)+(((Agc2.CurCount+User2.CurCount)*((1/ (1+IntrstRate)^s1.CurCount)))+((Agc3.CurCount+User3.CurCount)*((1/ (1+IntrstRate)^(s1.CurCount+s2.CurCount))))+((Agc4.CurCount+User4.CurCount)*((1/ (1+IntrstRate)^(s1.CurCount+s2.CurCount+s3.CurCount))))+((Agc5.CurCount+User5.CurCount)*((1/ (1+IntrstRate)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount))))))*((IntrstRate*(IntrstRate+1)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount))/ ((((1+IntrstRate)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount))-1)))

CostCrdPip	Cost of pipe when coordenatio	((TotOpCst.CurCount*PrjectLngh+PipUsrCst)+(((TotOpCst.CurCount*Cord3Not.CurCount+TotOpCstC.CurCount*Cord3cost.CurCount)*((233.78+5*(p1.CurCount))/ 233.78)*PrjectLngh+(PipUsrCst*Cord3Not.CurCount+PipUsrCstC*Cord3cost.CurCount)*((233.78+5*(p1.CurCount))/233.78))*T1f.CurCount*((1/ (1+IntrstRate)^p1.CurCount)))+(((TotOpCst.CurCount*Cord2Not.CurCount+TotOpCstC.CurCount*Cord2cost.CurCount)*((233.78+5*(p1.CurCount))/ 233.78)*PrjectLngh+(PipUsrCst*Cord2Not.CurCount+PipUsrCstC*Cord2cost.CurCount))*((233.78+5*(p1.CurCount))/233.78)*T2f.CurCount*((1/ (1+IntrstRate)^(p1.CurCount+p2.CurCount)))))*((IntrstRate*(IntrstRate+1)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount))/ ((((1+IntrstRate)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount))-1)))

Bpav	Benft Pavmnt	((AMCsR.CurCount+VOCsR.CurCount)+(AMCsR2.CurCount+VOCsR2.CurCount)+(AMCsR3.CurCount+VOCsR3.CurCount)+(AMCsR4.CurCount+VOCsR4.CurCount)+(AMCsR5.CurCount+VOCsR5.CurCount))

PIPEbeneft2	pipe benet inflatiion	(((TotOpCst.CurCount*PrjectLngh-(TotOpCst.CurCount*PrjectLngh*(((wrstt/ ((1+IntrstRate)^p1.CurCount))-wrst)/(bst-wrst))))*(1/ ((1+IntrstRate)^p1.CurCount)))+((TotOpCst.CurCount*((233.78+5*(p1.CurCount))/ 233.78)*T1f.CurCount*PrjectLngh)-((TotOpCst.CurCount*((233.78+5*(p1.CurCount))/ 233.78)*T1f.CurCount*PrjectLngh)*((((wrstt/((1+IntrstRate)^p2.CurCount))-wrst)/(bst-wrst)))))*(1/ ((1+IntrstRate)^(p1.CurCount+p2.CurCount)))+((TotOpCst.CurCount*((233.78+5*(p1.CurCount+p2.CurCount))/233.78)*T2f.CurCount*PrjectLngh)-((TotOpCst.CurCount*((233.78+5*(p1.CurCount+p2.CurCount))/ 233.78)*T2f.CurCount*PrjectLngh)*((((wrstt/((1+IntrstRate)^p3.CurCount))-wrst)/(bst-wrst)))))*(1/ ((1+IntrstRate)^(p1.CurCount+p2.CurCount+p3.CurCount)))+((TotOpCst.CurCount*((233.78+5*(p1.CurCount+p2.CurCount+p3.CurCount))/233.78)*T3f.CurCount*PrjectLngh)- ((TotOpCst.CurCount*((233.78+5*(p1.CurCount+p2.CurCount+p3.CurCount))/ 233.78)*T3f.CurCount*PrjectLngh)*((((wrstt/((1+IntrstRate)^p4.CurCount))-wrst)/(bst-wrst)))))*(1/ ((1+IntrstRate)^(p1.CurCount+p2.CurCount+p3.CurCount+p4.CurCount))))*((IntrstRate*(IntrstRate+1)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount))/ ((((1+IntrstRate)^(s1.CurCount+s2.CurCount+s3.CurCount+s4.CurCount+s5.CurCount))-1)))

BCC	B/C ratio	(PIPEbeneft2+Bpav)/(CostCrdPip+Cpav)