Probabilistic Life Cycle Assessment of Safety Valves

by

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Author's Declaration

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

I understand that my thesis may be made electronically available to the public.

Abstract

The objective of this this thesis is to develop a probabilistic model for assessing the life cycle performance of safety valves used in the nuclear piping system. The life cycle performance is quantified in terms of reliability and life cycle cost in a given operating interval of the plant. A key input to the probabilistic lifecycle analysis is the lifetime distribution of the component in question. The second important element is the estimation of costs of inspection and in-service testing of components as well as costs of repairs and replacement of failed components. Based on this information, the life cycle analysis aims to predict the reliability and expected cost of operating a component in a future time interval. This study illustrates how to develop methods and algorithms for probabilistic assessment of the life cycle of safety valves used in the nuclear piping system.

For statistically estimated parameters of the probability distributions of lifetime and various costs, historical operating data are required. This study uses about 20 years of historical data obtained from a group of temperature control valves used in the moderator system of a reactor. A maximum likelihood-based method is developed to estimate parameters of the lifetime distribution of a valve. The lifetime is defined as the time of first leakage in the valve since the time of installation. The ML method is based to consider complete and censored lifetime information. The distribution of repairs cost is also estimated by the ML method. The proposed method is applied to predict reliability and life cycle cost for various operating interval. This model can also be used to optimize the overhaul interval of the valve.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Professor Mahesh D. Pandey, for giving me the opportunity to conduct this study, for the many insightful discussions and his guidance throughout the years.

A special thanks goes to my colleagues Indranil Hazra, Noldainerick Manzana and other graduate students, friends and faculty staff from University of Waterloo for their continuous support.

I would also like to thank all my housemates, who just like that became my family. They always kept me motivated and played a pivotal role in providing me a home away from home.

Finally, I would also like to thank my parents, my cousins and my friends back home for believing in me and supporting me through thick and thin.

Dedication

To My Family and Friends

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Acronyms

TCV or TC Valve	Temperature Control Valves
OPEX	Operating Experience
CV	Copes Vulcan Manufacturer of CV600 TCV Valves
PDF	Probability Distribution Function
CDF	Cumulative Distribution Function
MTTF	Mean Time to Failure
MLE or ML method	Maximum Likelihood Estimation
WO	Work Order
OH	Overhaul
SD	Standard Deviation
LL	Log-likelihood

Chapter 1

Introduction

1.1 General

This thesis presents the engineering applications of equipment lifecycle data analysis. This chapter will first discuss the problem statement and the associated key elements. It is then followed by a background of the industrial equipment and its operation which gives a clear picture of the type of system being analyzed. The maintenance activities and their duration intervals are discussed. The chapter then concludes with an organization of rest of the thesis.

1.2 Background & Motivation

Incredible effort was dedicated by the industry in maintaining the equipment and documenting their operating experience for the past 20 years. These safety valves have been operating continuously to maximize plant efficiency. Being in the mid-life refurbishment cycle, the agency is replacing major components to keep the plant operating for the next thirty years. As a part of their regular preventive maintenance, the plant overhauled these safety valves at every 8 year interval. The reliability of these equipment however has arisen a question if this overhaul interval could be extended. This extension could result in major cost savings since the overhauls cost around $80k- $100k per valve. The past operating experience of the valve could help build the reliability basis for the decision of overhaul extension. A similar study was implemented to model the optimal time between surveillance inspections of safety relief valves in [1]. The maintenance activity of these equipment and corresponding cost involved with each task are assessed as an integral part of this thesis to project a complete picture on the equipment performance and reliability for the nuclear power generation facility.

1.3 Problem Statement

The primary goal is to develop a probabilistic lifecycle cost analysis model for a safety valve and predict the total cost of operation for the next thirty years. The lifecycle cost analysis requires finding out the lifetime distribution, the critical failure mode and the corresponding cost associated. Historical data for failures acts as the input for estimating the parameters of lifetime distribution. This data can also be used to figure out the most prevalent kind of failure in the equipment, which are leaks in the case study that is analyzed in this thesis. The probabilistic lifecycle cost model could help in predicting the expected number of failures and the expected cost of repairs in a future overhaul interval. An overhaul interval is the operating interval between two successive planned replacements of the component. This replacement activity is expensive but necessary to keep the system functioning reliably till the end of plant life. The objective of this lifecycle model would be to gauge the optimum overhaul interval for these valves. The duration of optimum overhaul interval would also be based on predicting the reliability, i.e., the probability of no leakage over a future interval.

1.4 Temperature Control Valves

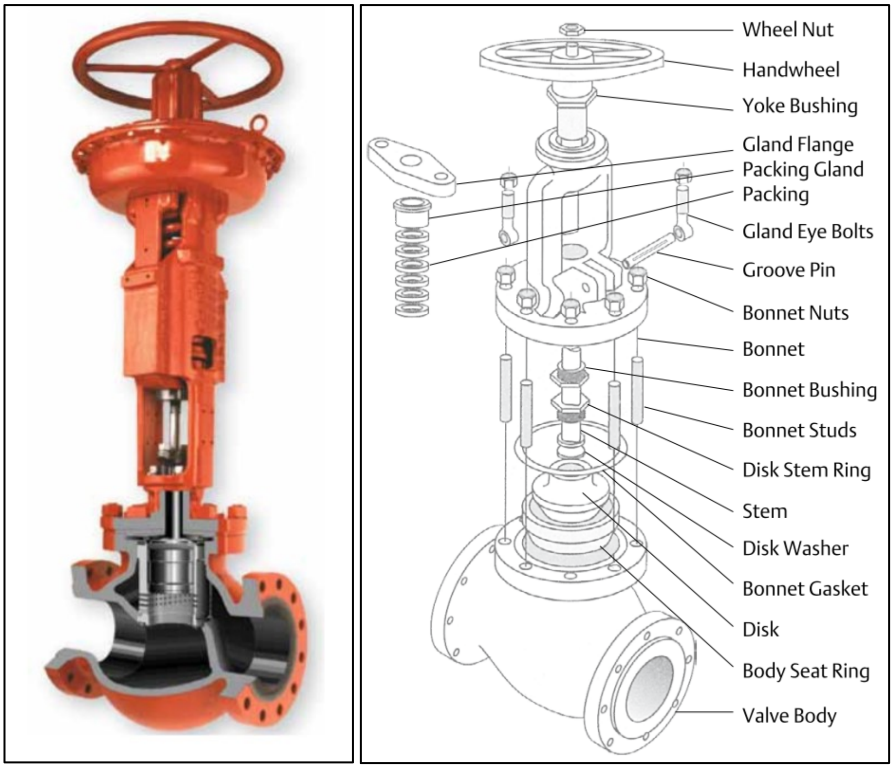

Figure 1-1: TCV - Copes Vulcan 600 schematic with internals

The 24 TC Valves analyzed in the case study are globe valves manufactured by SPX (Copes Vulcan) and Emerson (Fisher). They are plug and needle type with globe and angle configuration, complete with pneumatic actuators [2]. To accommodate wide variety of trim designs without compromising with recovery, the valve body design has a bowl with significant capacity and offers high structural robustness. The high performance trim designs which this valve is able to accommodate meet many critical service and severe duty constraints [3]. This is the preferred style of valve for applications in pump recirculation, feedwater control and feedwater start-up, cavitating service, critical pressure drop gas and steam service, and any potentially noisy or vibration-prone service[3]. All valve components, except elastomers and lubricants shall be suitable for at least 40 years of service when exposed to the specified conditions as per EPRI guideline 1022959.

1.4.1 Operation

The control valves regulate the fluid flow rate based on the closure member location when acted upon with a set force from the actuator. According to [4], to perform this function/purpose, the valve must:

- Contain the fluid without external leakage
- Have adequate capacity for the intended service
- Withstand the erosive, corrosive, and temperature influences of the process,
- Incorporate appropriate end connections to mate with adjacent pipelines and actuator attachment means to permit transmission of actuator thrust to the valve stem or shaft. [4]

1.4.2 Valve Notation

There are 4 reactor units in the power plant i.e. U1, U2, U3 and U4. Each unit comprises of 6 valves, two of each TCV1, TCV2 and TCV3.
TCV1 and TCV2 are 18" CV600 valves while TCV3 are 8" CV600 valves. In the rest of thesis, TCV1-2 would refer to the complete fleet of 16 valves (TCV1 and TCV2 in all four units) while TCV3 will refer to the remaining 8 valves. In the operating history of 20 years, some of the TCV3 valves were replaced from CV600 to Fisher657.

1.4.3 Type of Repairs

The operating life of each valve behaves similar to a repairable system model. The primary mode of failure for these safety valves are leaks 3.3.3. These leaks may be minor or major depending upon the intensity of repair involved. Since the historical data consists of cost associated with repairs as well, the major repairs are defined by the repairs costing >$10,000 while the minor repairs incur expenses <$10,000. The type of repairs, their frequency, and the number of repairs occurring each year from the data are discussed in detail in 3.3.3.

1.4.4 Inspection activities

Periodic maintenance of the safety valves are performed to keep in check the performance of the valves. These activities include in-service checks and tests to ensure the valves are operating with required efficiency. These activities contribute to the deterministic elements in the lifecycle model. Examples of inspection activities are depicted in Table 3-2. The annual frequency of these regular maintenance activities is tabulated herewith:

Table 1-1: Inspection interval for TCVs

Valve	Inspection Interval (years)
TCV1-2	3.03
TCV3	2.78

1.4.5 Overhaul Interval

Overhaul activities represent the replacement of the whole equipment. These are planned maintenance activities and also contribute to the deterministic aspects of the lifecycle cost model. These replacements significantly contribute to the operating cost of the valves. One of the objectives of the lifecycle model derived in this document is to optimize these intervals to reduce the cost of operation without compromising with performance. Historical data of past 20 years provides the range overhaul intervals planned to keep the system running with optimum reliability. This interval generally varied from 7 years to 10 years with a few exceptions. The average overhaul interval, however, is tabulated below for each valve type.

Table 1-2: Current Overhaul Interval Duration

Valve	Overhaul Interval (years)
TCV1-2	8.4
TCV3	6.6

1.5 Methodology

The probabilistic lifecycle cost assessment is performed with reference to the operating activities of a safety valve used as a case study in this document. This assessment involves modelling and analysis. The lifecycle model takes inputs from the various contributing inputs to the cost and life of the system and then represents the final output in form of an equation or a simulated model [5]. The resulting model is then analyzed to determine the operating costs for future time intervals. The model can also be used to analyze the various maintenance aspects of the equipment, like determining the optimum overhaul interval and the regular inspection frequency

The lifecycle model discussed in this thesis is based on theory of repairable systems. The models included in this theory are based on stochastic point process models discussed in Chapter 2.

The number of failures are determined from the point process models. The other inputs are the operating costs which are derived from different cost distributions depending on the maintenance activities. The figure below depicts the inputs to the lifecycle model.

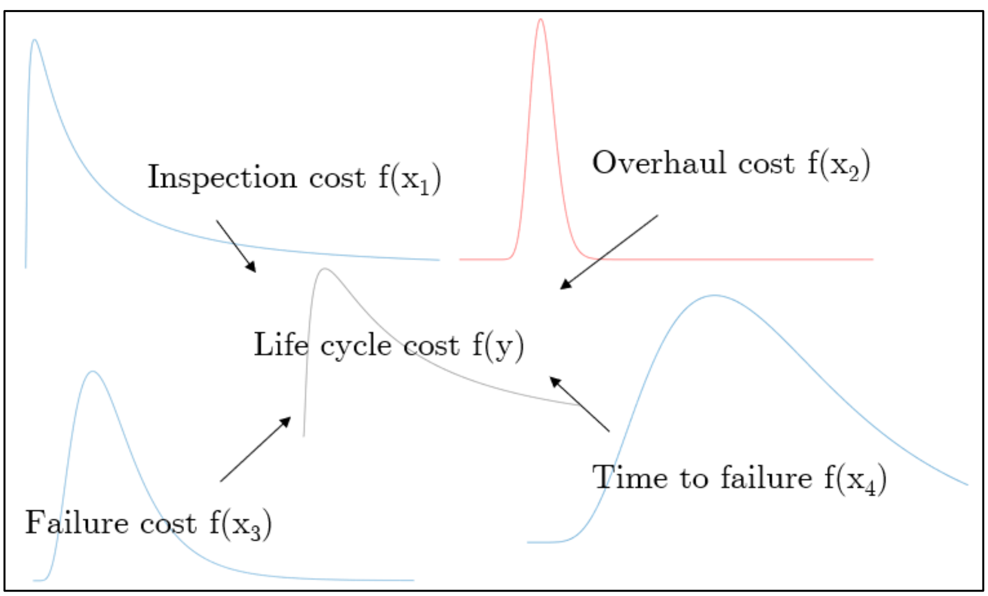

Figure 1-2: Inputs to Life cycle cost model of an equipment

The inspections and overhaul tasks represent the deterministic cost elements while the occurrences of failures represent the probabilistic cost elements. Finally, the total operational cost is simulated, with all these cost elements used as inputs. In this total cost model, the overhaul interval is kept variable to determine the how the total cost and reliability of the component changes as the overhaul interval is increased/decreased.

1.6 Stochastic process Model

Renewal Process

A series of strictly increasing sequence of random real numbers represent a simple point process. The times $S_1, S_2, \ldots S_n$ are randomly distributed in the interval $(0, t]$ representing the time to events (arrival times) and $T_1, T_2 \ldots . T_n$ are time between events (inter-arrival times). A point process is "renewal" process when the inter-arrival times form an independent and identically distributed, non-negative sequence of random variables [6]. Shown below in Figure 1-3 is a schematic of this process.

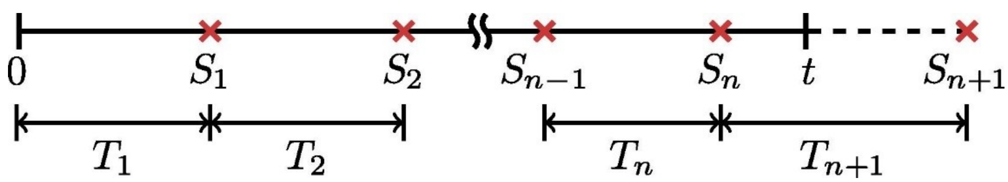

Figure 1-3: A schematic of renewal process [6]

If these inter-arrival times follow an exponential distribution, we obtain the well-known homogenous Poisson process. The ROCOF or the rate of occurrence of failures for the HPP model remains constant with respect to time.

Minimal Repair model

In this repairable system model, on occurrence of a leak, the system could be restored to operating condition by some process other than replacement of the entire system [7]. Definition 21 in [7] states that "*minimal repair means that the repair done on a system leaves the system in exactly the same condition as it was just before the failure*". Non-Homogenous Poisson Process (NHPP) is the most commonly used stochastic process for modelling the entire lifecycle of a complex repairable system [8]. Unlike the previous model (HPP), the inter-arrival times in this process are neither independent nor identically distributed. Contrary to the ordinary renewal process, the failures (events) which do not bring the equipment to “as good as new” condition, such as minor leaks in the safety valves could also be modelled using the non-homogenous Poisson process.

1.7 Objectives and Organization of Thesis

The main objective of this document is to present accurate distribution models for predicting reliability of TCVs. Life-cycle cost analysis for TCVs is performed to provide a cost-optimized maintenance cycle for the remaining plant uptime.

Chapter 1 provides the general introduction to the problem statement followed by the methodology to tackle the problem. The safety valves analyzed further in this document are introduced here and the maintenance activities performed to ensure their efficient performance are discussed. Finally, the mathematical point process models are introduced which would be discussed in detail in the next chapter. The basic concepts used in these models with necessary formulations for modelling, estimation and analysis. After the literature review of necessary concepts and background, Chapter 3 recapitulates the 20 year OPEX history of TCVs, providing metrics and visual illustrations depicting maintenance activities and their frequency for all 24 TCVs. Chapter 4 performs life-cycle cost analysis for the operating life of the TCVs, providing a suitable operating cost model for the equipment. Chapter 5 discusses the observations from the model and the reliability results. Chapter 6 gives some concluding remarks and recommendations on maintenance cycles for the equipment.

Chapter 2

Probabilistic Life-Cycle Cost Methodology

2.1 Elements of life-cycle cost analysis

To get an integrated perspective towards maintainability, reliability and logistic support, we need a better angle to look at the operational lifetime. The life cycle cost analysis provides a meaningful approach towards this agenda. A life cycle cost analysis compares initial, maintenance, repair, and operating costs over the life of the equipment. It is a valuable assessment that helps industries build and maintain their equipment as assets and not commodities. The sketch in Figure 2-1 gives a proposed valve lifecycle with an overhaul interval of nine years, planned inspection every three years and randomly occurring failure events (leaks).

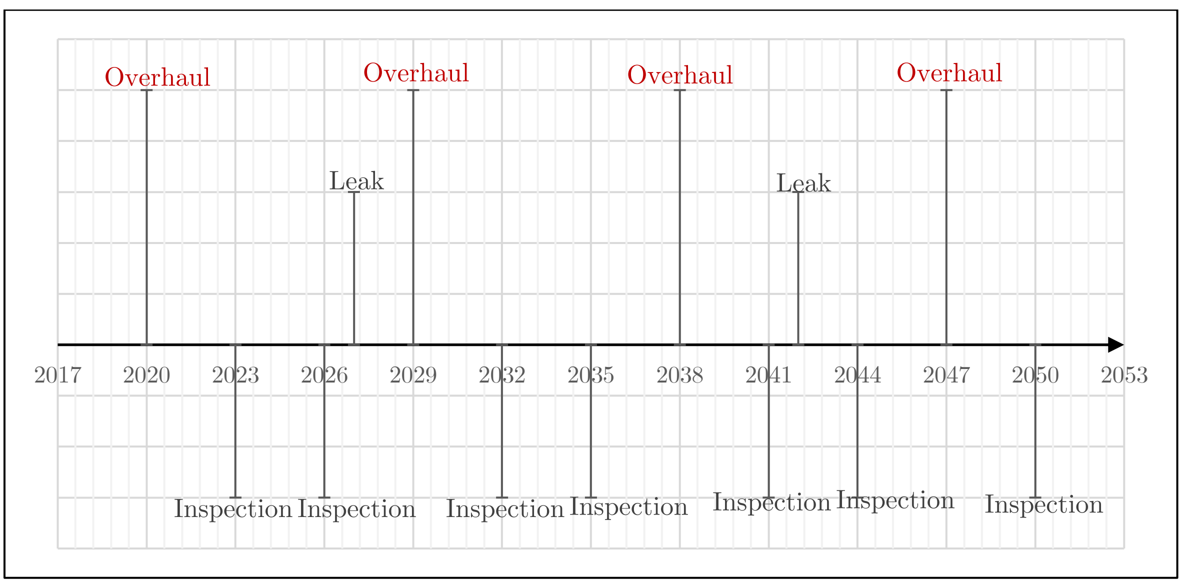

Figure 2-1: Lifecycle of a typical valve

This chapter first discusses the concept of lifetime distribution based on parametric distributions Using the parametric distributions, the mean and median lifetimes of an equipment are discussed. The methodology for applying the historical data of maintenance cost in the analysis using parametric distribution is then discussed. Then the mathematical model for repairable systems is formulated. This model is intended to provide the distribution of occurrence of random failures. Afterwards, statistical analysis to estimate the parameters for equipment life and operation cost is discussed. The estimated parameters also help in determining the future reliability and the probability of first major or minor leak. Finally, the formulation for total lifecycle cost using monte carlo simulation with inputs from different probabilistic and deterministic elements is then presented.

2.2 Model Inputs

Accidents and unexpected hazards are analyzed in the probabilistic part. The occurrence of leaks are assumed to be randomly distributed events and to model the lifecycle cost, we require the following inputs:

2.2.1 Lifetime Distribution

The first input for modelling is finding out the lifetime distribution of the component. Parametric distributions like Weibull and lognormal distributions provide a great variety of shapes for product life modelling. The probability of first occurrence of a leak within the given overhaul interval can be determined from the estimated parameters of the lifetime distribution. Consider the random variable X is the probability model consisting of outcomes and corresponding probabilities [9]. A continuous distribution with probability density $f(x)$ where $f(x) \geq 0$ for all x is the mathematical model consisting of relative frequencies for population histogram summing up to unity [9]. The mean of X is given by the expected value μ;[10]

$$\mu = E(X) = \int_{-\infty}^{\infty} x f(x) dx \tag{1}$$

For a theoretical life distribution, μ defines the mean time to failure or the expected life for the component. However, the 50% point, also called the median is commonly used as "typical life" of the component. It represents the age when half of the population fail before that age and the other half survives. If $F(x)$ is the cumulative distribution for the continuous probability distribution $f(x)$, and $100P$ is the $100P$th percentile point x_P of that distribution then P is the solution of the equation;

$$P = F(x_P) \tag{2}$$

Similar components subjected to similar environments may fail at different unpredictable times. Waloddi Weibull (1951) popularized the use of Weibull distribution among engineers for its great variety of shapes and empirically fits many kinds of data. Further details on the Weibull distribution could be referenced from [9]. It is described by;

$$f(x;\theta,\beta) = \frac{\beta}{\theta^{\beta}} x^{\beta-1} e^{-(\frac{x}{\theta})^{\beta}} \tag{3}$$

Where β and θ are shape and scale parameters respectively and take strictly positive values.

The parameter θ is also referred to as the characteristic life and is always $100 \times (1 - e^{-1})$ or 63.2th percentile. When $\beta = 1$, Weibull distribution becomes the exponential distribution which used to be widely used for life distribution.

The exponential and gamma distributions play an important role in reliability problems. Time to failure of equipment are often nicely modeled and predicted by exponential distributions [10]. Given the parameters β and θ the gamma distribution is given by;

$$f(x;\theta,\beta) = \begin{cases} \dfrac{1}{\theta^{\beta}\Gamma(\beta)} x^{\beta-1} e^{-\frac{x}{\theta}}, & x > 0 \\ 0, & elsewhere \end{cases} \tag{4}$$

where $\beta > 0$ and $\theta > 0$. The special case of gamma distribution in which $\beta = 1$ is called the exponential distribution;

$$f(x;\beta) = \begin{cases} \dfrac{1}{\theta} e^{-\frac{x}{\theta}}, & x > 0 \\ 0, & elsewhere \end{cases} \tag{5}$$

2.2.2 Cost of Maintenance

The second input to the lifecycle model is the cost of maintenance activities. This lifecycle cost comprises of deterministic and probabilistic elements. Regular maintenance activities may include inspection cost, labor cost, fuel cost etc. These fall under deterministic cost elements. The occurrence of a failure such as a leak and the corresponding corrective maintenance activities contribute to the probabilistic cost elements.

The probabilistic cost of repairs for the faults can be determined by estimating the parameters for failure cost distribution, similar to finding out the lifetime distribution of the component.

2.3 Modelling the Equipment Reliability

A repairable system can be restored to working condition on the occurrence of a failure by performing a repair. Based on operating experience, safety valves belong to the category of repairable systems. The equipment reliability for these systems is best modelled through the utilization of stochastic point processes.

Stochastic Point Process

A stochastic point process is a mathematical model for a physical phenomenon characterized by highly localized events distributed randomly in a continuum [11].The highly localized events are failures and the continuum is time, when the stochastic point process is applied to repairable systems. The repair times are assumed to be negligible and the system is operated at all possible times. When the counting of failures is stopped at a particular instant, it is referred to as a time-truncated process.

The two main stochastic point processes covered in this thesis and applied to this repairable system are categorized on the basis of type of repair performed.

- Renewal Process – (repaired to as good as new condition)
- Non-homogenous Poisson Process – (repaired to as bad as old condition)

2.3.1 Renewal Process

In this process model, the system after repairs is restored to as good as new condition. The time to failure data is independently and identically distributed. In Renewal process approach the time to first failure is assumed to be valid for every subsequent failure of the component [5].

HPP being the subset of RP is the simplest one wherein the time between successive failures follow IID exponential random variables, with constant failure rate, capable of being estimated fairly easily. An attempt to use HPP to analyze the entire failure history of steam-turbine generating units was done by Tan et al [8].

The counting variable $N(t)$ for the failure point process includes the number of failures in the interval [0,t) If expected number of failures is absolutely continuous and given by $E[N(t)]$, then the time rate of change of expected number of failures (ROCOF) is its derivative w.r.t time represented by $\lambda(t)$. For the system where the component is replaced every time a fault occurs, $\lambda(t)$ is the conditional probability of first failure.

For the homogenous Poisson process, the defining conditions for counting $N(t)$ are:

- $N(0) = 0$;
- $N(t), t \geq 0$ has independent increments
- $\lambda(t) = \lambda$; i.e. the ROCOF is constant w.r.t time
- The mean or expected number of failures are given by

$$E[N(t)] = \lambda t \tag{6}$$

- The $(n > 0)$ number of failures in an interval $t_i - t_{i-1} = t_{di}$ are distributed with mean λt_{di} such that the probability mass function is given by;

$$P(N(t_{di}), \lambda t_{di}) = \frac{(\lambda t_{di})^n e^{-\lambda t_{di}}}{n!} \tag{7}$$

The is reliability defined by the occurrence of 0 failures in this interval. Hence, if $n = 0$, and λ is constant then the expression for reliability is such that;

$$R(t_{di}, \lambda t_{di}) = e^{-\lambda t_{di}} \tag{8}$$

2.3.2 Minimal Repair Process

Non-homogenous Poisson Process is the most common stochastic point process used for modelling the life cycle of complex systems.

When the ROCOF varies with time, the Poisson distribution has the mean defined by;

$$v(t) = \int_{t_{i-1}}^{t_i} \lambda(t)dt \tag{9}$$

Which gives the event distribution as;

$$P(N(t_{di}), v(t)) = \frac{(v(t))^n e^{-v(t)}}{n!} \tag{10}$$

The expression for reliability is given by;

$$R(t_{di}, v(t)) = e^{-v(t)} \tag{11}$$

This model is applicable to cases wherein the minimal repair corrective measures are taken to ensure the operation of the equipment in case of any failures. The repair should return the equipment back to the condition as it was in just before the failure. Therefore, the ROCOF remains continuous and non-independent in this case.

The most common form for ROCOF followed for NHPP model is the "power law" model. The rate of occurrence of failure for power law is given by;

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \tag{12}$$

The parameter β defines how the system improves or degrades over time. If $\beta < 1$, the ROCOF is decreasing the system tends to be improving, otherwise when $\beta > 1$, the system deteriorates over time. If $\beta = 1$, the ROCOF becomes

$$\lambda(t) = \frac{1}{\theta} \tag{13}$$

Which is independent of t and hence is constant w.r.t time as per HPP assumption in 2.3.1. The expected number of failures are for NHPP model is given by;

$$E[N(t)] = \nu(t) = \left(\frac{t}{\theta}\right)^{\beta} \tag{14}$$

The main objective from the process models is to obtain the above mentioned expected number of failures for a future time interval. This result is important to obtain the expected cost of failures. However, statistical estimation of the parameters for each model is necessary to figure out these results. The procedure for parameter estimation is described below.

2.4 Statistical Estimation

2.4.1 MLE

To compute the parameters for the lifetime distributions in 2.2.1, in general, the Maximum Likelihood Estimation is used. The Likelihood factor for a two-parameter distribution can be described by the following equation[12]:

$$L(t_1, t_2, \dots . t_n; \theta, \beta) = \prod_{i=1}^{n} f(t_i; \theta, \beta) \tag{15}$$

Censoring is used to describe a type of incomplete data. In most applications of survival analysis, the random variable is the time to some event such as a fault. A visualized depiction of complete lifetime and right censored lifetime can be observed in the following figure.

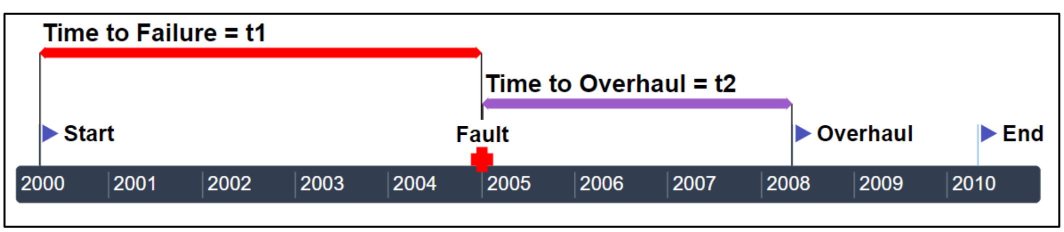

Figure 2-2: Right Censored and Complete Lifetimes

In the above figure, t1 is referred to as complete lifetime and t2 is referred to as right censored lifetime. It is assumed that after the failure at t1, the valve is repaired to as good as new functioning.

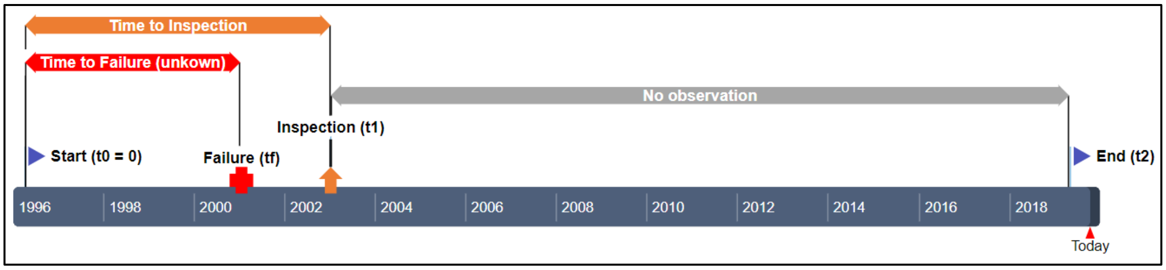

Figure 2-3: Interval Censored Lifetime

In the event of interval censored lifetimes, a failure happens at a certain point in the lifetime of the valve, but it is not detected until inspection is carried out. In the above figure, t_1 is the time to inspection and time to failure is unknown.

If the function has k right censored lifetimes, m interval censored lifetimes and n is the total number of complete lifetimes, then the likelihood function changes to

$$L(t_1, t_2, \ldots . t_n, r_1, r_2, \ldots . r_{k,}, s_1, s_2, \ldots . s_{p,}; \theta, \beta) = \prod_{i=1}^{n} f(t_i; \theta, \beta) \prod_{i=1}^{k} R(r_i; \theta, \beta) \prod_{i=1}^{p} F(s_i; \theta, \beta) \quad (16)$$

Where $f(t)$ is the two parameter probability density function and $R(r)$ is the reliability function. L is the Likelihood function with t_i as the i^{th}complete lifetime and r_i as the i^{th}right censored lifetime and s_i as the i^{th} interval censored lifetime. It is convenient to maximize the log-likelihood function and solve the set of simultaneous equations to obtain the parameters.

$$\frac{\partial \ln L(t_1, t_2 \ldots . . t_n; \theta, \beta)}{\partial \theta} = 0, \qquad \frac{\partial \ln L(t_1, t_2 \ldots . . t_n; \theta, \beta)}{\partial \beta} = 0 \quad (17)$$

These models presented here are univariate life distributions and are suitable for modelling IID random variables that represent average behavior of population's reliability characteristics [13]. The arrival times form a failure point process when the repair times are neglected.

Best fit model

Given a set of parametric models for the set of data, the preferred model is the one with the least AIC value. The goodness of fit assessed by the log-likelihood value is accompanied with a penalty for overfitting due to an increased number of estimated parameters. If k is the number of estimated parameters and L is the maximum value of the likelihood function, then AIC value is given by:

$$AIC = 2k - 2\ln(L) \tag{18}$$

2.4.2 Estimation for NHPP model

Depending upon the way the observations are performed, the statistical inference of point process models could be classified into two cases viz. time-truncated and failure truncated case. In failure truncated case, the time of testing stops at random and the number of failures are fixed. If the testing stops at a predetermined time, t then that dataset is time truncated. The data set in the case study involves the latter case. Hence the estimation method for time truncated case is described herewith.

The point estimation for β and θ takes into account the number of failures N is random as well as the failure times $t_1 < t_2 \ldots.. < t_N$. The likelihood equation is derived from the joint density for $(N, T_1, T_2 \ldots \ldots T_N)$ is given by;

$$f(n, t_1, \ldots. t_n) = \begin{cases} f_N(n) f(t_1, \ldots.. t_n | n), & n \geq 1 \\ f_N(0), & n = 0 \end{cases} \tag{19}$$

Since the random variable N follows Poisson distribution with mean $\left(\frac{t}{\theta}\right)^{\beta}$, so;

$$f_N(n) = \frac{\left[\left(\frac{t}{\theta}\right)^{\beta}\right]^{n} e^{-\left[\left(\frac{t}{\theta}\right)^{\beta}\right]}}{n!}, \qquad n = 0,1,2 \ldots. \tag{20}$$

The conditional distribution of $T_1 < T_2 < \cdots. < T_N$ given $N = n$, and the corresponding joint density derived by Basu, [7] and given as;

$$f(n, t_1, \ldots. t_n) = \frac{\beta^n}{\theta^{n\beta}} \left(\prod_{i=1}^{n} t_i\right)^{\beta - 1} e^{-\left[\left(\frac{t}{\theta}\right)^{\beta}\right]}, \qquad n \geq 1, 0 < t_1 < t_2 \ldots.. < t_n < t \tag{21}$$

And

$$f(0) = e^{-\left[\left(\frac{t}{\theta}\right)^{\beta}\right]}, \qquad n = 0 \tag{22}$$

The log-likelihood function is given by:

$$l(\theta,\beta|n,t) = nlog\beta - n\beta log\theta + (\beta-1)\sum_{i=1}^{n} logt_i - \left(\frac{t}{\theta}\right)^{\beta} \qquad if\ n \geq 1 \tag{23}$$

and

$$l(\theta,\beta|n=0,t) = -\left(\frac{t}{\theta}\right)^{\beta} \qquad if\ \ n = 0 \tag{24}$$

The log-likelihood function is maximized to estimate the parameters for this distribution.

The time to failure data for each valve in each overhaul interval is extracted. The number of failures (n) are counted in this interval, the log of time to failures for each fault in this interval is summed up. This information is used to calculate the log-likelihood function value for that interval. This log-likelihood is calculated for all the overhaul intervals in all the valves. These log-likelihood values are then summed up to obtain the final log-likelihood sum which is then maximized to obtain the parametric value of β and θ.

$$L(\theta,\beta|l_1, l_2 \dots l_k) = \sum_{i=1}^{k} l_k \tag{25}$$

Here L is maximized to obtain the θ & β estimates.

2.5 Total Lifecycle Cost Model

The aim of this model is to generate the total operating cost for the next thirty years. In the context of TCVs, the inputs to the LCC model includes the following:

- Estimated parameters for the point process models $\theta\ and\ \beta$.
- Cost distribution of failures (C_x) and the number of failures (N_x)
- Overhaul Cost distribution (C_o) and Overhaul Interval (t_o)
- Inspection Cost distribution (C_i) and inspection interval (t_i)

2.5.1 Simulation model

Given the distributions for N_x, C_i, C_x *and* C_o the monte-carlo simulations could be performed to generate lifecycle models with randomly occurring leaks, and corresponding costs. The leaks are failure events randomly occurring with inter-arrival times following the power law. The time to first failure in this model follows the Weibull distribution. The subsequent failures are distributed according to the power law process. The approach to randomly generate leak times is described below:

1. A random number $X_1 \in (0,1)$ is generated.
2. The time to first failure $Y_1 = \theta(- lnX_1)^{\frac{1}{\beta}}$ is calculated.
3. If this time is less than the overhaul interval, (t_o) then the failure is recorded.
4. If the first failure is recorded, the next failure time is calculated by

$$Y_i = \left(Y_{i-1}^{\beta} - \theta^{\beta}\, lnX_i\right)^{\frac{1}{\beta}} \text{ for } i = 2, \ldots, \text{n.} \tag{26}$$

5. The corresponding costs are similarly generated based off the failure cost distribution.
6. Depending on the number of overhauls in the thirty year period, the number of overhauls and corresponding cost from the cost distribution for each overhaul are generated.
7. The cost of inspection is generated from its cost distribution and the total cost in the thirty year period is recorded, depending on the inspection frequency.
8. Finally, the total cost is calculated for 1 simulation keeping t_o fixed. This is performed 10,000 times. To visualize the trend, we plot these simulated costs (y axis) and the varying overhaul interval t_o in the (x axis).

2.5.2 Optimization of Overhaul Interval

As the overhaul interval increases, the valve would not be replaced for a longer duration, which in principle would increase the number of faults and correspondingly the cost of repairs. This is done to ensure the valve functions efficiently without any problems. However, this increase in the overhaul interval also implies a decrease in the overhaul cost, in the span of thirty years. Hence, the objective is to reach a cost-based optimized overhaul interval which expends minimum cost without compromising much with reliability of the system. The simulation results would provide a variation of both lifecycle cost and the repair cost which may provide a complete picture on the cost implications for the estimated optimum overhaul interval.

2.5.3 Assumptions in this model

1. The inter-arrival times are distributed by power law with parameters θ *and* β
2. The overhaul interval t_o varies. In the context of TCVs, it is assumed to be varying from 5 years to 30 years.
3. The costs for each maintenance task (inspection, overhaul, repair) has its own parent distribution. The costs corresponding to the occurrence of each task is generated randomly from the distribution.
4. The total cost generated in a timeline gives one value of the total operating cost for a specified overhaul interval.
5. A timeline is defined as the duration of 30 years (in the context of TCVs) for which the equipment is supposed to operate with a specified number of overhauls. If t_0 is initially set as 5 years, then a timeline for 30 years would have 6 planned overhauls. The total number of failures occurring in each overhaul interval would be added up for each timeline to give the total number of failures. Similar addition would be done for failure costs.
6. Each timeline with a specified overhaul interval would be run 10,000 times.

Note that the time of overhaul in this span is kept variable. This is to ensure that we obtain a system which is reliable as well as cost efficient and is planned to be replaced at an optimum overhaul interval in the remaining life of the nuclear power plant.

2.6 Reliability Analysis

Different repair strategies have dissimilar influences on the system reliability following a failure, defined as the probability of no failure in between a time interval. Given the lifetime distribution of the component $f(t)$, the probability of failure of a component as a function of time is defined by

$$\Pr(T \leq t) = \int_0^t f(\theta)d(\theta) = F(t), \qquad for\ t \geq 0 \tag{27}$$

Where $F(t)$ denotes that the component will fail sometime up to time t. The reliability of the component is defined as the converse of this function, the probability of no leak for the time interval t, given by

$$R(t) = 1 - F(t) \tag{28}$$

2.6.1 Reliability for the stochastic point process

Essentially, in case of repairable systems, the reliability $R(t)$ loses its significance. The system remains to function for a long time even though the reliability becomes small as demonstrated by [11]. The applicability of reliability assessment for repairable systems is presented with an industrial context in this thesis

For overhaul interval t, the event distribution follows the poisson distribution as;

$$P(N(t), v(t)) = \frac{(v(t))^n e^{-v(t)}}{n!} \tag{29}$$

The expression for reliability is given by keeping $N(t) = n = 0$;

$$R(t, v(t)) = P(N(t) = 0, v(t)) = \frac{(v(t))^0}{0!} e^{-v(t)} = e^{-v(t)} \tag{30}$$

For the minimal repair model following the power law function, the expected value function is given by,

$$\nu(t) = \left(\frac{t}{\theta}\right)^{\beta} \tag{31}$$

Using this mean function for NHPP model, the reliability is given by;

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}} \tag{32}$$

The above expression represents the probability of zero failures for a stochastic point process model given the failure intensity function follows the power law function.

2.6.2 Mission Reliability

Considering the safety valve is replaced on the advent of the first major leak that occurs, mission reliability gives the probability that the valve will operate for the duration of a mission (x), given that it is operating at the beginning of the mission [12]. If the faults considered in the analysis initiate a valve replacement, the system is assumed to non-repairable and at the age t from the start of the mission; The mission reliability is given by

$$R(t, t + x) = \frac{R(t + x)}{R(t)} \tag{33}$$

Where $R(t)$ and $R(t + x)$ represent the reliability at the start of x and at the end respectively. This concept could be illustrated from the figure depicted below.

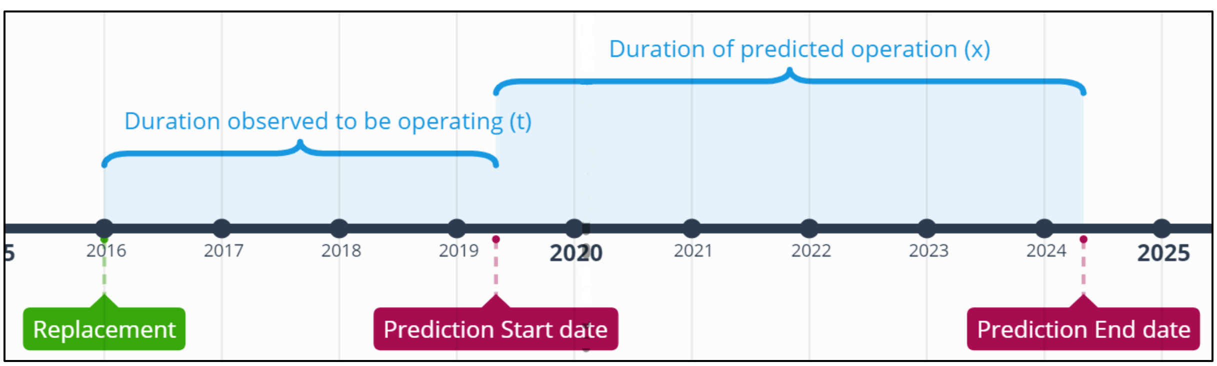

Figure 2-4: Timeline to depict durations t and x.

2.7 Remarks

In this chapter we discussed the theoretical concepts used the rest of the thesis. Two prominent stochastic point process models, Renewal Process and NHPP are discussed to model the failure arrival times in the equipment. Statistical estimation using MLE was derived for lifetime distribution of equipment and the process models. The case of time truncation for statistical inference is dealt in detail to address the TCV case study. The methodology to calculate various cost distributions for maintenance are then discussed. The expected values from these distributions are then used for the total lifecycle cost equation. Finally, a discussion on the basic reliability concepts is also performed for overhaul interval analysis. The next chapter would dive into the discussion of key elements of the historical data provided in the case study.

Chapter 3

Safety Valve Operating Experience

3.1 Introduction

This chapters aims to summarize the 20 year historical data for the temperature control valves in a crisp and visually pleasing manner. Once the data is understood, the probabilistic methodology for analysis discussed in the previous chapter could be applied to generate the lifecycle model. The data is typically available in the form of work orders (WO).

The chapter first presents an overview of the operating history of 24 TC valves. This overview includes the different task types and their percentage contribution to the total maintenance activity in terms of number and cost. After that, categorization of data is done to create a homogenous statistical population. This homogenously distributed data would further act as the input for modelling lifetime distribution and performing analysis. In the next chapter.

3.2 Operating Experience (OPEX)

The overall summary of TCV data is depicted in the table below. This summary describes the number of Work Orders analyzed, types of work orders, observation period, total cost incurred for respective type of work orders and the average cost per task as well.

Table 3-1: Work Order Summary from OPEX data

Work Order Summary	Details
Total Number of Work Orders	753
Operating interval for data	20 years
Total number of TCVs	24

To analyze the OPEX data, the work orders provided in the data were categorized into three work order types:

1. Overhauls

2. Regular maintenance/Inspections.

3. Leaks/Faults and their repairs

Overview of Tasks

The distribution of work orders tasks for TC Valves with respect to the type of work orders task is summarized by Figure 3-1.

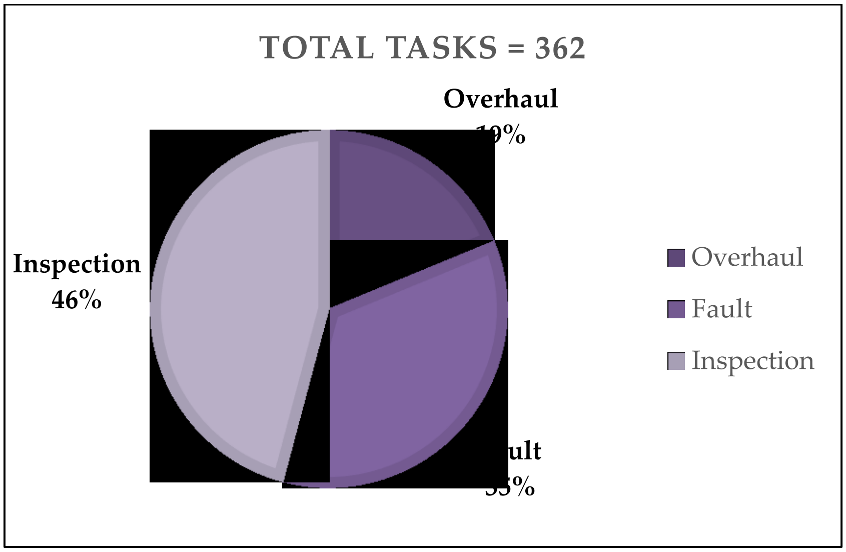

Figure 3-1: Task Type Distribution

It can be observed from the above figure that almost half of the work orders are related to preventive maintenance and inspections of TC Valves. However, they contribute to only 5% towards the total cost incurred ($6.3M) in the life cycle of all TC Valves combined. Similarly, for the faults and repairs. The number of work orders associated with faults account for 35% of the total tasks which contribute to mere 10% of the total cost as can be observed in Figure 3-2.

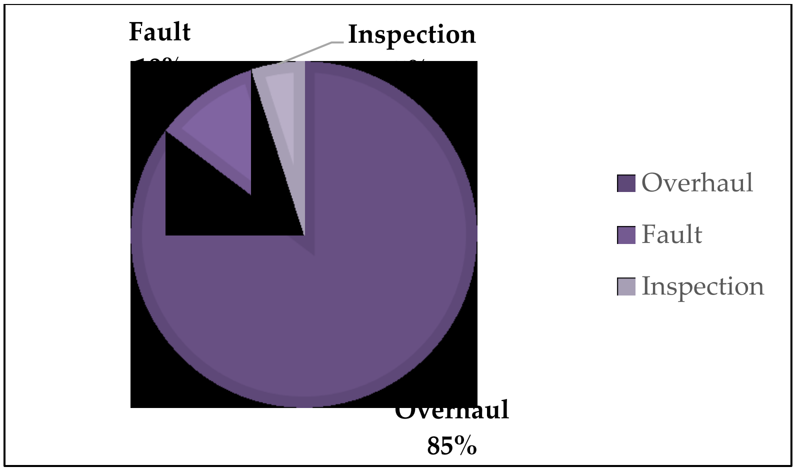

Figure 3-2: Total Cost Distribution with Task Types

Since the overhauls contributed to almost 85% of the total cost incurred in keeping the valves operational for last 20 years, extending the overhaul interval would certainly help in significant amount of cost savings in the future. To learn more about how a typical TCV was maintained in the last 20 years, a timeline for work order tasks is plotted herewith indicating the type of tasks and the cost associated with them.

3.3 Work Order Types

3.3.1 Overhaul

In an overhaul, a valve is dismantled and many of its parts, such as actuators, positioners are replaced. In this period, three overhaul campaigns of TCVs in year 2000, 2008 and 2015 were completed at an average for each valve.

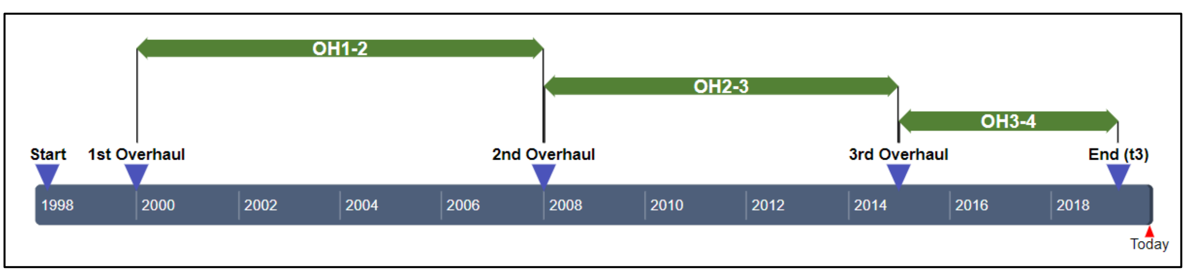

Figure 3-3: Overhaul Interval depiction

3.3.2 Inspections

In the category of work orders, inspections, valve tests, flow scans, and other maintenance checks are performed. All the maintenance tasks covered here contribute to the deterministic element of the lifecycle model. Within TCV3 the most prevalent work order for inspections was flow scanning. Within TCV1-2 the most recurring work orders for inspections were Air Hold Tests. A brief list from the OPEX data is depicted below.

Table 3-2: Types of Inspection Tasks

S.No.	Inspection WO Description
1.	Air Hold Test
2.	RT Inspection of Valve drain pipes
3.	Backup Instrument Air Leak Rate Test
4.	Air Hold Test
5.	Eq Walkdown & Accessories
6.	Air Hold Test
7.	MC Assist OPS with Post MTCE Test
8.	Air Hold Test
9.	Evaluation Of the V/V and Piping
10.	Inspect Non-FAC location DLPSW29
11.	Inspect Pipe Associated with Valve
12.	Flow scanning
13.	Inspect Non-FAC location DLPSW28

Number of Tasks Performed Annually

The total number of deterministic maintenance tasks occurring every year is summed up to illustrate the total number of inspection tasks performed annually.

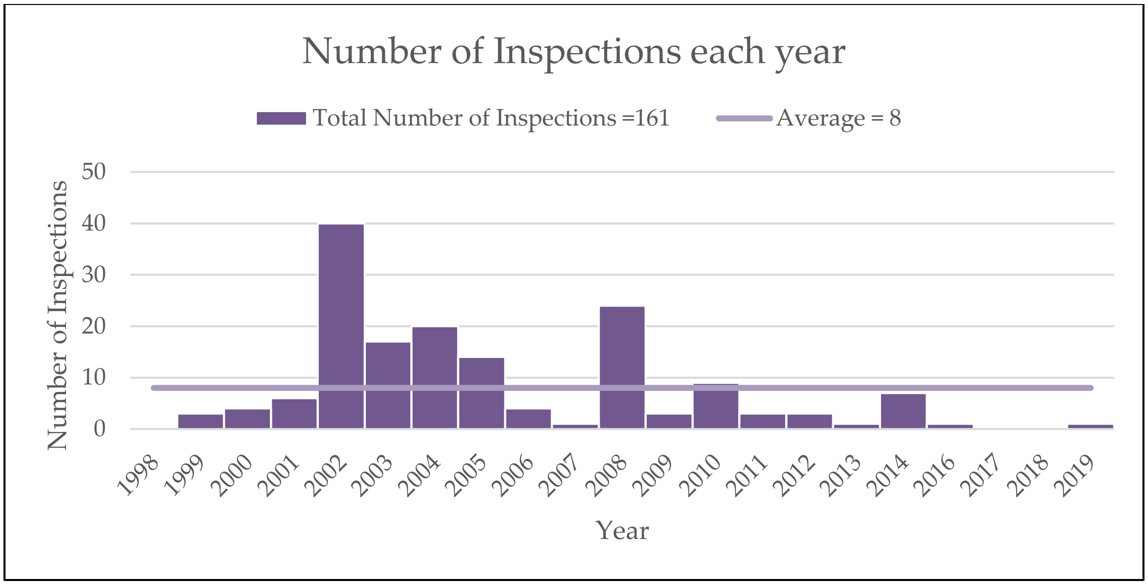

Figure 3-4: Annual number of Inspections

Total Cost of Inspections performed annually

Similarly, the total cost of incurred in the inspections and regular maintenance activities is summed up for each year for all the valves and is illustrated below.

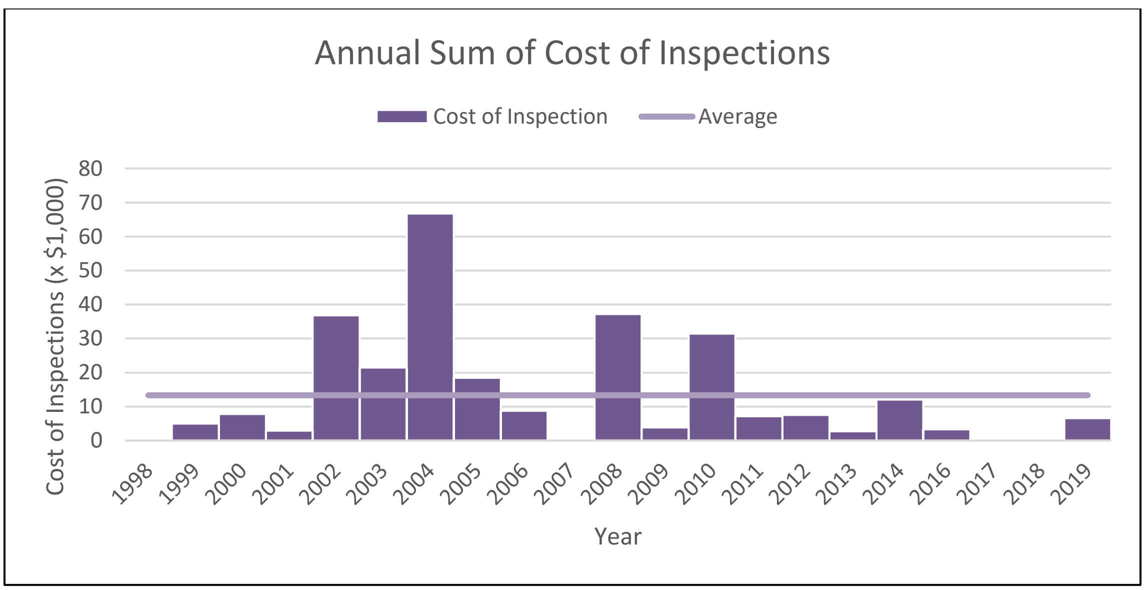

Figure 3-5: Total of Cost of Inspections each year

3.3.3 Repairs

This category includes the maintenance activities contributing to the probabilistic element in the lifecycle model. A repair performed or a fault event in the work order description, both deliver the same intent that a fault occurred and consequently it was repaired. Moreover, a leak is the most frequent kind of fault. Hence, a fault, leak or repair would be used interchangeably in this thesis. A list of faults modes based on the OPEX information for 24 TCV valves in the observation period of 20 years can be seen below:

Table 3-3: Type of faults in OPEX

S.No.	Fault Description in Work Order
1.	Packing Leak
2.	Repack: Gland bottomed out
3.	Stem Leak
4.	Replace Positioner
5.	Actuator Repair
6.	Positioner Air Leak
7.	Gland Leak
8.	Remove damaged insulation
9.	Erratic Control Intermittently

Leaks

The most prevalent repair mode in the TCV is a leak (gland leak, packing leak etc.). Therefore, the time between failures derived in the previous chapter can refer to the time between consecutive leaks in the valve. When a minor leak occurs, retorquing or minor repairs may do the trick and bring the valve to normal working condition. These events can fall under the minimal repair model. However, when a major leak occurs, the valve needs to be repacked, the packing needs to be changed and the actuator or positioner may also be needed to be replaced. This type of major repair significantly affects the failure rate of the valve.

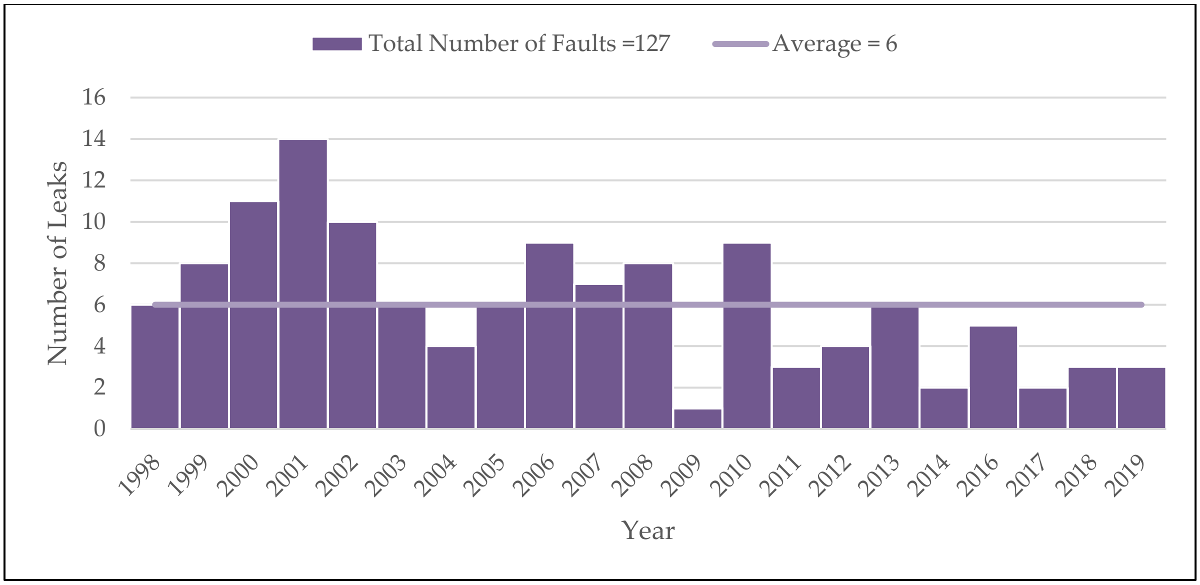

Figure 3-6: Total Number of leaks each year

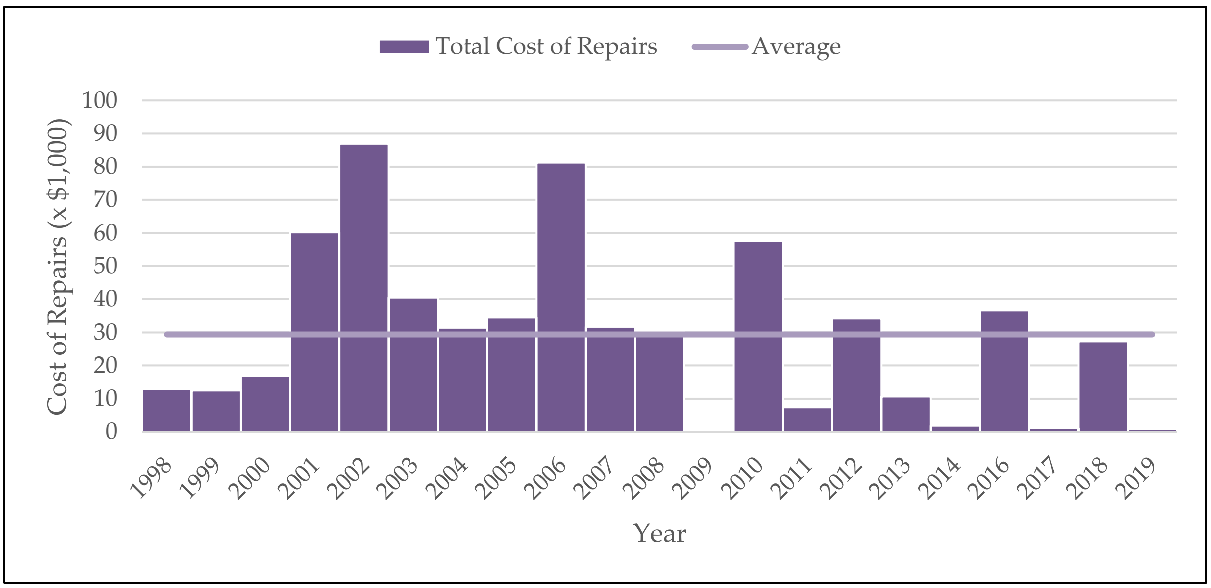

Figure 3-7: Total Cost of repairs each year

Maximum number of faults/leaks (14) were recorded in 2001 while the minimum were recorded in the year 2009. The average annual cost of repairs for the TCV pool is $30,000.

3.3.4 Operating history of a typical valve

Shown below is a typical timeline of events for a TCV wherein it undergoes 3 overhauls and several faults and inspections. This provides us with a basic idea of TCV lifetime. The deterministic maintenance activities are shown below the axis while the probabilistic maintenance activities (leaks) are depicted above the horizontal axis.

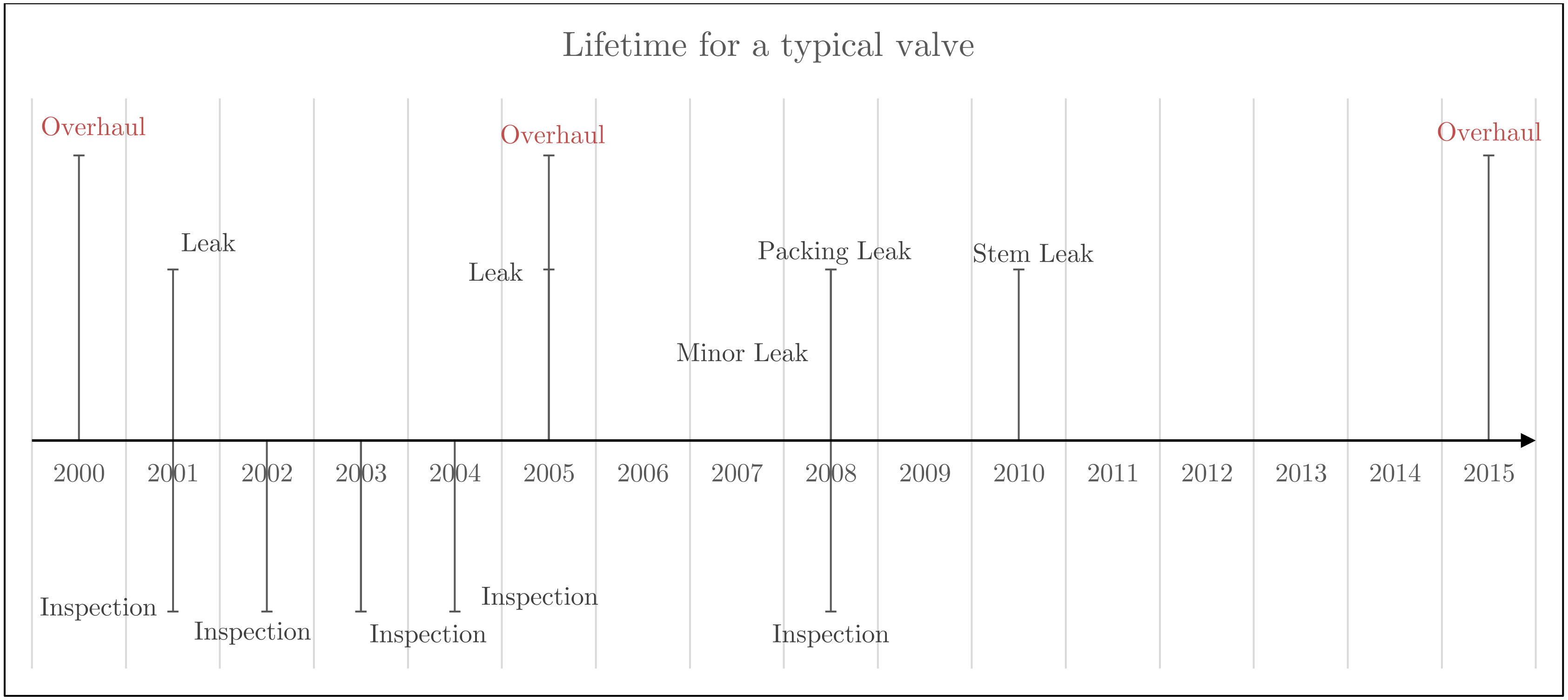

Figure 3-8: Typical Maintenance Task Timeline for a TCV

3.4 Homogenous Statistical Population

The homogenization is performed through categorization of the historical data. The flowchart below depicts the categorization for better understanding of the analysis.

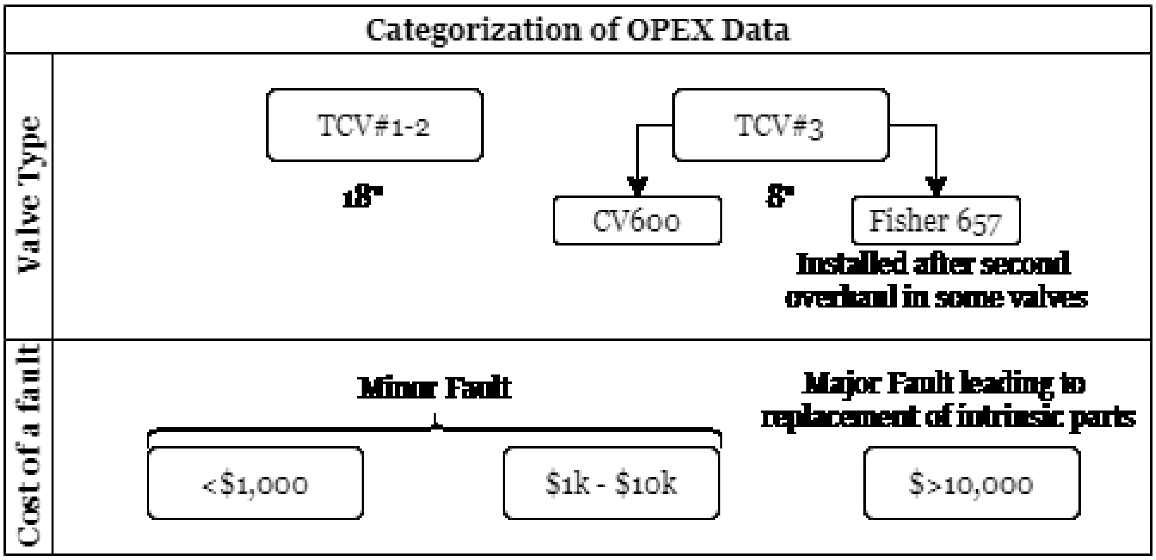

Figure 3-9: Classification of Data

This two-fold categorization of data segregates the relevant and recent information required to accurately estimate the lifetime distribution of the valves. The primary modes of categorization are valve type and cost of repairs.

3.4.1 Valve Types

As mentioned in 1.4.2, the functioning remains the same in all three types of valves, however, TCV#1 and TCV#2 are bigger 18" valves while TCV#3 valves are smaller 8" valves with a slightly different work order history. Moreover, in between the operation period, some of the TCV#3 valves were replaced from Copes Vulcan to Fisher, Model 657(70)H-ET-3582I-67CFR.

3.4.2 Repair Cost

A closer look at the type of repairs performed and the frequency of faults, it is observed that some repairs are more critical than the others. Some repairs are small and quick, while the others are critical enough to initiate a repack.

Table 3-4: Fault Distribution based on cost

Cost category	Number of Leaks
<$10,000	105
>$10,000	22

Introduction of a threshold on cost incurred for repair efficiently categorizes the faults, if they initiated a repack and purchase of new valve components to replace the old ones, thus renewing the life of valves to as good as new.

3.5 Remarks

In this chapter we discussed the wholistic overview of the OPEX data. The three main types of maintenance tasks covered in this case study are overhauls, repairs/faults/leaks and regular maintenance tasks like inspections. We further categorized the data based on cost of maintenance tasks, and the type of valve. This was done to produce a homogenous population of the statistical data. Now the next chapter uses this data for complete lifecycle cost analysis. The concepts and equations formulated in Chapter 2 are applied on this dataset.

Chapter 4

Analysis

4.1 Introduction

The idea of life-cycle cost in this document pertains to the cost incurred for a valve system to work continuously at required efficiency with a specified maintenance strategy in place. The previous chapter discussed the historical data of the equipment operating life. This data is now utilized to formulate the probabilistic lifecycle model. This chapter aims to apply the concepts and approach introduced in Chapter 2 to the TCV dataset introduced in Error! Reference source not found.. Firstly, the lifetime distribution and the mean time to first major leak are estimated. It is followed by estimating the inputs to the lifecycle cost model ($C_i, C_x, and\ C_o$]). Finally, total lifecycle cost model is simulated, and the observations are discussed.

Data

The time between leaks is extracted from the historical dataset. The initial point of observation for calculation of lifetime is taken as the point of first overhaul. The total number of leaks after the first overhaul are 109. The equipment failure data for major leaks is used to model the lifetime distribution of the equipment. The distribution would help in predicting the probability of first major leak after the valve is set in operation. However, for the minimal repair process model, all the data points (minor and major leaks) are used.

Table 4-1: Number of leaks (categorized)

Valve	**All leaks (minor & major)**	**Cost>$10,000 (major)**
TCV 1-2	**70**	11
TCV3	**39**	11

4.2 Lifetime Distribution

From the above dataset, the time to major leaks provide complete lifetime data. We aim in this section to calculate the time to first major leak. A summary of complete and right censored lifetimes is depicted in the table below:

Table 4-2: Summary of complete and right censored lifetimes for faults for TCV1-2

TCV#1-2				
Cost Category	Duration	Number of Repairs	Sum of lifetimes (days)	Average Duration (years)
>$10000	Complete	11	12537	6.3
	Right Censored	43	94333	12.5
	Total	54	106870	

It should be noted that the average duration observed for a complete lifetime is observed to be 6.3 years. Similar to TCV1-2, the summary for complete and right censored lifetimes for TCV3 of type CV600 is tabulated below.

Table 4-3: Summary of lifetimes for faults for TCV#3-CV600

TCV#3 - CV600				
Cost Category	Duration	Number of Repairs	Sum of lifetimes (days)	Average Duration (years)
>$10000	Complete	10	10370	6.5
	Right Censored	21	31095	8.4
	Total	31	41465	

Interestingly, the average duration of complete lifetime for the TCV3 is 6.5 years, which is similar to that of TCV1-2. Since some of the TCV3 valves were replaced to Fisher Valves, all of them after the second overhaul, therefore the summary of lifetimes for these valves is relevant only for OH2-4.

Table 4-4: Summary of lifetimes for faults for TCV#3-Fisher657

TCV#3 - Fisher657					
Overhaul Interval	Cost Category	Duration	Number of Repairs	Sum of lifetimes (days)	Average Duration (years)
OH2-4	>$10,000	Complete	1	1598	4.4
		Right Censored	4	6193	4.2
		Total	5	7791	

Utilizing the complete and right censored data for different categories, MLE is used to estimate the Weibull distribution parameters and the median time to the first major leak.

4.2.1 Estimated Parameters

The estimated parameters and the mean time to failure corresponding to different parametric distributions were calculated, divided into different cases based on categorization. The table depicting the parameters and mean lifetimes for all the distribution can be found in the Error! Reference source not found.. The hazard rate of Weibull distribution is depicted as the intensity function of the NHPP model as per the power law. Therefore, to find the probability of occurrence of first major leak, Weibull distribution's results would be most meaningful. The estimated parameters mean and median time to failures and the coefficient of variance are tabulated below.

Table 4-5: Estimated Weibull dist. parameters for time to first major leak

Valve	Scale θ ($years$)	Shape β	Mean TTF (years)	Median TTF (years)	COV
TCV1-2	37.9	0.80	42.8	24.0	1.3
TCV3-CV600	9.5	1.30	8.7	7.2	0.8

4.2.2 Observations

The shape parameter $\beta < 1$, for TCV1-2 which depicts that as the valve ages, the hazard rate is decreasing. This represents the case of early failures. For TCV3, the inverse is true, i.e. the hazard rate is increasing with age. The median time to failure observed for TCV1-2 is 24 years which is thrice as compared to TCV3. This is observed due to the fact that TCV3 is a pool of just 8 valves and 11 major leaks were observed while for TCV1-2, a total of 16 valves had 11 failures.

4.2.3 Assumptions adopted for estimation

To estimate the lifetime distribution of the TCVs using MLE, the following assumptions were adopted:

1. The major leaks provide the complete lifetime data. These data points as depicted in 3.4.2 cost greater than $10,000 for repairs.
2. The time between major leaks are assumed to be following a Weibull distribution, since the distribution is very flexible to fit various kinds of data as suggested in 2.2.1.
3. No downtime for repairs are assumed in this case. The valves are assumed to be replaced and be back in service immediately after the leak occurs.

4.3 Cost of Maintenance

To calculate the total lifecycle cost for the next thirty years, the mean cost for the inputs considered below are calculated first.

1. Cost of inspection activities (C_i)
2. Cost of leaks (C_x)
3. Cost of overhauls (C_o)

The above mentioned costs are calculated for each type of valve (TCV1-2 & TCV3) for complete OPEX observation history.

4.3.1 Weibull Probability Plots of cost data

The probability plot method is a simple way to visualize the data fit w.r.t a specific parametric distribution. The Weibull probability paper is used, and the data fit is observed.

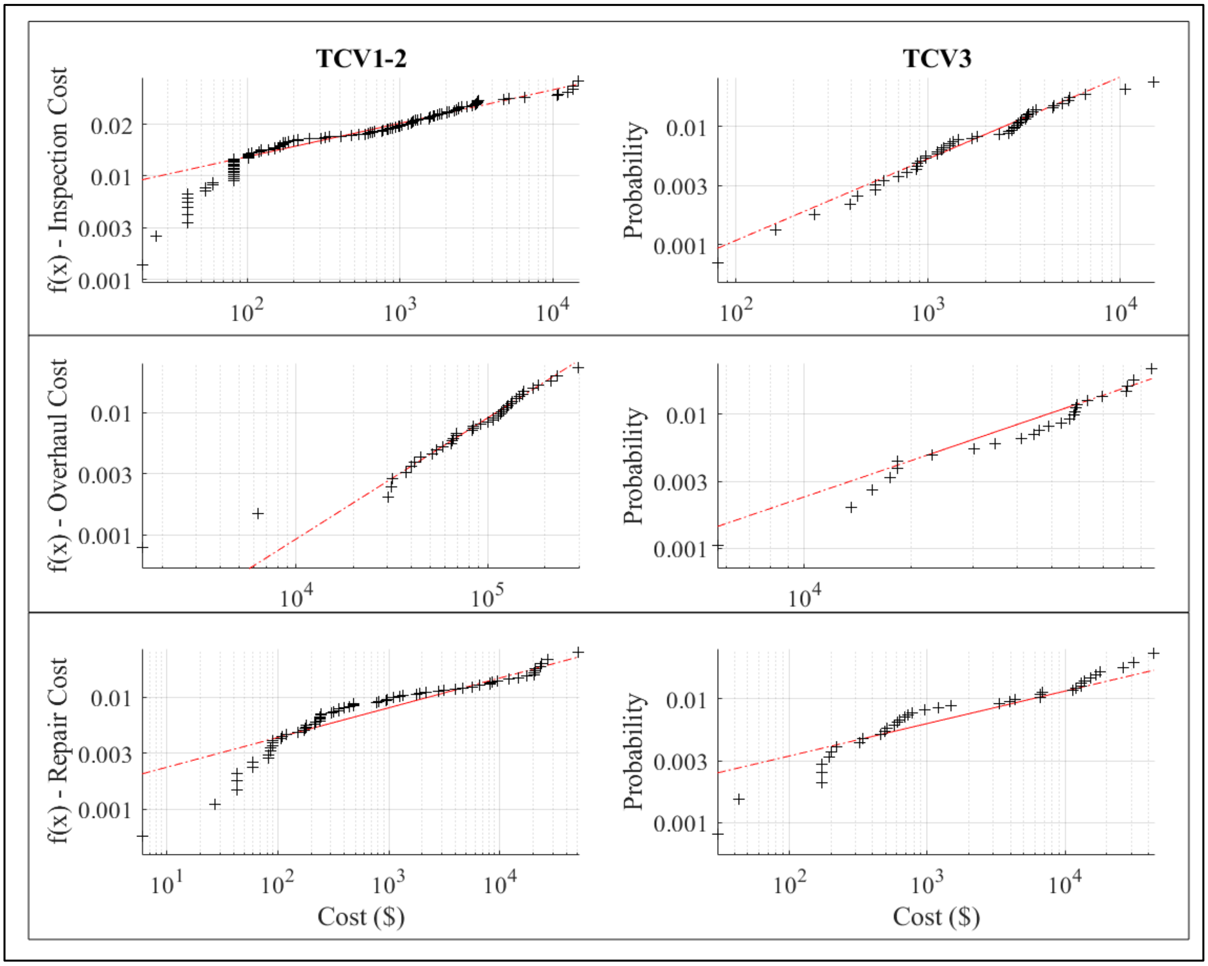

Figure 4-1: Weibull PPP for various cost distributions

All three maintenance costs are considered to follow the Weibull distribution and the distribution parameters are estimated using MLE. The parameters estimated below for the repair cost for leaks (C_x) the inspection and overhaul cost, are derived from the data points considered for the complete observation period, the initial point being the instance of first overhaul. The estimated cost distribution parameters and corresponding mean, SD and median costs are tabulated below.

Table 4-6: Estimated Weibull Cost distribution parameters

Valve	Cost	Data Points	Shape (θ)	Scale (β)	Mean Cost $	SD ($)	Median Cost $	COV
TCV1-2	C_i	116	0.64	$1,059	$1,481	$1,303	$595	0.88
	C_o	41	1.60	$111,000	$99,492	$147,316	$88,338	1.48
	C_x	30	0.49	$2,118	$4,468	$2,071	$997	0.46
TCV3	C_i	50	1.10	$2,662	$2,567	$3,750	$1,910	1.46
	C_o	25	1.99	$53,188	$47,142	$67,530	$44,237	1.43
	C_x	14	0.58	$4,161	$6,571	$4,749	$2,209	0.72

4.3.2 Observations

The mean cost for repairs C_x is $5k for TCV1-2 and $7k TCV3 with a COV of 0.5 and 0.7 respectively. This indicates the dispersion of cost from mean is not significant. The mean cost of overhauls for TCV3 is $50k but the for TCV1-2, its almost double. This is due to the fact that TCV1-2 are larger sized valves and replacement costs are higher. The mean cost of regular maintenance or inspections comes out to be greater for TCV3 costing around $2.5k and lower for TCV1-2 around $1.5k. The average annual inspections intervals for the TCVs are tabulated below:

Table 4-7: Average Inspection Interval for TCVs

Valve	Inspection Interval (years)
TCV1-2	3.03
TCV3	2.78

The frequency of regular maintenance for each valve comes out to be 3 years as per the operating experience. This indicates that this cost for regular maintenance which is $1.5k for TCV1-2 is incurred after every 3 years. The Weibull distribution fitting the data points for each maintenance task and both valve types is represented in the figure below.

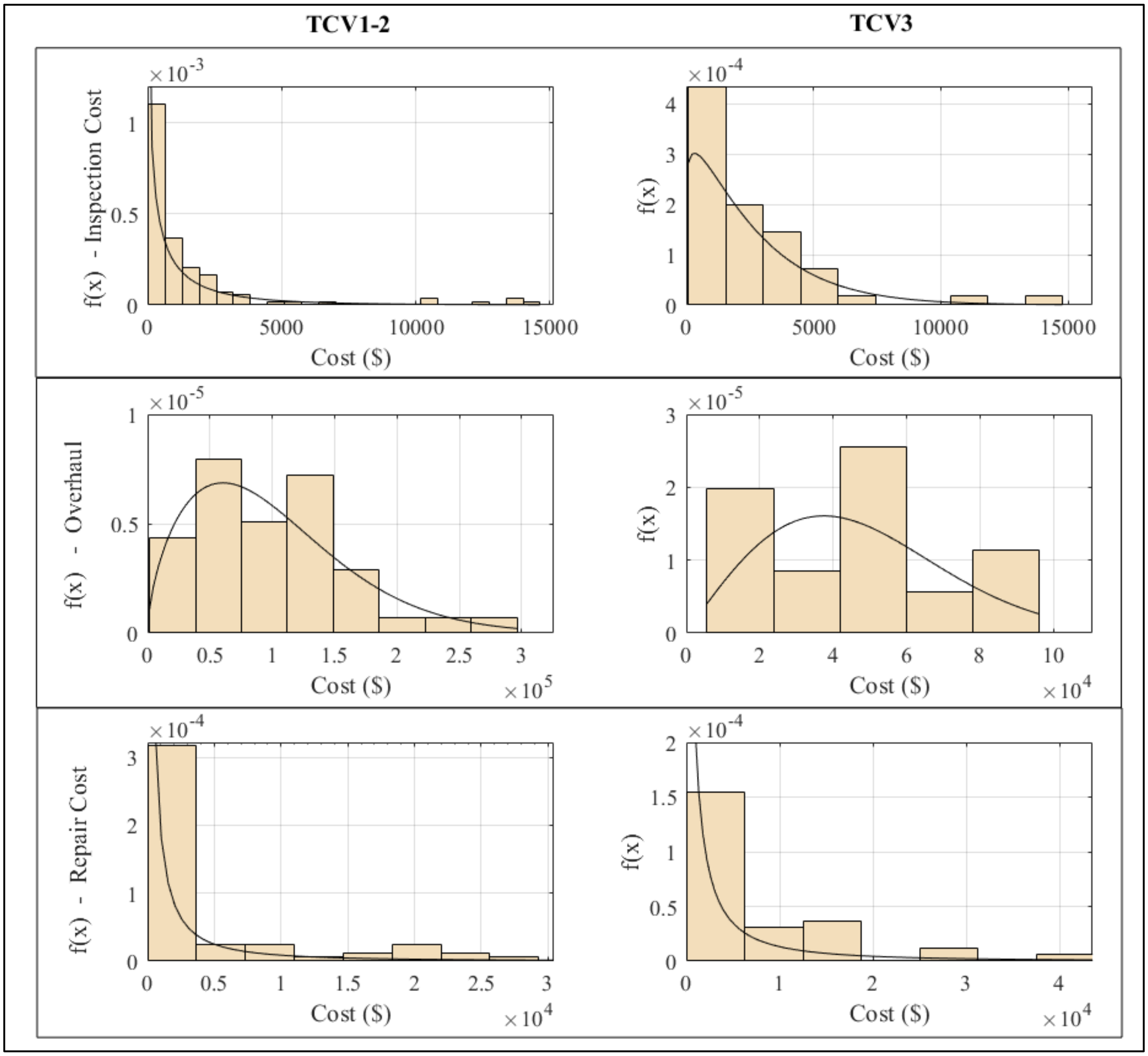

Figure 4-2: Estimated Weibull Maintenance Cost distributions for each valve category

Most of the inspections, as can be observed from the above figure cost less than $5k. However, the overhaul cost seem to be quite dispersed through the spectrum. This implies that in some cases, some parts of the valve are replaced, and valve is repacked instead of replacing the whole valve. An important observation from the leak cost distribution above is that most of repairs incur less than $10k. This implies that most of the leaks require minor repairs. Therefore, the approach for minimum repair models should be adopted. In the next section, the estimation of parameters for the stochastic point process models is performed.

4.4 NHPP Process model

4.4.1 Estimation of Parameters

Point estimation of parameters for the minimal repair process model is discussed in this section. The log-likelihood function for the estimation as mentioned in 2.4.2 is given by:

$$l(\theta, \beta | n, t) = nlog\beta - n\beta log\theta + (\beta - 1)\sum_{i=1}^{n} logt_i - \left(\frac{t}{\theta}\right)^{\beta} \qquad if\ n \geq 1 \tag{34}$$

and

$$l(\theta, \beta | n = 0, t) = -\left(\frac{t}{\theta}\right)^{\beta} \qquad if\ \ n = 0 \tag{35}$$

For each overhaul interval in each valve history,

n represents the number of leaks occurred (major or minor)

$\beta\ and\ \theta$ represent the shape and scale parameter respectively

t represents the overhaul interval

t_i would represent the arrival times to n failures

The log-likelihood calculated for each interval for each valve is summed up as follows;

$$L(\theta, \beta | l_1, l_2 \dots l_k) = \sum_{i=1}^{k} l_k \tag{36}$$

This final log-likelihood is then maximized to obtain values of $\beta\ and\ \theta$.

4.4.2 Assumptions

1. The failure times for both major and minor leaks are used as input in this estimation.
2. The inter-arrival times are assumed to follow the power law process.
3. No downtime for repairs are assumed in this case. The valves are assumed to be repaired and be back in service immediately after the leak occurs.

4.4.3 Description of Dataset

For the variables defined as per the log-likelihood equation in 4.4.1, an example set of time to failure values is described below. This dataset belongs to one overhaul interval for one valve in the span of 20 years of its operation till date.

Table 4-8: Example dataset used in parametric estimation

Valve	**TCV1**
n (no. of leaks)	4
t (overhaul interval) OH1-2	3626 days

Inter-arrival times (days)	**Arrival times (ti) (days)**
629	629
1956	2585
491	3076
52	3128

In the overhaul interval above, the $t_1, t_2 \dots t_n$ are arrival times to n failures. All these failures are complete and not right censored. The right censoring is taken care by the truncated interval duration t, which only means that when the next overhaul occurs, t ends. The log-likelihood is calculated for the above dataset using equation 34 to obtain l_1. If one TCV had suppose three overhauls in the span of twenty years, this means it had two intervals for which l_1 and l_2 are obtained. Each overhaul interval with its duration t is a time-truncated duration. That is, the observation stops when the next overhaul occurs. If the next overhaul interval for the same valve doesn't have any leak then, l_2 is calculated as per equation 35.

Then for the another TCV, with 4 overhauls in twenty year period, l_3,l_4 and l_5 are obtained. These log-likelihoods are calculated for all the 16 TCVs (TCV1-2) and 8 TCV3s. Some have two LLs, and some have more. All of these are LLs are summed together to obtain the final LL calculated in equation 36. The values of β *and* θ for which the maximum sum is obtained are the estimated parameters.

4.4.4 Parameters

Following the description above, the estimated parameters for the minimal repair process (NHPP) considering all the minor and major leak data described as per the example format in Table 4-8 are obtained as follows:

Table 4-9: Estimated parameters for NHPP

Valve	*Shape* (β)	Scale (θ) (days)
TCV1-2	0.88	1456.75
TCV3	0.92	1347.12

4.4.5 Observations

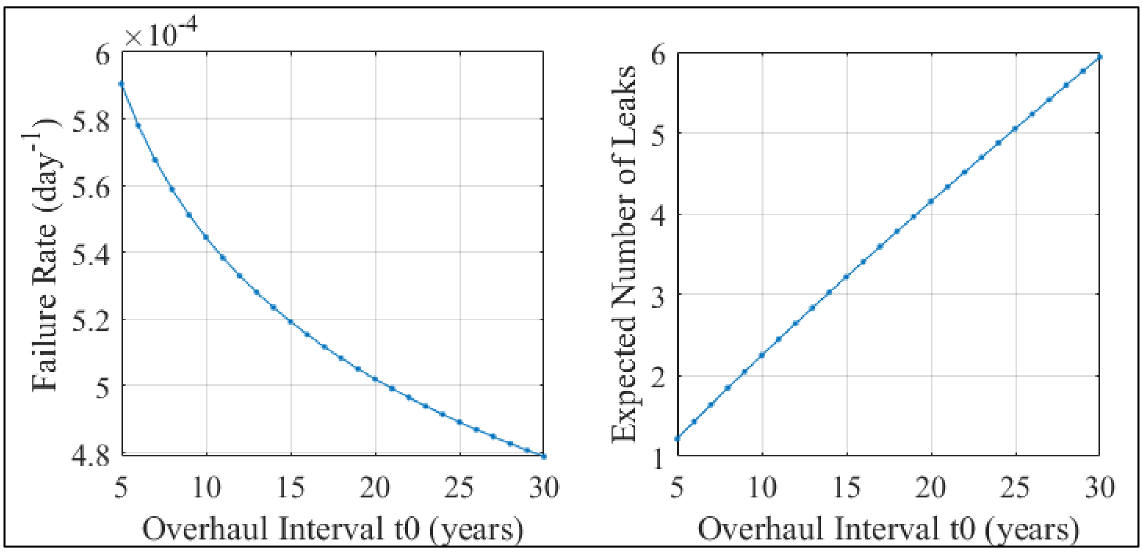

Figure 4-3: Failure Rate and Expected number of leaks

In the above figure, the intensity function (λ) and the expected number of failures ($E[N(t)]$ are plotted as per the power law model for varying overhaul intervals (t). The NHPP shape parameter (β) is less than 1. This represents that the rate of occurrence of failure tends to be inversely proportional to the duration of overhaul. This implies the fact that the system is actually getting better after each repair. The expected number of leaks would decrease as the duration of overhaul interval increases. The inter-arrival times to failure are distributed as per the power law and tend to increase after each failure. The impact of this observation in the lifecycle cost is positive. Since the we linearly increase the overhaul interval t_0 from 5 to 30 years, the rate of increase of number of leaks is not linear but negative w.r.t time which implies lower lost for leaks after every repair.

4.5 Total Lifecycle Cost

To generate the total cost, the simulation model discussed in 2.5.1 uses the cost distribution inputs from Table 4-6 and the failure distribution parameters estimated for the minimal repair process from Table 4-9. Since both TCV1-2 and TCV3 behave similarly as per the NHPP model, the LCC model is analyzed here for TCV1-2 only.

4.5.1.1 Number and Cost of leaks

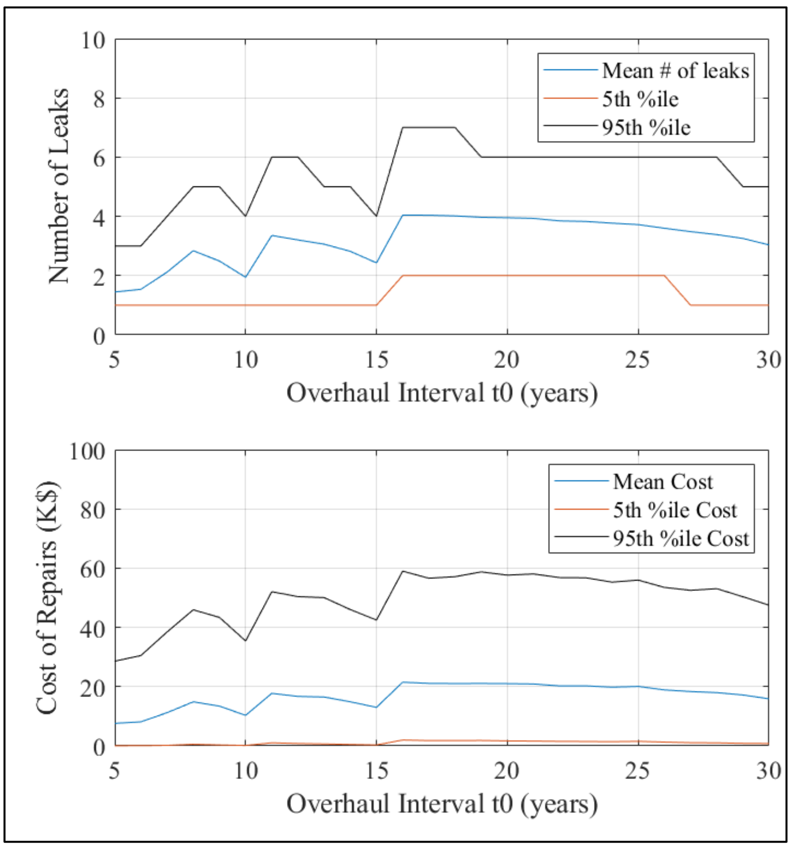

Figure 4-4: Variation of Number of Leaks and cost with overhaul interval (TCV1-2)

In the above figure, at each overhaul interval, the mean, 5th and 95th percentiles values for the number of leaks and corresponding cost generated from 10,000 simulations run are plotted. This above figure is a simulated example with randomly generated failures in each overhaul interval. It can be observed that the mean number of failures are 4 and decreasing on average for each overhaul interval varying from 15 years and above. This clearly depicts that as the overhaul interval increases, the expected (mean) number of failures actually decrease, w.r.t that overhaul interval. This is a representation of how many leaks ought to occur given the minimal repair model in one TCV. In the next figure, the total overhaul cost and the total lifecycle cost are simulated and represented with varying overhaul intervals.

4.5.1.2 Total Lifecycle Cost

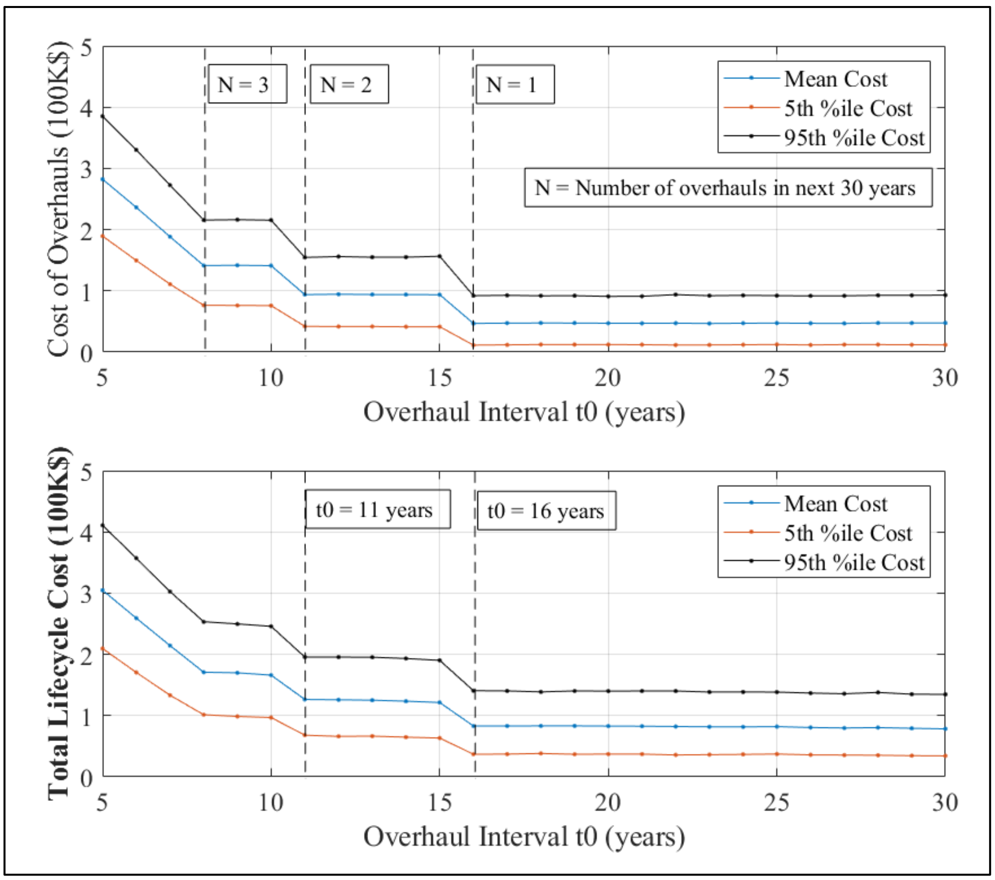

Figure 4-5: Variation of lifecycle cost with overhaul interval (TCV1-2)

The above figure depicts the impact of overhaul cost in the total lifecycle cost of the TCV. In this simulated example, at each overhaul interval, the mean, 5th and 95th percentiles values for the total operating cost are represented. The lifecycle cost includes the randomly generated cost of overhaul, inspection and leaks as per their corresponding distributions. It can be clearly observed that since almost all the cost is contributed from overhauls in operation of the valve, both graphs convey similar results.

If the overhaul interval is set at 11-15 years, there are only two overhauls possible in the span of 30 years. While if the overhaul interval is set 16 years or more, only one overhaul is possible. This implies that to reduce the overall cost of operation in the next thirty years, only the reduction in the number overhauls can have a significant impact. This plot is an example of how much cost the operation one TCV may incur in the next 30 years. In the next chapter, the variation of total repair cost and the total lifecycle cost for a specific t_0 would be discussed to get a better perspective on the impact of cost of repairs.

4.5.2 Assumptions

The main assumptions in the simulated model were discussed in 2.5.2. In context to TCVs, we assume the frequency of inspections to be 3 years, based on historical OPEX data. In the simulation model, we assume that any inspection activity doesn't have any effect on the performance of the valve. This implies that an inspection activity is not a repair activity. Another important assumption to be considered here is that since the any equipment downtime due to a failure is not considered, therefore at any point of time, the equipment is not unavailable. Hence availability analysis for lifecycle cost analysis is not considered.

4.6 Remarks

This chapter starts with the introduction of complete and categorized dataset extracted from the case study to be used in this analysis. The Weibull distribution was considered to give the most meaningful results for the equipment life using the complete and right censored life data. Then the Weibull distribution parameters were estimated using the historical data for costs for maintenance for each valve. The estimation of statistical parameters of NHPP model was performed next, and using those parameters, the total LCC distribution was obtained, with varying overhaul intervals. An important observation was made which suggested that the shape parameter of the model was less than 1. This implied that the rate of occurrence of failure in the model decreased with the increase in the overhaul intervals. Using the information of leak occurrence from this model and all the cost variables, monte carlo simulations were performed to obtain the total lifecycle cost. Then the impact of overhauls in the total cost was discussed. In the next chapter, this model is further discussed after which the reliability analysis for extended overhaul intervals is performed.

Chapter 5

Results

In the previous chapter, a simulated lifecycle cost model for TCV1-2 was generated using the inputs from different contributing costs and lifetime distribution of valves. In this chapter, the variation of lifecycle cost and the cost of repairs with the overhaul interval is discussed. The aim of this chapter is to optimize the overhaul interval of the safety valves. This is done in light of the reliability results for the occurrence of no major leaks.

5.1 Variation of lifecycle cost

From Figure 4-5, for each value of t_0 (overhaul interval), there are 10,000 simulated values of the total lifecycle cost from which the mean, 5^{th} and 95^{th} percentile values are plotted. These values are assumed to follow a probability distribution. Since the total lifecycle cost observes a dip only when N (number of overhauls) decreases, t_0 at which the LCC dip is observed are analyzed. Figure 4-5, this case occurs when $t_0 = 11$ and 16 years. Here, the total cost data is fitted into parametric distributions. Various pdfs (Weibull, lognormal, normal, gamma, uniform) were fitted to find the best distribution.

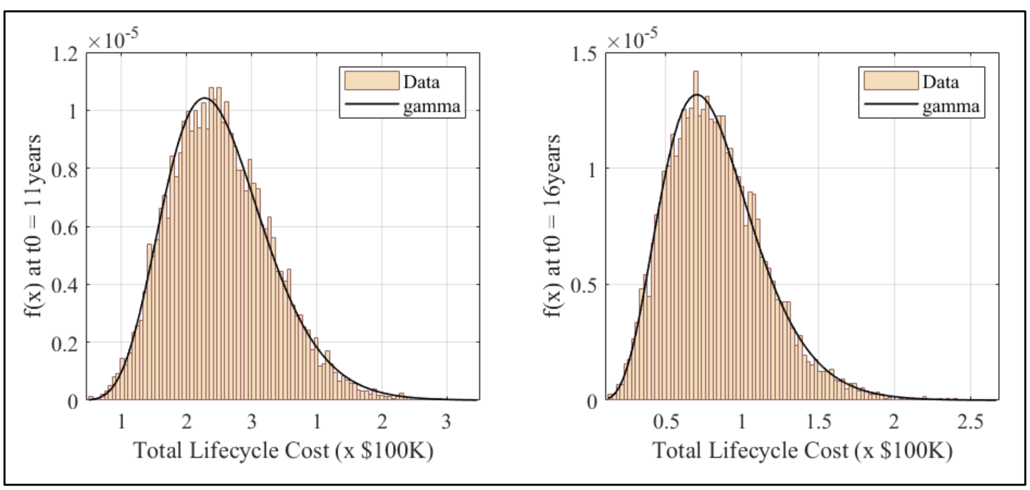

Figure 5-1: Lifecycle cost distribution at t_0=11 & 16 years

The best-fit distribution based on AIC values turns out to be gamma. The variation of gamma parameters w.r.t the overhaul interval is depicted in the graph below.

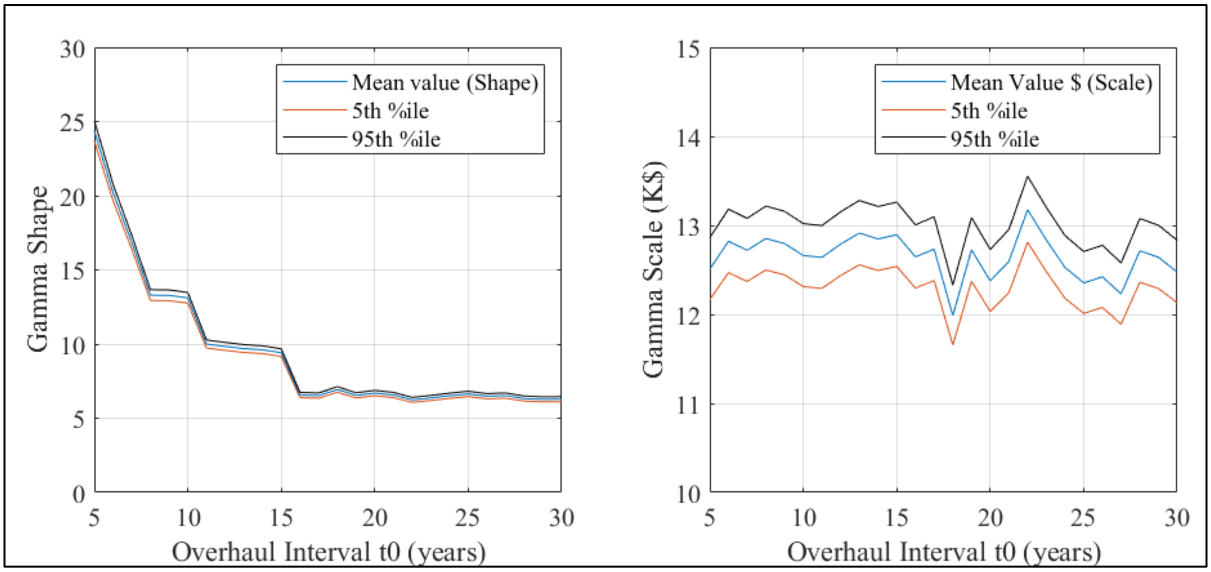

Figure 5-2: Variation of gamma parameters for LC cost distribution

The dips in the value of gamma shape parameter with respect to N (number of overhaul in 30 years) is clearly depicted in the above figure. If the overhaul interval is more than 15 years, there is only one overhaul possible. This generates almost similar operating costs since the other costs (cost inspections and leaks) are negligible when compared to the cost of overhaul. The gamma distribution parameters, corresponding 90% confidence interval and the mean operating cost for the overhaul interval t_0 = 11 and 16 years is depicted below.

Table 5-1: Lifecycle cost model parameters for t_0 = 11 and 16 years

t_0	11 years			16 years		
		90% CI			90% CI	
Parameter	value	5%ile	95th%ile	value	5%ile	95th%ile
Gamma Shape (β)	10.00	9.73	10.27	6.56	6.39	6.74
Gamma Scale (θ)	$12,640	$12,291	$12,998	$12,646	$12,295	$13,006
Mean	$126,356			$82,982		
SD	$39,964			$32,394		

5.2 Variation of repair cost

The variation of repair cost for each overhaul interval needs to be investigated. Similar to the previous analysis, for each value of t_0, there are 10,000 simulated values of the total cost of repairs incurred due to random leaks generated from the NHPP model. These simulated values might as well be assumed to be distributed according to a parametric distribution. Similar pdfs are fitted to find the best-fit distribution.

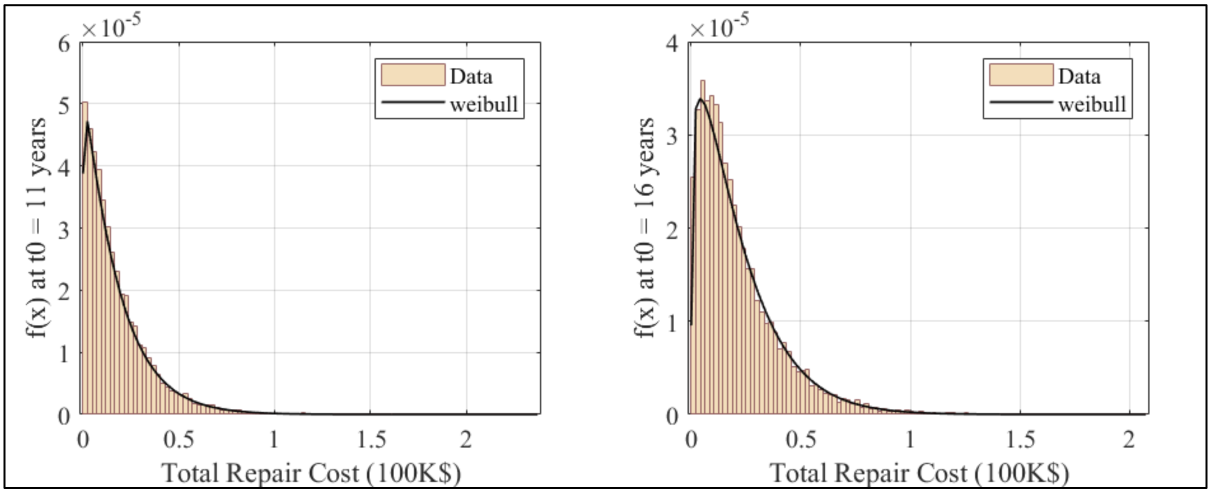

Figure 5-3: Variation of Leak Repair Cost at t_0 = 11 and 16 years

The best fit distribution in this case is depicted by the Weibull distribution. The variation of the Weibull shape and scale parameter is shown in the figure below.

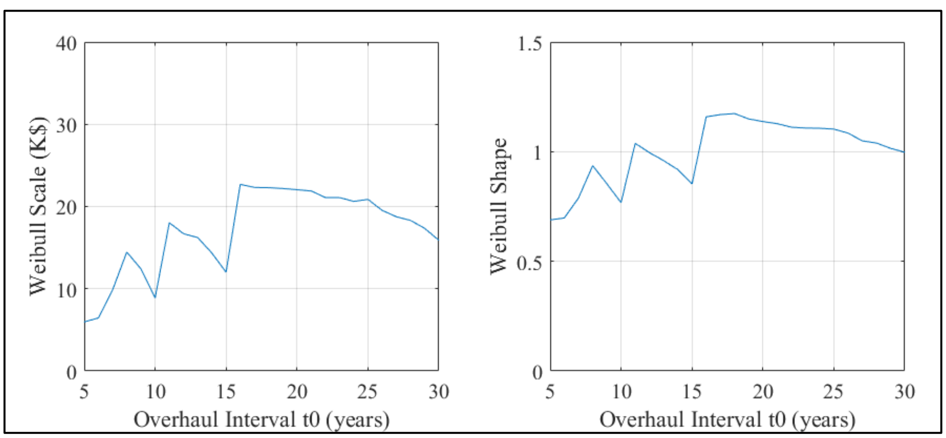

Figure 5-4: Variation of Weibull parameters for Repair Cost distribution

Table 5-2: Total repair cost model parameters for t0 = 11 & 16 years

t_0	11 years			16 years		
		90% CI			90% CI	
Parameter	value	5%ile	95th%ile	value	5%ile	95th%ile
Gamma Shape (β)	1.04	1.02	1.05	1.16	1.14	1.18
Gamma Scale (θ)	$18,030	$17,675	$18,393	$22,694	$22,293	$23,103
Mean	$17,762			$21,552		
SD	$17,118			$18,655		

Given the fact that the time to first leak in NHPP model is derived from the Weibull distribution, the total repair cost parameters (especially scale) vary similar to the mean total cost of leaks for 10,000 simulations w.r.t t_0. The mean total cost of repairs is $18k for 11 year overhaul interval and $22k if t_0 is 16 years. This implies that even if there is a recorded increase in the cost of repair at 16 years, the net impact of $4k is negligible to the decrease caused by the overhaul cost, resulting in a net decrease of $50k in the total lifecycle cost for $t_0 = 16$ years as observed in Table 5-1.

5.3 Reliability Results

The reliability with respect to the occurrence of no major leak during a time interval can be calculated from the corresponding parameters for the lifetime distribution. The reliability corresponding to extended overhaul intervals is calculated below. A complete table using data points from all categorizations could be in the Error! Reference source not found..

Table 5-3: Reliability estimates for extended overhaul intervals

Valve	8yr	10yr	12yr	15yr	20yr
TCV1-2	0.75	0.71	0.67	0.62	0.55
TCV3-CV600	0.45	0.34	0.26	0.16	0.07

The corresponding reliability estimate plot for valves based on the faults occurring after second overhaul is described below.

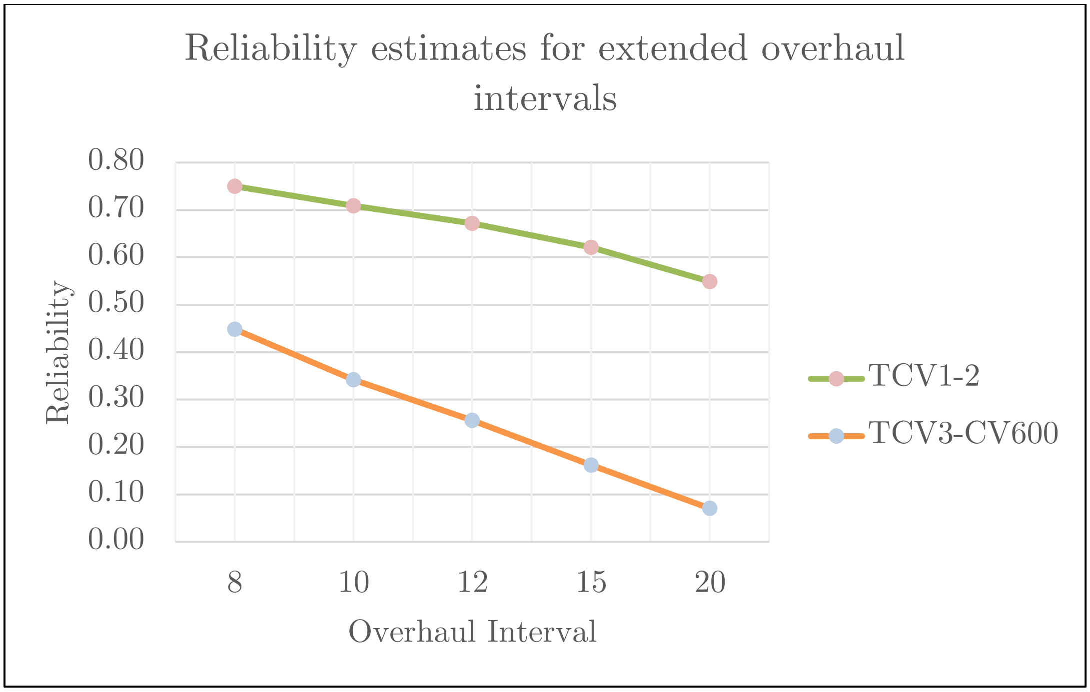

Figure 5-5: Reliability estimates based on lifetime distribution for major leaks

5.3.1 Limitations

The life cycle model is not complete in many aspects. In essence, the above is just a proposed operating life-cycle cost model. Following limitations and assumptions are inferred from this model.

1. A complete lifecycle cost model includes the cost for initial planning, implementation and the decommissioning cost at the end. This model only concentrates on the operating cost.
2. Due to the ambiguity in data for the downtime of an event (repair/overhaul), the downtime was considered to be zero in the model. Therefore, the implied downtime cost could not be accounted for.
3. The cost of inflation over the years has not been considered.
4. Since the NHPP shape parameter obtained was less than 1, there was no sign of system degrading. In fact, the system was observed to get better with every repair.

5. The primary mode of failure considered in the analysis is a leak which is immediately detected. There are different modes of failures observed in the TCV, some may be dormant as well but at all of them are assumed to be immediately detected and repaired.
6. TCV3 has a mixture of observations from different make and type of valves. Some are already replaced to Fisher657 and others are planned to be replaced. Therefore, the lifecycle cost for TCV3 in the next thirty years is not discussed here. However, the NHPP model gave similar results for TCV3 as well.

5.4 Discussion of Results

A total of 24 TC Valves were analyzed from the operating experience data which consisted of 753 work orders. Two-fold categorization of data based on valve type and cost produced homogenized data for application in total lifecycle cost analysis. The probabilistic elements in maintenance were the occurrence of faults, mainly equipment leaks. The estimated shape parameter for the NHPP model was calculated to be less than 1, describing an improving system. The inference from this behavior is that after each repair, the time to next leak increases. The simulated model for the lifecycle cost is observed to follow the gamma distribution for each value of t_0. For the total cost of repairs, the simulated model was observed to follow the Weibull distribution. These parametric variations of final costs are further used to analyze the optimum overhaul interval and the cost implications.

5.4.1 Optimum Overhaul Interval

The initial idea of LCC analysis for the safety valves was that as the overhaul interval was increased, the total repair cost would also increase but the total overhaul cost in the 30 year period would decrease. Hence the variation in the total lifecycle cost and the total repair cost with t_0 would help in investigating if an optimum overhaul interval could be reached. However, the decrease in the total lifecycle cost due to the decrease in the number of overhauls largely overpowered the increase in the total repair cost. Another inference from the low cost of repairs is the continuous inspection and maintenance activity that was put in place. It ensured the valve was in proper condition at regular intervals.

For a better perspective, the lifecycle cost for two overhaul intervals were further analyzed, 11 year and 16 year. The basic idea was that for t_0 = 11 years, number of overhauls for the next 30 years would be N_0 = 2 and for t_0 = 16 years, N_0 = 1. As we transitioned the overhaul interval from 11 to 16 years, the net increase in the repair cost was calculated to be around $4k but the net decrease in the total lifecycle cost was about $50k. This created a problem in reaching an optimum overhaul interval based on changing cost. From the reliability point of view, the probability of no major leaks for t_0 = 11 years was calculated to be 0.69 and for t_0 = 16 years, it was calculated to be 0.61, which provides a net decrease of 11.6% in the reliability of the equipment in the system.

5.4.2 Cost Implications

Considering the current overhaul interval of 8 years for TCV1-2, if the overhaul interval is extended to 11 years, the mean cost for operation for each TCV is expected to incur around $0.13M. This is a saving of $0.05M, from the $0.18M being incurred as per the simulated model keeping $t_0 = 8$ years. For the pool of 16 TCV1-2 combined, this results in a cost saving of $700K in the next thirty years. Similarly, if $t_0 = 16$ years, then the net cost savings are $1.4M, which is almost double the savings as calculated for when t_0 is kept 11 years. These savings are largely due to the fact that 85% of the cost was for overhauling the TCVs. Therefore, extending the overhaul interval lead to these cost implications. The reliability analysis are used to calculate the probability of first major leak resulted in a decline of 8% if the overhaul is extended to 11 years and 18.6% if the overhaul is extended to 16 years.

Chapter 6

Conclusion

In this document, a lifecycle cost analysis based on preventive and corrective maintenance data was performed. The aim of lifecycle cost analysis was to cover all the aspects of the 20 year operating experience data provided. A number of key elements were required to calculate the complete operation cost of the equipment. These were the cost of deterministic and probabilistic elements for maintenance. The stochastic point process models were used to analyze the failure data and model the major and minor leaks. Maximum Likelihood method in general, is the most widely used method of parameter estimation. It was used in statistical estimation of the point process model. The interarrival times for leaks, assumed to be following the power law, are observed to be increasing after every repair formed. This implies the quality of repairs performed on the TCVs are excellent. For simulating the operating cost model, each input for the simulation model was considered to follow a different probability distribution. Even still, it was interesting to note that the final operating cost distribution followed the well-known gamma parametric distribution, instead of obtaining any complex mathematical function. The variation of the final repair cost at each overhaul interval was observed to follow the Weibull distribution. This model helped in investigating the optimum duration of the overhaul interval for the TCV. Even though a minima based on increasing repair cost and decreasing overhaul cost was not reached, the lifecycle cost was discussed for extended overhaul intervals based on the number of overhauls to be performed in the next thirty years. This was analyzed in the light of reliability results for extended overhaul intervals.

Finally, this thesis explored real industrial data, using it as an intricate part of the analysis to gauge the engineering applications of theoretical concepts.

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Appendix A

Best Fit lifetime distribution parameter estimates

The lifetime data was further categorized into overhaul intervals OH1-2 and OH2-4 to observe the difference in the behavior of valves before and after the second overhaul. These time to failures data points are now categorized herewith.

CASE 1: TCV#1-2 and All OH intervals

This is the first case in which fault observations costing greater than $10,000 are considered for TCV#1-2.

Table 0-1: Case1: TCV1-2 & All OH intervals

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	9.53	2.27	495.8	-92.2	188.3
Weibull	13822.14	0.80	42.8	-92.4	188.8
Gamma	0.78	17221.18	36.9	-92.4	188.9
Exponential	9715.45	0.00	26.6	-92.6	189.2
Normal	4521.86	2523.13	12.4	-97.2	198.5

CASE 2: TCV#1-2 and OH1-2

In this case the fault observations costing greater than $10,000 occurring within first overhaul interval are considered for TCV#1-2.

Table 0-2: Case2: TCV1-2 & OH1-2

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	9.14	1.83	136.1	-41.7	87.4
Exponential	9645.00		26.4	-42.1	88.2
Weibull	10939.81	0.91	31.3	-42.1	88.2
Gamma	0.92	11489.88	29.0	-42.1	88.3
Normal	4591.93	2614.73	12.6	-44.0	91.9

CASE 3: TCV#1-2 and OH2-4

In this case the fault observations costing greater than $10,000 occurring after second overhaul are considered for TCV#1-2.

Table 0-3: Case3: TCV1-2 & OH2-4

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	9.85	2.58	1436.3	-50.1	104.2
Gamma	0.71	23400.78	45.2	-50.2	104.3
Weibull	17140.18	0.73	57.2	-50.2	104.3
Exponential	9774.17		26.8	-50.5	105.0
Normal	4461.89	2455.87	12.2	-53.3	110.6

CASE 4: TCV#3 type CV600 and All OH intervals

In this case the fault observations costing greater than $10,000 are considered for TCV#3 type CV600 valves.

Table 0-4: Case4: TCV3-CV600 & All OH intervals

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	7.81	1.00	11.2	-75.3	154.5
Gamma	1.62	1944.98	8.6	-76.5	156.9
Weibull	3457.62	1.30	8.7	-77.2	158.3
Exponential	4146.50		11.4	-78.3	160.6
Normal	2573.59	1521.26	7.1	-79.5	163.1

CASE 5: TCV#3 type CV600 and OH1-2

In this case the fault observations costing greater than $10,000 occurring within first overhaul interval are considered for TCV#3 type CV600 valves.

Table 0-5: Case5: TCV3-CV600 & OH1-2

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	7.43	0.94	7.1	-58.0	120.0
Gamma	1.58	1431.16	6.2	-59.2	122.4
Weibull	2481.29	1.23	6.4	-59.9	123.7
Exponential	2673.00		7.3	-60.7	125.4
Normal	1977.41	1357.31	5.4	-61.9	127.8

CASE 5: TCV#3 type CV600 and OH2-4

In this case the fault observations costing greater than $10,000 occurring after second overhaul are considered for TCV#3 type CV600 valves.

Table 0-6: Case6: TCV3-CV-600 & OH2-4

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	8.25	0.73	13.7	-15.6	35.3
Gamma	2.85	1506.87	11.8	-15.9	35.9
Weibull	4820.18	1.92	11.7	-16.3	36.5
Normal	3633.62	1562.52	10.0	-16.6	37.1
Exponential	10040.50		27.5	-17.0	38.0

CASE 5: TCV#3 type Fisher657 and OH2-4

In this case the fault observations costing greater than $10,000 occurring after second overhaul are considered for TCV#3 type CV600 valves.

Table 0-7: Case7: TCV3-Fisher657 & OH2-4

Distribution	Par1	Par2	MTTF (years)	LL	AIC
Lognormal	7.85	0.41	7.7	-7.2	18.3
Gamma	7.46	360.82	7.4	-7.2	18.5

Weibull	2962.53	3.30	7.3	-7.5	19.0
Exponential	7791.00		21.3	-8.4	20.7

Final Extract considering Weibull lifetime distributions.

Table 0-8: Estimated Parameters of Weibull dist. for TTF

Valve	Interval	Scale β (*years*)	Shape α	COV	Mean TTF (years)	Median TTF (years)
TCV1-2	All	37.9	0.80	1.3	42.8	24.0
TCV1-2	OH1-2	30.0	0.91	1.1	31.3	20.1
TCV1-2	OH2-4	47.0	0.73	1.4	57.2	28.4
TCV3-CV600	All	9.5	1.30	0.8	8.7	7.2
TCV3-CV600	OH1-2	6.8	1.23	0.8	6.4	5.0
TCV3-CV600	OH2-4	13.2	1.92	0.5	11.7	10.9
TCV3-Fisher657	OH2-4	8.1	3.30	0.3	7.3	7.3

Corresponding reliability results w.r.t the Weibull lifetime distribution model the reliability estimates for extended overhaul intervals are given as follows.

Valve	Interval	8	10	12	15	20
TCV1-2	All	0.75	0.71	0.67	0.62	0.55
TCV1-2	OH1-2	0.74	0.69	0.65	0.59	0.50
TCV1-2	OH2-4	0.76	0.72	0.69	0.65	0.58
TCV3-CV600	All	0.45	0.34	0.26	0.16	0.07
TCV3-CV600	OH1-2	0.29	0.20	0.13	0.07	0.02
TCV3-CV600	OH2-4	0.68	0.56	0.44	0.28	0.11
TCV3-Fisher657	OH2-4	0.39	0.14	0.03	0.00	0.00